Upcycling Rare Earth Elements from E-waste: Early Evidence and Policy Directions from NEO-CYCLE project

NEO-CYCLE Policy brief No. 1

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This policy brief presents the progress of the NEO-CYCLE project after 18 months of implementation and outlines the way forward

Key results

- NEO-CYCLE has already demonstrated **lab-scale** validation that solid state chlorination (SSC) and electrochemical leaching enable the **recovery of Nd, Fe and B from HDDs (hard disk drives) magnets** converting them into usable secondary feedstocks.
- Lab-scale validated SSC and electrochemical leaching processes achieve **high Nd, Fe and B recovery rates** from HDDs magnets.
- Preliminary sustainability assessments highlight the critical **role of social aspects** and end-to-end value chain cooperation for successful **upcycling**.

Key directions forward

- **Creating market** for recycled materials
- **Ensuring** reliable **feedstock** for recycling
- **Propelling** recyclability and sustainability **data transparency**
- **Mainstreaming upcycling**
- **Creating financial incentives** for pilots of recycling and upcycling technologies and market uptake

Problem and context

Waste electrical and electronic equipment (WEEE) is one of the fastest-growing waste streams in Europe, and permanent magnets in electronics are an important but poorly recycled source of neodymium (Nd), iron (Fe) and boron (B).

The **Waste Electrical and Electronic Equipment** Directive (2012/19/EU)[1] already requires separate collection, proper treatment and minimum recovery and recycling targets for e-waste, but estimations show that m**ore than half of WEEE is still not collected** (Eurostat, 2025)[2] and that **recovery of critical raw materials (CRMs)**, such as rare earth elements in magnets, remains **limited.** These elements are strategic for clean technologies (e.g. wind turbines, electric vehicles, industrial motors), yet today they are largely supplied from mining outside the EU (EU, 2025)[3], exposing European industry to supply, price, and geopolitical **risks**.

In 2024, the **Critical Raw Materials Act** (CRMA) (Regulation (EU) 2024/1252)[4] established a common EU framework to **secure and diversify supplies of strategic and critical raw materials**, including **through higher recycling rates** and the development of Strategic Projects along the value chain. At the same time, existing recycling routes for rare-earth magnets are limited, energy-intensive, or not yet scalable, and they rarely produce high-value secondary products that can compete with primary raw materials.
New approaches and technologies boosting WEEE recycling and recovering CRM and tackling supply disruption risks are crucial.

NEO-CYCLE approach

The NEO-CYCLE project addresses these challenges by **developing and upscaling** integrated routes to recover Nd, Fe and B from end-of-life magnets and upcycle them into value-added products such as chemical intermediates, catalysts and functional materials. The project encompasses the whole value chain: from WEEE collection and magnet inventory (WP4), through process upscaling (WP5), upcycling into new products (WP6), digitalisation and model-based optimisation (WP7), to early sustainability and techno-economic assessments (WP9).

NEO-CYCLE aims to demonstrate, at TRL6, the sustainable upcycling of spent NdFeB magnets from hard disk drives, yielding high-quality end products in 4 industrial cases: pharmaceuticals, ammonia, fertilisers, and polymers.

[1] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32012L0019
[2] Eurostat. 2025. Waste statistics - electrical and electronic equipment. Availablehttps://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment
[3] European Union. 2025. Study supporting the evaluation of Directive 2012/19/EU on waste electrical and electronic equipment (WEEE). Directorate-General for Environment. Available via: https://environment.ec.europa.eu/news/new-evaluation-looks-how-improve-weee-directive-2025-07-02_en
[4] Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials. Available: https://eur-lex.europa.eu/eli/reg/2024/1252/oj/eng

