Rare Earth Circular Economy

Innovation Landscape Report

Contents

Written by Dr Amy Romaniuk, Innovate UK Business Connect

Edited by Dr Matthew Reeves, Innovate UK Business Connect

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1. Executive Summary

This Innovation Landscape Report on Rare Earth Circular Economy forms part of a series of reports into the UK Rare Earth Elements (REEs) Value Chain, commissioned by Innovate UK as part of the Circular Critical Materials Supply Chains (CLIMATES) Programme which was established to develop and support critical materials supply chains within the UK, beginning with REEs.

Other reports in the series include Rare Earth Exploration, Extraction, Beneficiation and Concentration, Rare Earth Processing, Rare Earth Permanent Magnet Manufacturing and Rare Earth Permanent Magnet Alternatives

This report aims to summarise the UK opportunity and the current state of the innovations being developed for the circular economy of REEs, including the recycling of Rare Earth Permanent Magnets (REPMs).

This includes mapping technologies and capabilities that already exist within the UK, and highlighting gaps that require future innovation support and investment, focusing on the following circular economy topics along the value chain:

- **Extraction and mining**
- **Design for recycling and disassembly**
- **Collection, sorting, and disassembly of magnet-containing products**
- **Direct reuse strategies for permanent magnets**
- **Short-loop recycling methods for REPMs**
- **Long-loop recycling methods for REPMs**
- **Magnet manufacturing**
- **Materials tracking**

2. Background context

The 2024 Criticality Assessment has identified minerals considered key to the UK economy and vital to many modern technologies.

Thirty four minerals or material groupings are identified as being "critical", including those required for battery manufacture, such as lithium and cobalt.

Rare earth elements (REE) are key to the production of permanent magnets and continue to feature on the critical minerals list, since permanent magnets are a key component of electrical parts found within net-zero technologies such as wind turbines and electric vehicles.

Work by the British Geological Survey (BGS) alongside the UK Critical Mineral Strategy identified REE as being susceptible to threats in economic and supply disruption due to reliance on overseas markets.

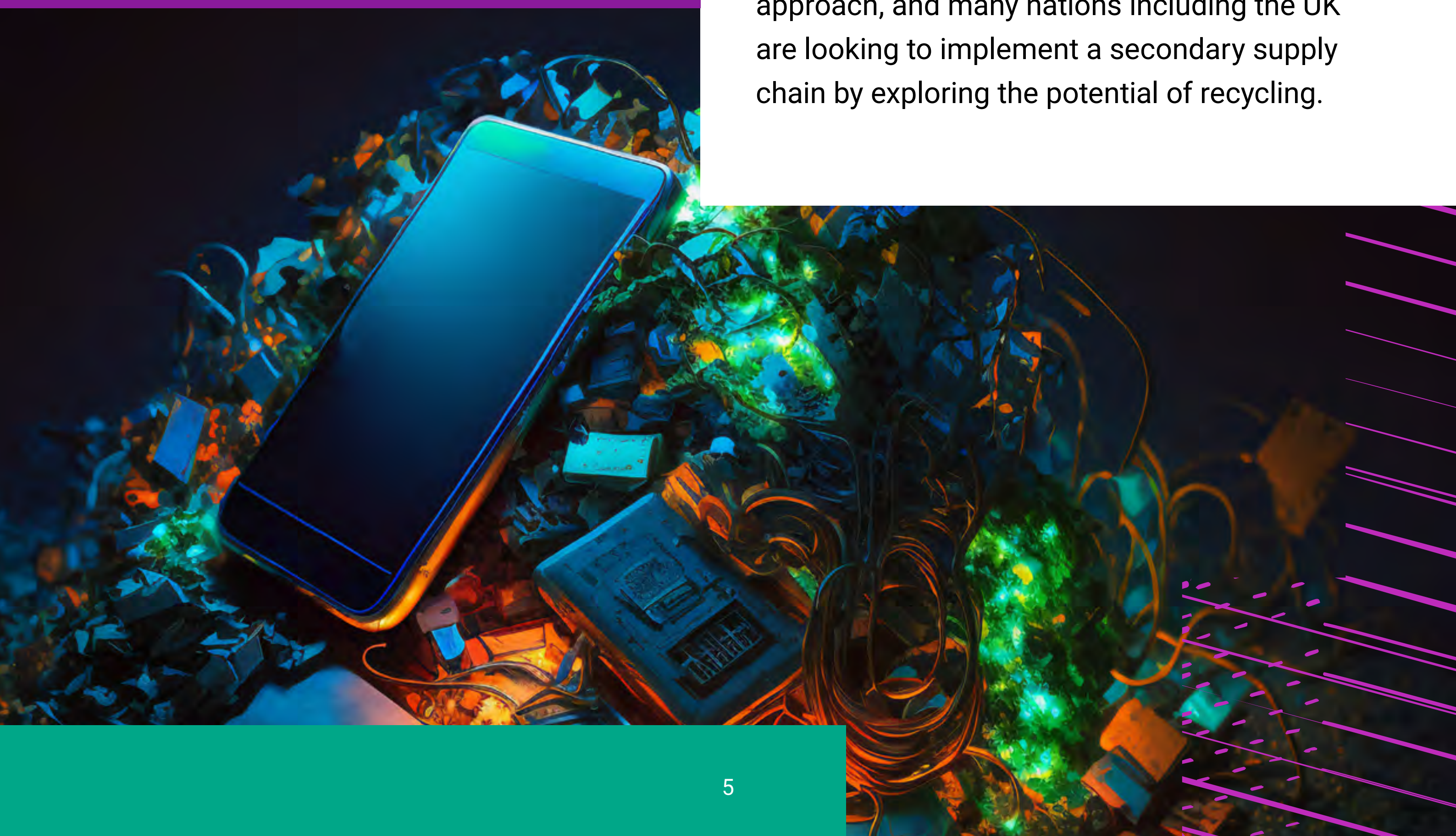
While there is an abundance of REPM distributors residing in the UK, most magnets are manufactured overseas, with China being the leading supplier of REPM, as well as being the main producer of primary REE, accounting for over 60% of production and 90% of refining.

Over the past 20 years, China has implemented policies to maintain its leading market share in the supply of REE and REPM, increasing risks and creating volatility in the supply chain for nations which rely on these minerals to meet the demand for clean energy technologies (León & Daphne, 2023).

Working with international collaborators, the UK Critical Mineral Strategy commits to expand UK capability and to source and supply critical minerals, support global critical mineral markets, and encourage responsibility and transparency in the supply of these key minerals.

In doing so, the strategy highlights the importance of a circular economy approach as an alternative way to achieving a secure supply of REE to produce new magnets, eliminating the need to rely on primary REE supply.

Recycling end of life (EoL) products for magnet material to create a secondary supply of REPM may enable a viable circular approach, and many nations including the UK are looking to implement a secondary supply chain by exploring the potential of recycling.



3. Introducing the circular supply chain

A circular economy can be described as a systems approach to an industry where the production of waste is avoided by ensuring products are designed in a way that the product and/or the material has longevity, or can be reused, recycled or composted.

The Ellen Macarthur Foundation states that a circular economy should benefit business, people, and the environment, and alongside material reuse, should encourage environmentally friendly practices that consider biodiversity, minimise impact on nature, and commit to regeneration of the natural environment (Ellen Macarthur Foundation, n.d).

Circular supply chains are often guided by the principles of recovery, reuse, remanufacturing, and recycling, and tend to be more complex than a standard linear supply chain. In addition to reuse, recycling and remanufacturing, innovative business models are needed to turn EoL products into valuable commodities.

An example of a company that is pioneering circular economy principles in the automobile industry is Riversimple, a hydrogen-powered vehicle manufacturer based in Powys, Wales, that uses innovative and sustainable component designs, as well as having an innovative vehicle leasing business model, ensuring that Riversimple has control over the recycling and refurbishment of EoL vehicles and parts (Riversimple, 2023). This business model provides a sustainable, traceable, and transparent supply chain, which is considered to be of growing importance to consumers.

Circular economies are being considered by governments across the globe, with policies on circularity increasing. In 2024, Chatham House reported that 540 policies relating to circular economy have been published, spanning 110 countries, highlighting the dedication of policy makers to move away from linear economies (Barrie & Schröder, 2023). The EU has introduced policies such as the Waste Framework Directive (European Commission, n.d.), Eco-design for Sustainable Products Regulation (European Commission, n.d.), and the Circular Economy Action Plan (European Commission, n.d.) to support the transition to a green economy.

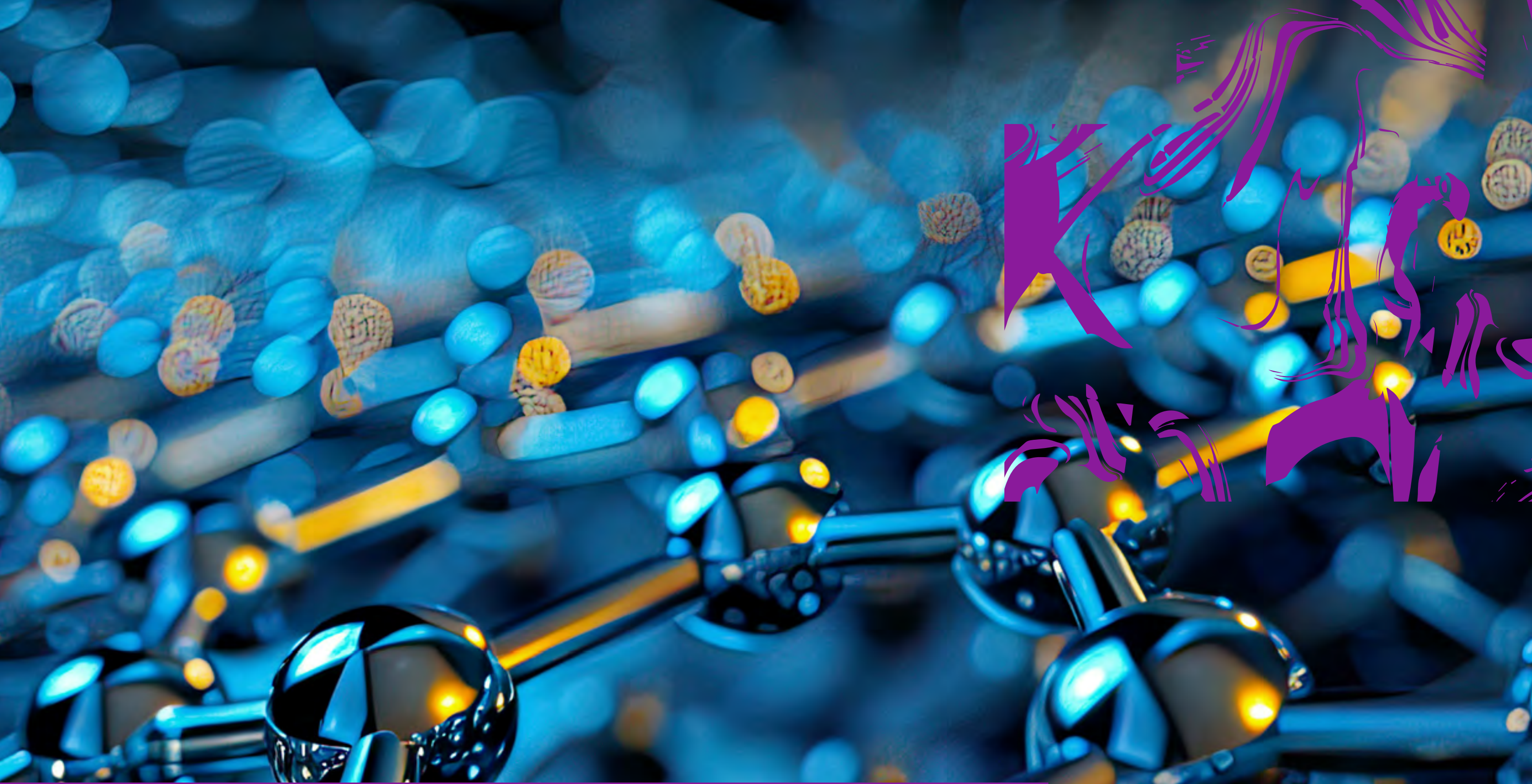
The UK government published a policy paper on a Circular Economy Package to reinforce its stance on sustainable economies since leaving the EU (Department for Environment, Food & Rural Affairs, 2020).

Furthermore, the UK has launched the UKRI National Interdisciplinary Circular Economy Research (NICER) programme, a £30 million programme funded by URKI to support the development of a circular economy for the UK. The NICER programme created the CE-Hub to coordinate activities across multiple sectors of the programme, and Met4Tech, a centre for circularity of technology metals, both led by Exeter University (UKRI National Interdisciplinary Circular Economy Research, 2022) .

Nonetheless, circular supply chains are complex, and in the case of REE and permanent magnets, careful consideration across the whole value chain is needed.

REE should be extracted and processed in a way that is responsible, sustainable, and that prioritises the use of low-energy and low-emission processes.

REPM and magnet-containing products should be manufactured following the same principles and designed in a way that ensures reuse, remanufacturing, and recycling once reaching EoL, ensuring the entire supply chain is traceable and transparent.



3.1 A vision for the UK's rare earth permanent magnet circular supply chain

To realise the value of a circular economy for REPMs, the products with the highest wt% of REE should be considered initially to demonstrate that producing new magnets from secondary supply of REE is commercially viable.

There are a range of material chemistries contained within the permanent magnet (PM) category (including SmCo, AlNiCo, ferrites, and others). The subclass of PMs, REPMs, that this report concerns are composed of an alloy of neodymium, iron, and boron (NdFeB), that might also contain a small amount of other REEs including praseodymium, dysprosium and terbium.

The REE content in (sintered) NdFeB magnets is around 30wt%. NdFeB magnets make up 95% of commercially manufactured permanent magnets due to their superior magnetic strength, physical robustness and high coercivity (resistance to demagnetisation), relative to other types (Zorpette, 2023).

These properties mean that NdFeB magnets are commonly the magnet of choice for the drive motors of hybrid and electric vehicles, as well as in the generators of offshore wind turbines.

Table 1 displays common products that may act as sources of secondary REEs for the circular economy and the associated lifespan of the product in which they are contained. Offshore wind turbine generators contain the largest magnets by weight and have lifespans of 25 years. The growing offshore wind industry and EV industry, sped up by the UK Industrial Decarbonisation Strategy (Department for Energy Security and Net Zero, 2021), will make these products increasingly viable as sources of secondary REEs.

NdFeB magnets can also be found in many consumer electronics technologies such as mobile phones, hard disk drives and smart TVs, medical technologies such as magnetic resonance imaging (MRI) scanners, and energy technologies such as photovoltaics.

Examples are shown in Table 1.

EoL Products containing NdFeB permanent magnets.

Product	Approx. Lifespan of Product	Approx. Magnet Size in Product (Yang et al, 2016)	Notes
Offshore Wind Turbine (generators)	Up to 25 years (National Gird, 2023)	1000-2000kg	16% of REE in 2007 were used for the wind industry (Kumari et al, 2018).
Electric Vehicles (drive motors)	15-20 years (National Grid, 2022)	1kg	2-5kg of magnets needed (approx. 1/5th of this is REE)
MRIs	10 years (Vikas, Sahu & Sharma, 2020)	200-750kg (Liang et al, 2022)	550-600 MRI scanners exist within UK hospitals (OECD, 2020)
Waste Electrical and Electronic Equipment	2-3 years	1-10g	REE also found in batteries, cathode ray tubes and circuit boards (Ramprasad et al, 2022)

The circular economy as envisioned for REE and permanent magnets is displayed in Figure 1 and follows the principles of reduce, reuse, recover, and recycle – **more details on alternative materials for permanent magnets are contained in Innovate UK's Rare Earth Permanent Magnet Alternatives report.**

REEs should be extracted in a manner that is responsible and sustainable, with considerations made to ensure minimal impact to the local environment.