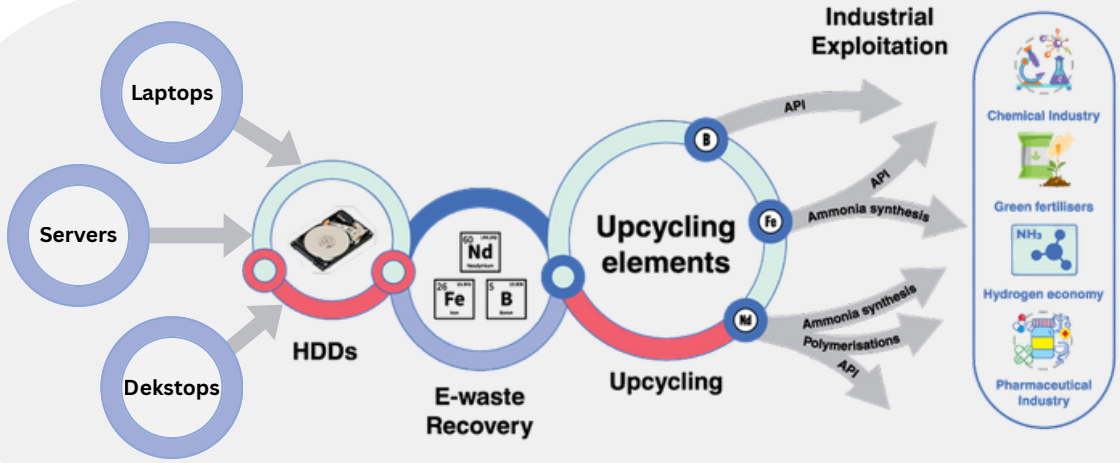


Fig.1. Conceptual scheme of Nd, Fe, B recovery and upcycling from e-waste in NEO-CYCLE project

Core technological pillars of NEO-CYCLE:

• Two complementary extraction routes for NdFeB: (i) **solid-state chlorination (SSC)** in a rotary kiln, and (ii) **a non-selective electrochemical leaching (SENE)** route using an electrochemical cell.

• **Hydrometallurgical separation and purification** to obtain Nd oxalate/oxide, Fe hydroxides and boron oxides from both routes.

• **Upcycling pathways** that convert recovered Nd, Fe and B **into advanced catalysts, nanomaterials and active pharmaceutical ingredient (API) precursors, including applications in agriculture and fertiliser production.**

• Digital twins and model-based **optimisation** to design, control and scale the processes efficiently from lab to pilot case.

• **Sustainability assessments** (life cycle assessment **(LCA)**, life cycle costing **(LCC)**, social life cycle assessment **(S-LCA)**, circularity indicators and digital product passport **(DPP)**) to guide technology development from the outset towards robust environmental, economic and social performance

Nd, Fe and B extraction and recovery: first results

Solid-state chlorination:

- Lab workflows and mass balance have been established as a basis for a **200 kg $Nd_2Fe_{14}B$** pilot concept, covering crushing, mixing with NH_4Cl, rotary kiln operation at 300–600 °C, gas treatment and downstream leaching/precipitation.
- Conceptual and basic engineering for an SSC pilot plant, including block flow diagram, process flow diagram, equipment list and preliminary P&ID (Piping and Instrumentation Diagram), is completed, enabling upscaling to **200–500 kg per batch**.

Electrochemical leaching:

- A physics-based Poisson–Nernst–Planck model for the electrochemical cell has been developed, capturing electromigration, diffusion, precipitation and electrode reactions.

Separation and purification:

- Nd and Fe are separated via leaching and oxalate/$Fe(OH)_3$ precipitation, with lab-scale proof that **Nd oxalate and Fe hydroxide meeting downstream requirements** can be obtained from both SSC and SENE leachates.
- **Boron recovery** has been demonstrated using ion exchange and precipitation, with concentration factors >10 from SENE leachates and pathways to boric acid/boron oxide for further use in catalysts or fertilisers.

Sustainability of upcycling: preliminary assessments

Preliminary **life cycle sustainability assessments** (LCSA) guide the technical partners (WP4) towards more sustainable processes **for future scale-up**. This assessment uses low-TRL data, mainly from lab-scale experiments, so it must be considered that the processes are not yet optimised, which may lead to higher sustainability impacts. Nevertheless, when assessing these processes, it is important to consider that they are competitive with established markets and optimised processes outside Europe, and that NEO-CYCLE is shaping a European value chain for CRM.