Common ore types for the extraction of REE include monazite and bastnasite, as well as mineral sands and ion-adsorption clays. However, the REE of interest (e.g. Nd, Dy) are only ever present as small fractions of the ore bodies (approx. 1-5%), with less economically important lanthanum and cerium present in much larger quantities (>50wt%) **– more details on the mineralisation and abundance of REE are contained with the Innovate UK Rare Earth Element Exploration, Extraction, Beneficiation and Concentration report.**

REEs are processed into REE oxides before being metallised into alloys ready for magnet manufacture **– more details on these processes can be found within the Innovate UK Rare Earth Processing and Rare Earth Permanent Magnet Manufacturing reports.**

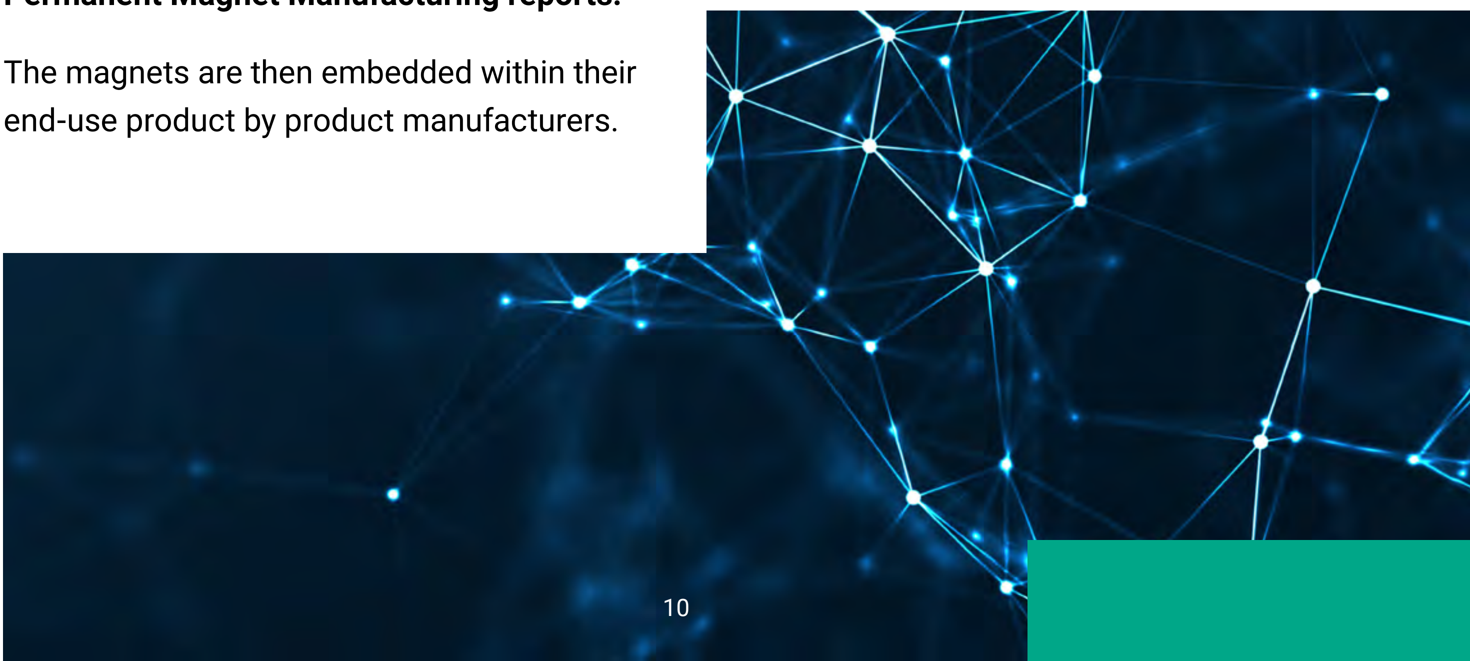
The magnets are then embedded within their end-use product by product manufacturers.

In addition to manufacturing of the magnets and products, a key principle for the circular economy that must be considered is designing products and components for disassembly and recycling **– this is discussed further in Section 4.2.**

For a REE circular economy, this means designing REPMs that have longevity but can be recycled when they become discarded or damaged.

It is also crucial to design magnet-containing products so they can be disassembled at EoL to recover the magnet. Once recovered, the magnet can be used directly in other products, recycled by remanufacturing the magnet material into new magnets (short-loop recycling), or recycled by reprocessing back into metals/metal oxides ready to be re-manufactured back into permanent magnets (long-loop recycling).

Finally, throughout the circular supply chain, materials tracking should be used to trace REEs, including from primary extraction to re-entering the supply chain as secondary REEs, to encourage sustainable and responsible use of natural resources by showcasing transparency in the supply chain.



A circular rare earth permanent magnet supply chain.

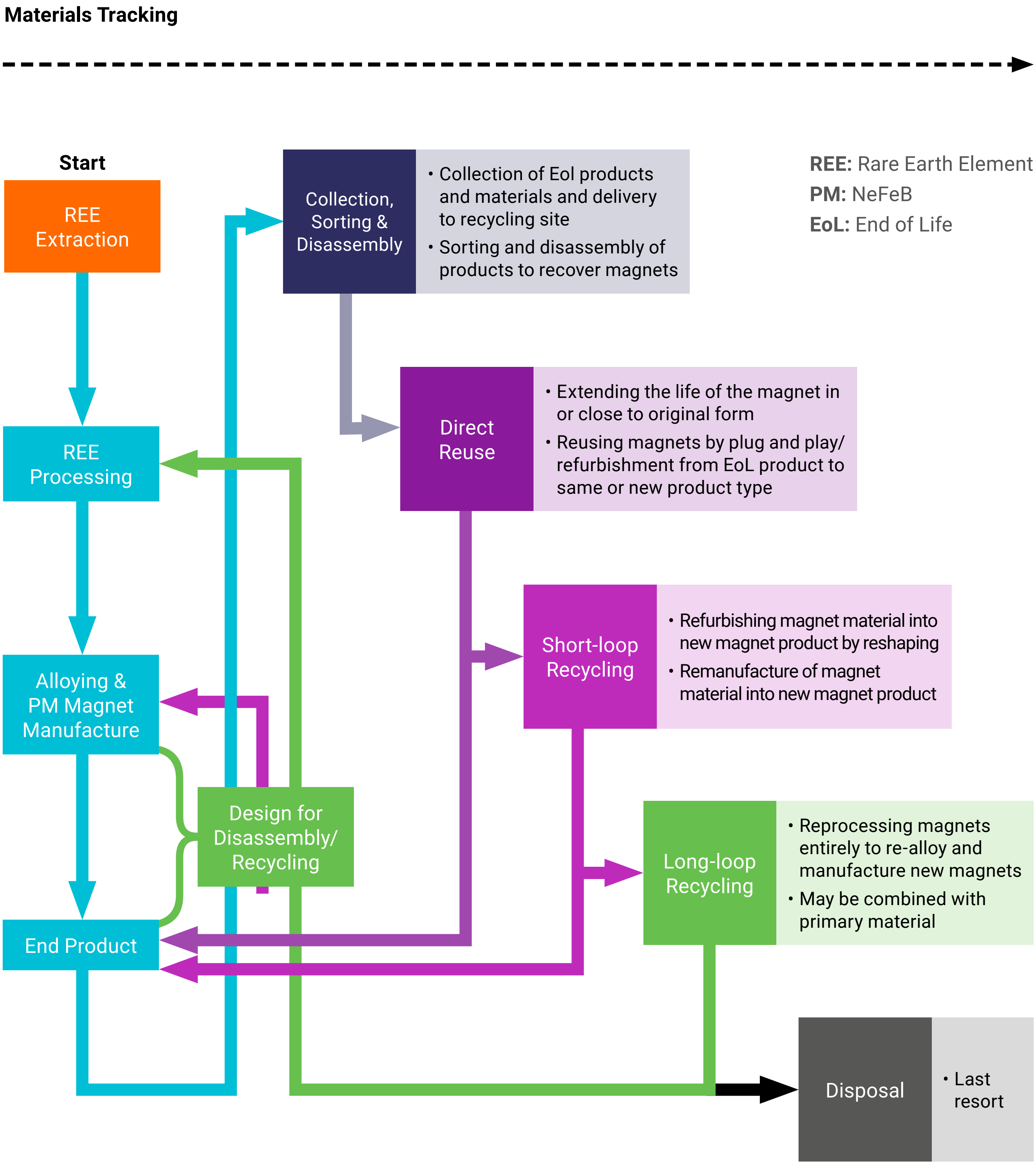


Figure 1: A circular rare earth permanent magnet supply chain

Battery Circularity

It is estimated that 150,000 tonnes of electric vehicle batteries will reach end of life per year by 2035 (Piperidou & Hindocha, 2023).

Cobalt and lithium are needed for the manufacture of electric vehicle batteries, and like REE, are listed on the UK's Critical Minerals list. Significant progress has been made globally towards a circular economy for batteries that will ensure a sustainable, transparent, and responsible supply chain.

The Global Battery Alliance (GBA) (Global Battery Alliance, 2025) was created to "establish a sustainable and responsible battery value chain". The GBA is a collaboration of over 150 organisations including industry, academia, and government, and has set up a Critical Minerals Advisory Group developing a digital passport for batteries and working towards increasing access to energy through the GBA's Access to Energy programme.

Innovate UK published the UK Battery Recycling Vision to 2035 report (Piperidou & Hindocha, 2023) which sets out steps to ensure that the UK is primed and ready to capitalise on a secondary battery supply chain by establishing a circular economy that recovers battery materials as feedstock for UK battery manufacturing facilities.

3.2 Driving forces for a rare earth permanent magnet circular supply chain

Various factors are at play to drive the UK towards a circular REPM supply chain.

- **Strategic supply –** China continues to dominate the REE supply chain, with 70% of all REE being mined and produced in China in 2022 (Liu et al, 2023). The growing net-zero economy in the UK will mean that local demand will increase, making the UK vulnerable to geopolitical supply chain risks. At the same time, the UK will have to compete with global players as their demand also increases for net-zero technologies and their associated materials. As no primary (domestic) REE production industry exists within the UK, strategic supply of secondary REE provides an opportunity for an emerging industry, as well as security over the supply to domestic sustainable industries.
- **Sustainability –** Over recent years, the UK has seen an increase in the demand for electric vehicles and a growing wind industry because of consumer demand for more sustainable transport, as well as domestic policy incentives that have contributed to increase in demand for REE-containing products. This has led to a drive to recover materials, create recycling streams, and send less to landfills.
- **Future state of materials –** There is a predicted volume increase as demand for EV and turbine generators is expected to increase significantly in coming years. The global demand for REEs is expected to more than triple by 2040 (IEA, n.d.).
- **Economic opportunity –** Recovery of REE from magnets found within EoL products is an emerging industry within the UK.

3.3 Barriers to a rare earth permanent magnet circular supply chain

- **Recycling supply chain and logistics –** At present, there is no national waste collection pathway for the recovery and collection of magnets and magnet-containing products. Acquisition of waste is currently being managed on an individual basis by those interested in developing a secondary REE supply chain.
- **Recovery of permanent magnets from waste streams –** Technical challenges exist in the recovery of permanent magnets from products. REPMs vary in size and shape and, in the case of electric vehicles, are found in multiple locations, in addition to the drive motor. This makes the process of full recovery of REPMs very labour-intensive, which is cost and time prohibitive.
- **Lack of incentives –** No specific incentives exist to encourage recycling of REPMs in the consumer and commercial landscape yet. Similarly, there is a lack of incentive for businesses to explore circular business models.
- **Commercial viability –** For recycling companies, current processes are not yet commercially viable and the post-removal supply chain doesn't fundamentally exist yet. There is no cost forecast for magnets recovered to-date with which to compare to the primary supply chain. Magnets produced by secondary material need to be available at a reasonable cost to be attractive.
- **Funding –** There is a need to demonstrate remanufacturing and recycling processes at scale. This will require capital to scale processes and infrastructure; therefore, investment is needed to allow companies to grow to meet demand.
- **Regulation & legislation –** Clarity on regulation is needed to allow organisations to recycle and reprocess in a compliant manner.
- **Competing with primary extraction of REEs –** The barrier to market entry is high for secondary material while primary extraction materials remain plentiful and low-cost for producers in areas such as China. In addition to cost, recycled REPMs need to compete on quality compared to those produced via primary supply.
- **Timing –** Larger magnets, such as those used in offshore renewables, have long product lifespans and therefore long lead times exist for recirculation of these materials.

4. State of the innovation

Innovation related to developing a circular REE economy within the UK is an active area.

Various projects have been funded through 2023 and 2024 via the CLIMATES programme and the outcomes of these projects will have a positive impact on REE circularity and will support the development of the innovations in this area.

4.1 Extraction and mining

At the point of extraction and mining for REEs, there are various considerations that can and should be made relevant to the circular economy.

Use of electric or hybrid vehicles on site means lower emissions associated directly with mining. Mining companies with good sustainability credentials and use of mining waste and byproducts can be considered under the principles of a circular economy (Onstad, 2023).

Mining for REEs isn't actively taking place within the UK, however more broadly in Europe, exploration for REEs is taking place in Greenland and Sweden (Goodenough et al, 2015).

REE-containing deposits have been found in Sweden (Per Geijer, Karuna) and in Southern Greenland. Nonetheless, opportunities do exist for UK-based innovations to contribute to the supply chain via innovations that support extraction and mining activity, as well as exploring opportunities for extraction from alternative sources of REE such as local mining wastes, fly ash and other by-products.

Waste valorisation by extracting REE from mine tailings (the leftover material after extracting the main mineral product from the ore) is an area of increasing international interest. Mine tailings are the most valuable waste and are likely to contain the most REEs from all mining wastes (Kinnunen et al, 2022).

Extraction and mining innovation is covered in detail in the Innovate UK Rare Earth Element Exploration, Extraction, Beneficiation and Concentration report.

Innovations and UK capability

While mining isn't actively taking place in the UK, many organisations are active in projects related to extraction.

Table 2 summarises projects with UK involvement related to extraction.

Relevant Projects **Table 2 –** Projects associated with extraction of REEs.

Project Title	Project Partners	Funder	Project Value	Summary
Closing the loop on REEs for MAGnets (REEMAG)	Nanomox Ltd, Science and Technologies Facilities Council, Green Rose Chemistry Ltd	Innovate UK (CLIMATES cohort 1)	£290K	Valorisation of magnet waste
A Sustainable Solution for the Recovery of Scandium and Yttrium from UK generated TiO2 Waste	GSA, University of Lincoln	Innovate UK (CLIMATES cohort 1)	£633K	Recovery of REE from titanium oxide waste
PhytoREE	Phyona, Brunel University	Innovate UK (CLIMATES cohort 1)	£89K	Plant based extraction of REE from old colliory sites by phytomining
Mine to Magnets – Securing a Supply of Rare Earth Elements from Volcanic Tuffs for UK Magnet Manufacture	Seloxium, University of Oxford	Innovate UK (CLIMATES cohort 1)	£472K	Exploring the extraction of REE from geo-thermal wells located in and around volcanic tufts
Creating a low carbon, environmentally sustainable and socially just value chain for rare earth magnets	Pensana	Innovate UK (CLIMATES cohort 1)	£317K	
ReREE: Establishing feasibility of a novel process to recover rare earth elements from mining tailings for re-entry into a UK supply chain	Altilium, University of Exeter	Innovate UK (CLIMATES cohort 1)	£436K	Feasibility, economic and environmental assessment of REE recovery from mine tailings
ROTATE	Imperial College London	EU Funded (Horizon Europe)	€14.2M total cost	Developing net zero technologies including technologies for valorisation of waste for extraction of critical minerals

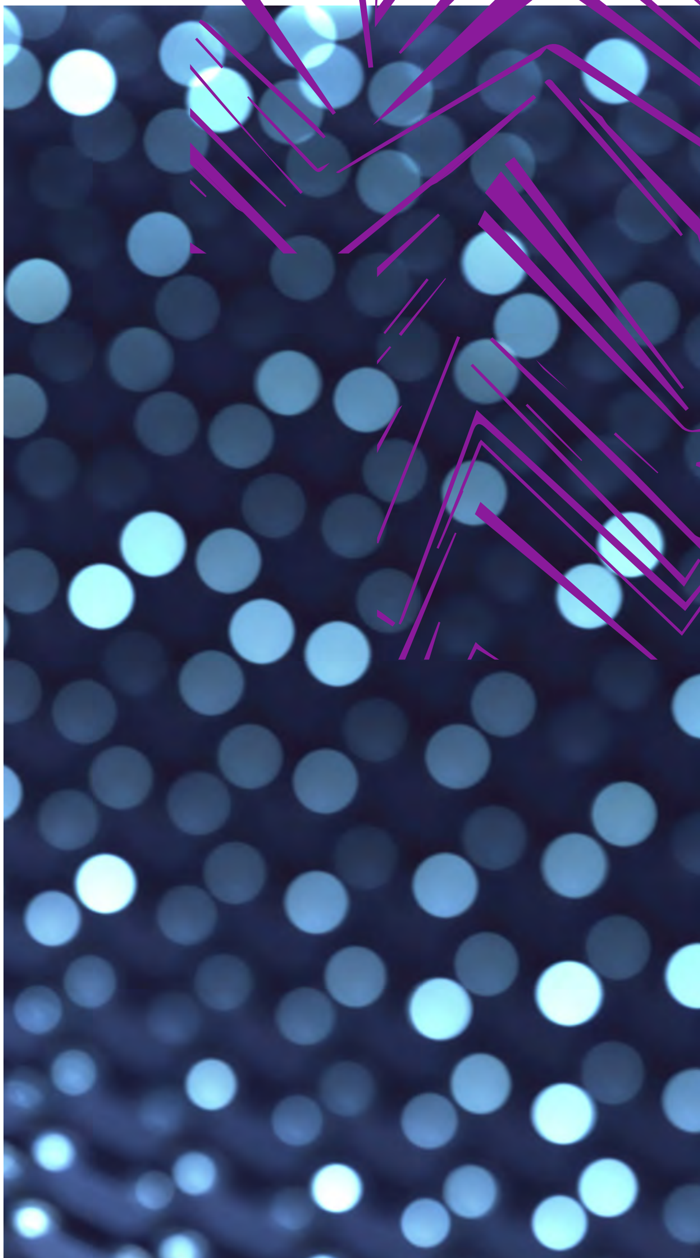
Note: For EU projects, only UK partners have been specified