- LCA results using the **Product Environmental Footprint (PEF)** method show that **Eutrophication and Resource Use** are the most significantly affected impact categories within NEOCYCLE's WP4 processes.
- A low-TRL adapted **LCC** shows that, at this stage, **costs are mainly driven by labour and energy use**.
- The **S-LCA** indicates that the **Society subcategory has the highest risk**.

Alignment of the project results with EU policies

NEO-CYCLE provides bankable evidence that CRMA/WEEE policy targets are achievable, offering policymakers the technical roadmap to turn e-waste magnets into high-value EU supply chains:

NEO-CYCLE and the Critical Raw Materials Act

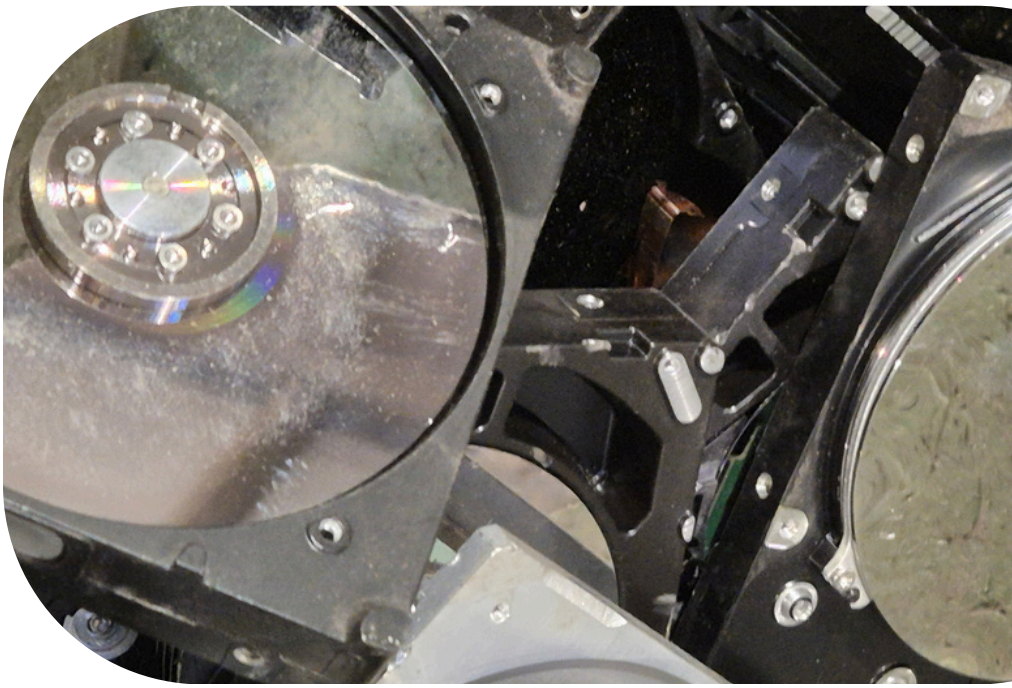
The Critical Raw Materials Act requires 25% of EU annual consumption of strategic raw materials to come from recycling by 2030, alongside support for Strategic Projects that meet technical, sustainability and social criteria. **NEO-CYCLE provides the technical evidence that this NdFeB recycling target is achievable at TRL6, by**:

- Demonstrating lab-scale SSC and SENE routes that **recover Nd, Fe and B** from WEEE magnets, with **TRL5–6 pilots** ready to prove industrial feasibility for Strategic Projects.
- Developing LCAs, LCCs and S-LCA that meet CRMA requirements for **environmental/social robustness and cross-border benefits**.
- Creating **circularity indicators and DPP prototypes** to track recycling capacity and secondary flows from waste streams.