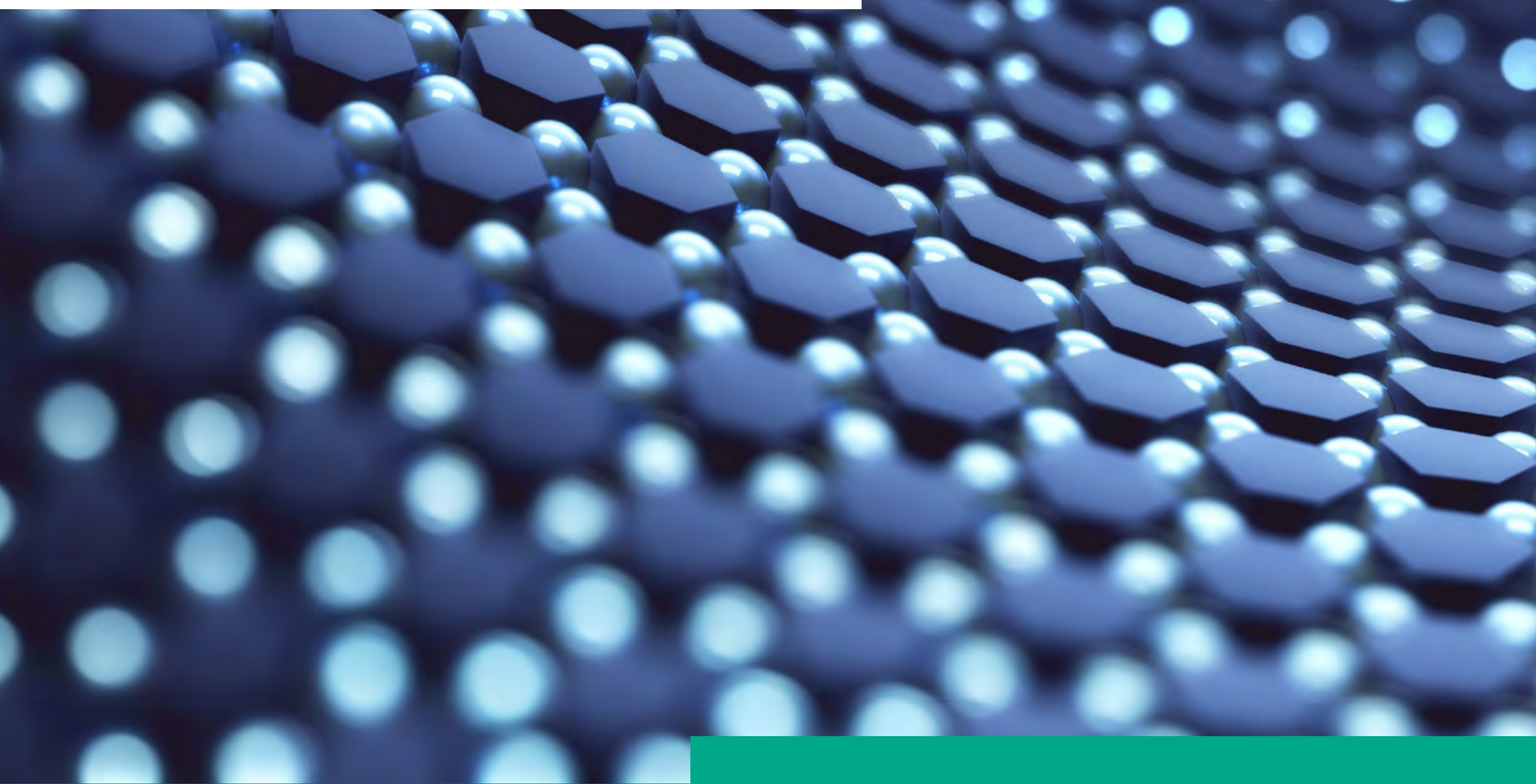
Observations and recommendations

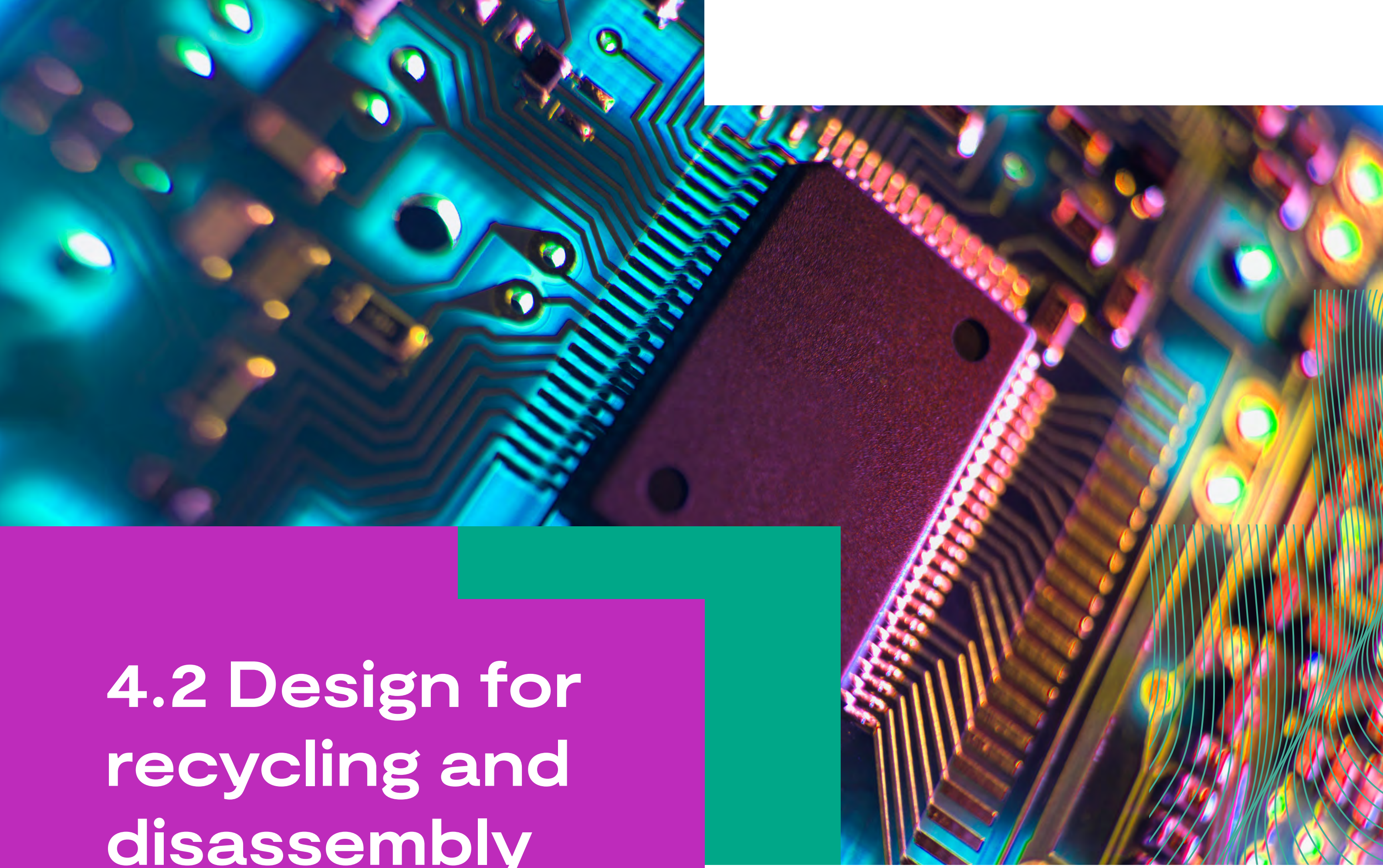
Opportunities exist for extraction in the UK in relation to the circular economy for REE.

As summarised in the Innovate UK Rare Earth Element Extraction report, waste streams may be a valuable REE resource for the UK economy such as from by-products associated with mining or unrelated waste such as fly ash. Valorisation of waste is becoming an area of increasing interest within the UK, as highlighted by Table 2.

Support for UK research and innovation may enable recovery of these waste streams, which may subsequently enable a supply chain outside of international price fluctuations. Detailed recommendations relating to extraction can be found in the Innovate UK Rare Earth Exploration, Extraction, Beneficiation and Concentration report.







4.2 Design for recycling and disassembly

The potential available neodymium from EoL wind products, automotive products and hard disk drives globally is expected to be about 2.3 Gg (Rademaker, Kleijn & Yang, 2013).

However, despite the potentially vast supply of secondary neodymium, recycling products at EoL is often challenging due to the lack of design considerations at the point of creation. This means that EoL product recyclers have to create solutions to disassemble products and recycle component parts, meaning waste management is often a reactive process.

Product design for longevity and reuse/recycling is a key principle within a circular economy and must be considered for magnets and magnet-containing products.

This includes designing a product where waste is minimised and is produced without pollution, contains materials that can remain in circulation and can regenerate nature alongside creation of the product. The products and the magnets themselves must be designed in a way that enables longevity, so that their use can be prolonged.

EV drive motors and wind turbine generators have historically been designed with performance and efficiency as the main design specifications, therefore have not been designed for disassembly or recycling of component parts. Removing magnets from these motors is extremely difficult due to the placement in some designs complicating their potential for direct reuse strategies.

Re-designing these motors using circular principles needs to be done in a way that meets current motor performance otherwise new designs with circular potential will not be adopted. Designing the magnet in a plug-and-play fashion may allow for lamination stacks of smaller magnets to be incorporated in various designs of motors and generators, and interviews with a UK automotive supplier suggested that standardisation may help with this. However, the material for lamination needs to be removable and recyclable.

A report published in July 2022 by the Offshore Renewables Energy Catapult, which aimed to map end of life materials from the offshore wind industry in Scotland, highlights several important considerations for magnet recycling from wind turbines. It is anticipated that electrical components (including those containing magnets) of wind turbines will be shredded, meaning that recovery will be extremely difficult. There should therefore be consideration towards removing magnets before shredding.

Handling magnets of this size and strength can itself be challenging – transportation of magnetised magnets can be dangerous and can pose a health and safety risk to personnel and poses further danger to those with medical implants.

The report also highlights that currently, there are no large-scale wind turbine generator manufacturers in the UK, meaning that any recycled magnet production would have to ship magnets overseas – the report notes facilities in Denmark, Germany and Spain (Catapult, n.d.).

Innovations and UK Capability

While vehicle and turbine manufacturers are considering design for future disassembly to enable the recovery and recycling of component parts, there are limited examples of product suppliers working on this at present, with efficiency still being the main design criteria. However, there is an effort in the UK to design processes that could recover materials from end-of-life products as they are.

- GKN Hybrid Power Ltd and the University of Nottingham are designing a synchronous motor which has lower emissions and is designed to be recycled.
- University of Birmingham, Granta Design and Less Common Metals are designing motors that can be reused as part of an EU-funded consortium, as well as looking at recycling processes for permanent magnets.
- Useful Simple Projects, a UK based design consultancy with a focus on sustainability explored the design of NdFeB magnets to enable a circular economy by designing standard magnets for hard disk drives (UKRI, 2025).

Relevant Projects Table 3 – funded projects relevant to design for recycling

Project Title	Project Partners	Funder	Project Value	Summary
Training Network for the Design and Recycling of Rare-Earth Permanent Magnet Motors and Generators in Hybrid and Full Electric Vehicles (DEMETER Project) (European Commission, n.d.)	Uni of Birmingham, Granta Design, Less Common Metals	EU Funded	€3.8M total cost	Developing environmentally-friendly processes for the recycling of REE PMs from hybrid and electric vehicles and designing hybrid and electric drive motors that can be reused
Novel synchronous motors for electric vehicles (HEFT Project) (European Commission, 2025)	GKN Hybrid Power Ltd, University of Nottingham	EU Funded	€3.5M total cost	Developing motors that are better for the environment and are more aligned with circular economy principles

Note: For EU projects, only UK partners have been specified

Observations and recommendations

Organisations developing REPM-containing products should make design considerations that allow for recycling once a product has reached EoL. Magnet manufacturers should design magnets in a way that they can be recovered and re-used or recycled. Policy interventions to encourage design for recycling should be considered.

4.3 Collection, sorting, and disassembly of permanent magnet-containing products

Collection of EoL products and recovery of the magnets within is required to achieve a circular supply chain. The diversity of waste streams that contain REE permanent magnets adds logistical complexity and makes sorting and disassembly challenging.

While the UK's Critical Minerals Strategy recognises the importance of recovering critical materials from EOL products, there is currently no defined or nationalised pathway to collect and recycle REE-containing material. Collection and recovery of REPM waste is being carried out in the UK by recyclers such as EMR and Magnet Sales and is being explored through grant funded projects such as Rare-Earth Extraction from Audio Products (REAP) as described in Table 4.

However, collection and sorting of magnet-containing waste on a larger scale is not yet considered commercially viable at present for recyclers, due to the lack of onward supply chain and the resource associated with extracting these materials.

Furthermore, magnets are generally embedded in assembled waste and require shipping of assembled products to recycling sites for disassembly, increasing the cost of transportation as the percentage weight of REEs in assembled waste is low, therefore the cost of shipping is expensive relative to the volume of REEs. In many cases, magnets are transported still magnetised by placing chalks between the magnets, commonly referred to as 'live'.

Transportation of live magnets to, and handling at, recycling sites presents several risks. Live magnets can cause trapping and crushing incidents for handling personnel due to the magnets' strong affinity to ferrous material and pose a particular risk to those with pacemakers and medical implants. Demagnetisation of magnets prior to transportation can avoid this and is achieved by heating the magnet above the Curie temperature, or electrically by passing AC through a coil near the magnet, producing an external demagnetising field, or a combination of the two. However, thermal demagnetisation is energy intensive and requires significant heat for large magnets or large quantities of magnets (several hundred degrees Celsius). Air transportation of live magnets is particularly challenging – magnets are normally classed as dangerous goods and can interact with flight electronics therefore strict regulations are in place.

Once magnet-containing waste has been collected, the components must be disassembled to recover the magnets. The variety of products means that no one process exists for disassembly, and magnets are often placed deep within the product which makes recovery difficult. Smaller magnets from vehicle waste e.g. from motors in electric windows are extremely difficult to recover and can be very labour intensive. The commercial gains from recovering intact smaller magnets are outweighed by the cost of recovery. Interviews with UK recyclers suggested that vehicles are generally shredded when valuable products have been removed for recycling, making recovery of magnets deep within a vehicle post shred challenging as any remaining magnet waste is lost in ferrous scrap. While larger magnets can be more easily recovered, the process is still manual and time consuming.

While mechanical fixings are possible, it is common practice to glue magnets in place, making removal difficult and can lead to damage of the magnet's coating, leading to corrosion of the inner material, making it unsuitable for direct reuse. Laminations of magnets are particularly challenging to remove without damaging the magnet when they have been glued in place.

Innovations and UK Capabilities

To improve the economics of recovery for recyclers of permanent magnets, automation of the process is needed. Robotic technologies are currently being explored to disassemble products in the UK. These include

- Robotic approaches are being developed to disassemble electric vehicles, such as those being developed at the Centre for Sustainable Manufacturing and Recycling Technologies (SMART), Loughborough University (SMART, n.d.)
- HyProMag and the University of Birmingham have employed the use of a robotic arm to work alongside a cutter in an automated assembly line to free REE permanent magnets from hard disk drives (Burkhardt et al, 2023).
- The Advanced Manufacturing Research Centre (AMRC) has general capabilities on automation and robotics (AMRC, n.d.).
- While not disassembly, Magnomatics, in collaboration with AMRC, were able to robotically add permanent magnets to the generator of a wind turbine, demonstrating enhanced safety over manual placement, reducing the total time to assemble to 5 mins (from 55mins for manual assembly), and reducing the cost of assembly by £15K per generator (AMRC, n.d.)
- The University of Birmingham has been awarded £34.6 million for a state of the art sustainable manufacturing facility. The EPSRC Manufacturing Research Hub in Robotics, Automation & Smart Machine Enabled will support innovation around reuse, repurpose, repair, remanufacture and recycle and will be key to the future of the UK's circular economy (University of Birmingham, 2024, UKRI, 2025).