NEO-CYCLE and WEEE Directive and its revision

Recent evaluations (EU, 2025)[5] of WEEE Directive highlight important gaps within implementation: many Member States do not meet the 65% collection target; only around 40% of WEEE is recycled; recovery of critical raw materials, such as rare earth elements, from small electronics remains very low; and treatment quality varies significantly across facilities. **NEO-CYCLE directly addresses these gaps for NdFeB magnet-containing equipment by:**

- **Demonstrating technically feasible processes** to recover neodymium, iron and boron from **end-of-life ICT equipment** (laptops, servers, desktops), thereby increasing the potential material yield per tonne of collected WEEE and showcasing "high-quality recycling" of critical materials.
- Providing process-level LCA, LCC and S-LCA data that can **inform future minimum treatment standards, quality criteria and secondary-material benchmarks** in the revision of the **WEEE** Directive and the upcoming **Circular Economy Act.**
- Developing DPP concept and circularity indicators that can **support better tracking of magnet-containing products, improve transparency along take-back and treatment chains**, and underpin more harmonised Extended Producer Responsibility (EPR) approaches for CRM-rich e-waste.



[5] EU. 2025. Study supporting the evaluation of Directive 2012/19/EU on waste electrical and electronic equipment (WEEE). Directorate-General for Environment. Available via: https://environment.ec.europa.eu/news/new-evaluation-looks-how-improve-weee-directive-2025-07-02_en

Strategic policy pillars to advance upcycling of rare earth elements

Market Creation *(to close the price gap and boost demand for secondary CRM)*

- **Mandate minimum recycled content** (10–15%) for permanent magnets in new EU **electronics and electric vehicles** (EVs).
- **Provide financial incentives** using NEO-CYCLE's LCC data to justify **price premiums during scale-up** and incentivising **Carbon Border Adjustment Mechanism** (CBAM) for recycled content or revising **environmental subsidies** to reward lower long-term footprints of upcycled materials.
- **Require "green" certification** for pharmaceuticals and catalysts to prioritise secondary Nd/B inputs, converting WEEE magnets into **high-value chemical intermediates rather than just raw magnets.**

Supply Security (*for reliable feedstock*) and Capacity Building

- **Set NdFeB magnet-specific collection and recovery targets** within CRMA/WEEE frameworks, treating ICT equipment (laptops/servers) as priority stream and mandating pre-treatment to maximise rare-earth yield.
- **Establish legislative frameworks for Circular Economy Innovation Clusters** linking WEEE recyclers, chemical/pharma industries and public authorities, with dedicated Important Projects of Common European Interest (IPCEI) or Innovation Fund windows for rare-earth elements upcycling pilots.
- **Push forward clustering of the projects** to support the identification of clustering priorities and **value-chain segments with the highest engagement potentia**l, enabling identification of expertise, overlapping areas of activity and potential gaps along the value chain.

Data Transparency and Access (*to reduce costs via DPP and improved sustainability performance*)

- **Mandate magnet composition and "ease-of-access" data in DPPs** for all computer components/servers, enabling recyclers to optimise pre-treatment and lowering processing costs by 20–30%.
- **Use NEO-CYCLE's LCA/LCC baselines to define high-quality WEEE treatment standards** in the WEEE Directive revision, ensuring CRM recovery while meeting environmental/social benchmarks.

NEO-CYCLE Resources

The implementation of the NEO-CYCLE project will continue until 31 August 2028.

The project does/will carry out various activities: training on E-waste recycling technologies; targeted activities to develop stakeholder cooperation; training on soft skills development; women's leadership in research and innovation; and support for sustainable development.

Website: https://neo-cycle.eu/

LinkedIn: https://www.linkedin.com/company/neo-cycle

X.com: https://x.com/neo_cycle

ZENODO: https://zenodo.org/communities/neo-cycle

YouTube: https://www.youtube.com/@NEO-CYCLE

Interactive 'magnetic' E-waste quiz: NEO-CYCLE quiz

Stakeholder engagement tool: https://neo-cycle.eu/stakeholders/

Compiled by AEI with main contributions from VMU, LCI, IDENER, ASRO, EcoCastulum, Flamma , Holoss, TUBAF, UniTO

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