Relevant Projects **Table 4 –** Projects relevant to collection, sorting and disassembly

Project Title	Project Partners	Funder	Project Value	Summary
Re-REwind (UKRI, 2025)	European Metal Recycling Ltd, HyProMag Ltd, Offshore Renewable Energy Catapult, Magnomatics and University of Birmingham	Innovate UK CLIMATES	£1.5M	Decommissioning and recycling of offshore wind turbines
Magtec Repurposed Magnets from Reuse, Reduce, and Reconditioning for REE Circular Economy (RE4REE) (UKRI, 2025)	Magnetic Systems Technology Ltd and Hirst Magnetic Instruments Ltd	Innovate UK CLIMATES	£192K	Recovery and reuse of magnets from electric vehicles
Rare-Earth Extraction from Audio Products (REAP) (UKRI, 2025)	HyProMag, EMR, Uni of Birmingham	Industrial Strategy Challenge Fund	£256K	Recovery and recycling of TV loudspeaker NdFeB permanent magnets
Project ROBOMAG (Magnomatics, 2021)	Magnomatics, Advanced Manufacturing Research Centre (AMRC)	Offshore Wind Growth Partnership	Data unavailable	Robotic addition of magnets to wind turbine generator

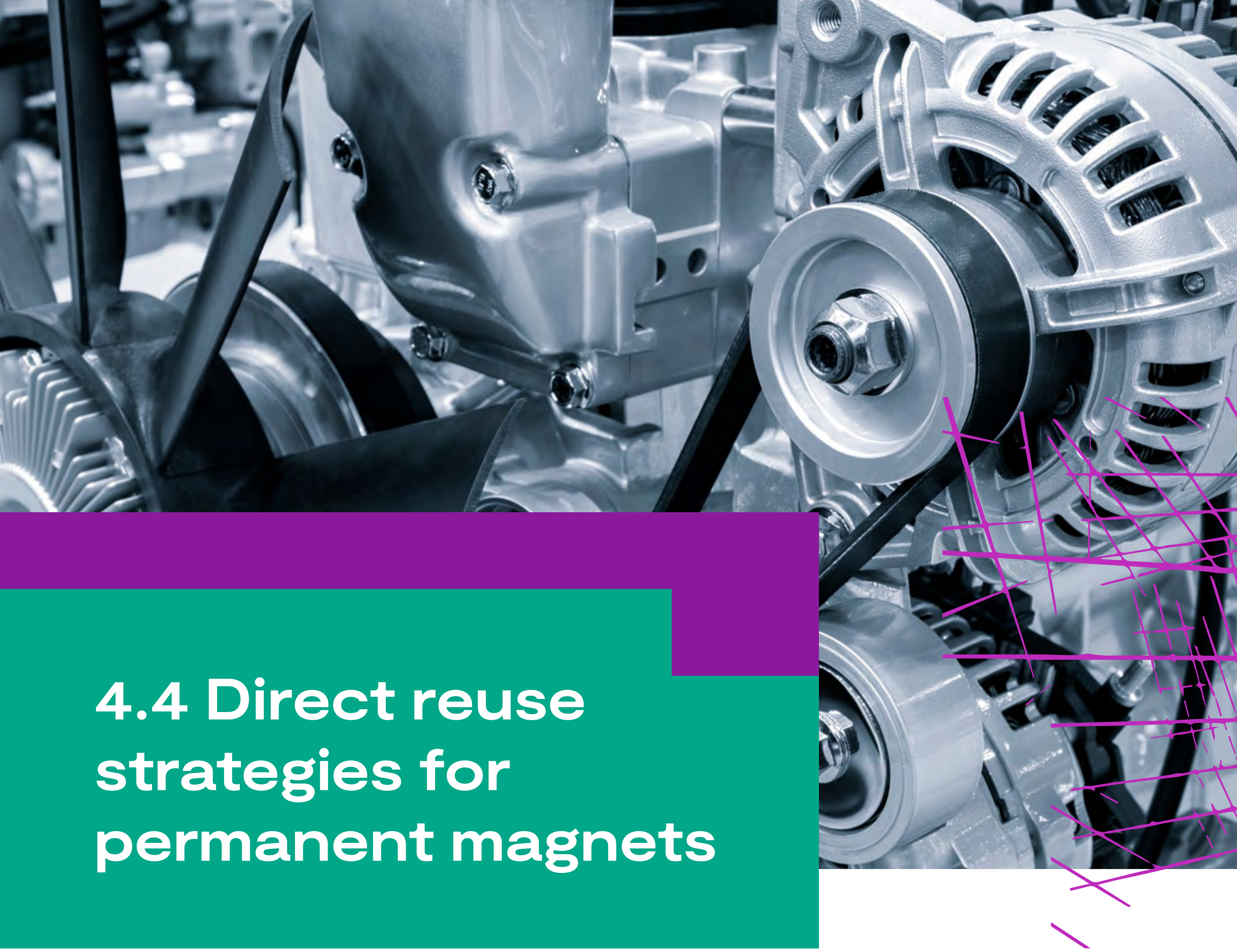
Note: For EU projects, only UK partners have been specified

Observations and recommendations

Innovations that are capable of full or partial automated disassembly are crucial to establish a commercially viable circular economy for rare earths in the UK. Opportunities for the UK rare earth community to collaborate with those developing robotic disassembly for related circular economies such as battery recycling would enable more cost-effective recovery of REPMs from EoL products.

Incentives to encourage recycling companies to create a recycling pathway, in collaboration with both product manufacturers in the wind and electric vehicle industry, and upstream with those developing recycling technologies for REEs, would help catalyse the circular supply of secondary REEs in the UK.

Education on the safe handling and storage of magnets would benefit the UK, as well as innovations that can effectively demagnetise large quantities of magnets in a timely and safe manner. Standards and training courses related to handling would benefit recyclers.



4.4 Direct reuse strategies for permanent magnets

Direct reuse strategies involve the removal of REPMs from end-of-life products such as electric vehicle drive motors, or decommissioned wind turbines, and placing them directly in a new product with minimal modification. This strategy eliminates the need to remanufacture or reprocess them which is ultimately a less energy and financially intensive option than short or long loop recycling. When combined with design from recycling and disassembly, the potential success of direct reuse of magnets is more likely. While the direct reuse approach appears to be the most simplistic and advantageous strategy, there are several challenges involved.

In the case of electric vehicles, due to the variability in size and concentration, it is likely that the only magnets that could be recovered for direct reuse are those found in the drive mechanism of electric vehicles. However, recovery of these magnets is still difficult due to the design of the motor itself (Yang et al, 2016).

To directly reuse magnets, first the magnet must be demagnetised to allow for easy removal and safe handling, as described earlier. Similarly, the magnet needs to be recovered undamaged and with the nickel/epoxy coating intact to prevent corrosion of the magnet in the new product. The lack of consistency in shape, size and elemental composition of magnets is also a challenge for direct reuse as it decreases the likelihood that one magnet can be used directly in another product. Additionally, magnet quality has improved over time, meaning that older magnets may have lower performance than the current standard.

In addition to direct reuse, refurbish and repurposing of magnets in different applications or industries is possible. The advantage of this approach is that it allows magnets to be used with minimal intervention, meaning that costs are relatively low. Challenges associated with this approach include – the magnet must be in a reasonable state to allow for repurposing and the size, shape and strength of the magnet dictate the end use.

Innovations and UK capabilities

Innovation opportunities were identified, with some UK based magnet manufacturers already adopting or exploring reuse, refurbishment or repurposing strategies where possible.

- MagnetSales, a UK based supplier of permanent magnets launched a recycling service in 2019 for NdFeB magnets. In addition to direct reuse, MagnetSales can remanufacture magnets by sintering magnet powder from spent magnets (Magnet Sales, n.d.). Since the launch of the service in 2019, Magnet Sales have recycled over 18,400 kg of NdFeB (as of 04JUN2024).
- Funded by CLIMATES, Magnetic Systems Technology Ltd are exploring direct reuse of magnets within their own electric motors.

Relevant Projects **Table 5 –** Projects related to direct reuse of REE permanent magnets

Project Title	Project Partners	Funder	Project Value	Summary
(RE4REE) Magtec Repurposed Magnets from Reuse, Reduce, and Reconditioning for REE Circular Economy (UKRI, 2025)	Magnetic Systems Technology Ltd, Hirst Magnetic Instruments Ltd	Innovate UK (CLIMATES Cohort 1)	£192K	Feasibility study to reuse magnets from permanent magnet motors

Note: For EU projects, only UK partners have been specified

Observations and recommendations

While challenges exist for direct reuse of magnets, with careful design, magnets can be reused or repurposed. Mechanical fixings of magnets to prevent damage to magnets during recovery from motors and generators, as seen with gluing magnets in place, should be explored to increase the possibility of reuse. Additionally, standardisation of magnets would increase the likelihood of magnets being reused in a plug and play scenario.

Better tracking of magnet contents would allow magnet and product manufacturers to reuse magnets of the same grade. Evidence of longevity and that old magnets can be reused as is without any drop in performance is needed to reassure product manufacturers that magnets can be re-used – this is particularly important for the offshore wind industry where turbines have a lifespan of up to 30 years, and maintenance after the turbine is commissioned is challenging and expensive. Funding may help with this.

4.5 Short-loop recycling methods for rare earth permanent magnets

Short-loop recycling is the process of recovering REPMs from EoL products and remanufacturing the magnet material into a new sintered magnet made of secondary REE alloy. This eliminates the need to take the waste material back to the processing stage and produce purified individual REE compounds for re-alloying.

Advantages of short-loop recycling over direct reuse is that magnets can be recreated with improved properties, new shapes to fit new motor and generator design and improved composition, without the requirement for energy-intensive chemical/metallurgical separation and refining (Bacchetta et al, 2022).

Innovations and UK capability

Hydrogen decrepitation is being explored within the UK for short-loop recycling. This is well established and employs the use of hydrogen to break down sintered magnet material and allow easy recovery of the material from EoL products. Benefits include shorter processing than recycling the magnets back to pure REE powders for re-alloying. The process is considered to be more environmentally friendly since it is less energy intensive and uses less harsh chemicals. The hydrogen needs access to the magnet material surface, which can be achieved by defecting the coating, which is often nickel coating for sintered magnets. This produces a powder that can then be jet milled before being repressed into a new sintered magnet.

Overall the hydrogen decrepitation process can remove magnets from components easily and is scalable, and can recover magnets from a variety of products.

Organisations within the UK are working towards implementing hydrogen technology for recycling and remanufacture of REPM waste. For some time, this work has been led by the University of Birmingham. Hydrogen Processing of Magnet Scrap (HPMS), developed by the University of Birmingham and now being commercialised by HyProMag, is a process that uses hydrogen to separate whole magnets from partially disassembled components. This produces a hydrogenated powder of magnet material which is separated from the waste by mechanical agitation from a rotating porous drum. This powder can then be used to manufacture magnets from secondary material by sintering, pressing, melting, spinning, HDDR processing, and recasting. The process claims to match or surpass the performance of magnets that are produced purely from primary material. While the process is not suitable for processing of shredded magnets as these are high in contamination, HPMS can handle mixed magnets including non-NdFeB magnets and is showing great potential to produce quality grade magnets that can surpass the performance of primary magnets.

HyProMag have built a development plant for their recycling process at Tyseley Energy Park, Birmingham with processing capacity of 400Kg per batch and the potential to process 100 tonnes per year of NdFeB magnets. Hydrogen is accessed via onsite production at Tyseley and can be used directly in the process.

Another method which is being explored in the UK for REPM recycling is Electric Pulse Fragmentation. An electric pulse is sent into the material which breaks down material boundaries, resulting in a fine powder. While this innovation is being deployed in magnet recycling in the UK by Lightning Machines, the equipment has been developed and manufactured by SELFRAG, a Swiss based equipment manufacturer that specialises in high voltage pulse power machines. The method has been used in mineral processing and is being explored for the recycling of fibre-reinforced composites (Institute of Materials, Minerals & Mining, 2022, European Commission, 2024).

Relevant Projects

Table 6 – Relevant short-loop related innovation projects

Project Title	Project Partners	Funder	Project Value	Summary
Decommissioning and recycling of offshore wind turbines (UKRI, 2025)	Innovate UK CLIMATES	European Metal Recycling Ltd, HyProMag Ltd, Offshore Renewable Energy Catapult, Magnomatics and University of Birmingham	£1.5M	Building a circular supply chain for NdFeB magnets for the wind industry
FragMag - Recovering Magnets with Electric Pulse Fragmentation (UKRI, 2025)	Innovate UK CLIMATES	Lightning Machines, University of Warwick	£74K	Using electric pulse technology to detach magnet material from resin
RaRE Project (UKRI, 2025)	Innovate UK	HyProMag, Unipart Powertrain Applications, Advanced Electric Machines Research, Uni of Birmingham, Bentley Motors, Intelligent Lifecycle Solutions, Metlase Ltd	£2.6M	Demonstration of a recycled motor with considerations for design for recycle
REEsilience (REEsilience, n.d., European Commission, n.d.)	EU Funded (Horizon 2020)	University of Birmingham, HyProMag	£2.1M (UK costs only)	Locating and determining value of REE
REAP (UKRI, 2025)	Innovate UK (Catalysing Green Innovation challenge)	HyProMag	£256K	Recycling permanent magnets from loudspeakers
SCREAM (Scream, n.d., UKRI, 2025)	Innovate UK Driving the Electric Revolution	HyProMag, Mkango, B&W Group Ltd, GKN Hybrid Power, Uni of Birmingham, EMR, Jaguar Landrover,	£3.3M	Scaling up of HPMS and produce rare earth carbonate to product magnets from secondary rare earths Developing a secondary supply chain for NdFeB magnets in the UK
Sustainable Recovery, Reprocessing and Reuse of Rare Earth Magnets in a European Circular Economy (SUSMAGPRO) (European Commission, n.d.)	EU Funded (Horizon 2020)	Uni of Birmingham, Less Common Metals, TWR Ltd, Bunting Magnetics Europe Ltd	€14.7M (total cost)	Reactor 50-100kg per batch
Rare Earth Magnet Recovery for Environmental and Resource Protection REMENENCE (European Commission, n.d.)	EU Funded	University of Birmingham, C-Tech Innovation Ltd	€5M (total cost)	Using hydrogen decrepitation to recover REE from waste electrical products

Note: For EU projects, only UK partners have been specified

Observations and recommendations

There are limited technologies for direct recycling in the UK therefore further investment in this area would increase the number of technologies that can be applied to short-loop recycling. Focus on scale up is needed to ensure capacity is there for when the supply chain expands.

4.6 Long-loop recycling methods for rare earth permanent magnets

Recycling by reprocessing, also known as long-loop recycling, refers generally to processes which involve taking REPMs and reprocessing the material back to individual purified REE powders for re-alloying. Many techniques for reprocessing use strong acids such as sulfuric and hydrochloric acid. Significant innovation is taking place in this area, e.g. introducing novel solvents and ionic liquids etc. for improved recovery, separation and purification with lower environmental impact. For more information about processing technologies applicable to both primary and secondary material, see the Innovate UK Rare Earth Processing report.

Innovations and UK capabilities

Ionic Technologies, based in Belfast, are commercialising a long-loop recycling process for REPMs using a combination of solvent extraction (SX) and ionic liquids (ILs) to produce virgin-grade REE powders, that can re-enter the supply chain alongside virgin REE powders being supplied to metal/alloy makers.

Other companies, such as Nanomox and Seloxium, are developing alternative processes for producing REE powders from a variety of sources, by adapting existing technologies to target REEs.

Relevant Projects **Table 7 –** Projects related to long-loop processing of REEs

Project Title	Project Partners	Funder	Project Value	Summary
Ionic Metals - Critical materials for magnets	Ionic Recovery Ltd and Imperial College London	Innovate UK CLIMATES	£334K	Recovery of REE from end-of-life mobile phones.
REEMAG - Closing the loop on REE for MAGnets	Nanomox Ltd, the Science and Technology Facilities Council and Green Rose Chemistry Ltd	Innovate UK CLIMATES	£290K	Using Oxidative Ionothermal Synthesis to recycle REE magnet waste as well as manufacturing high value REE materials
The EV Permanent Magnet Circular Supply Chain	Ionic Technologies Ltd, LCM Ltd and Ford Technologies Ltd	Innovate UK CLIMATES	£994K	Demonstrating use of recycled REPM in EV motor
A Sustainable Solution for the Recovery of Scandium and Yttrium from UK generated TiO2 Waste	GSA Environmental and University of Lincoln	Innovate UK CLIMATES	£633K	Recovery of Scandium and Yttrium from waste

Note: For EU projects, only UK partners have been specified

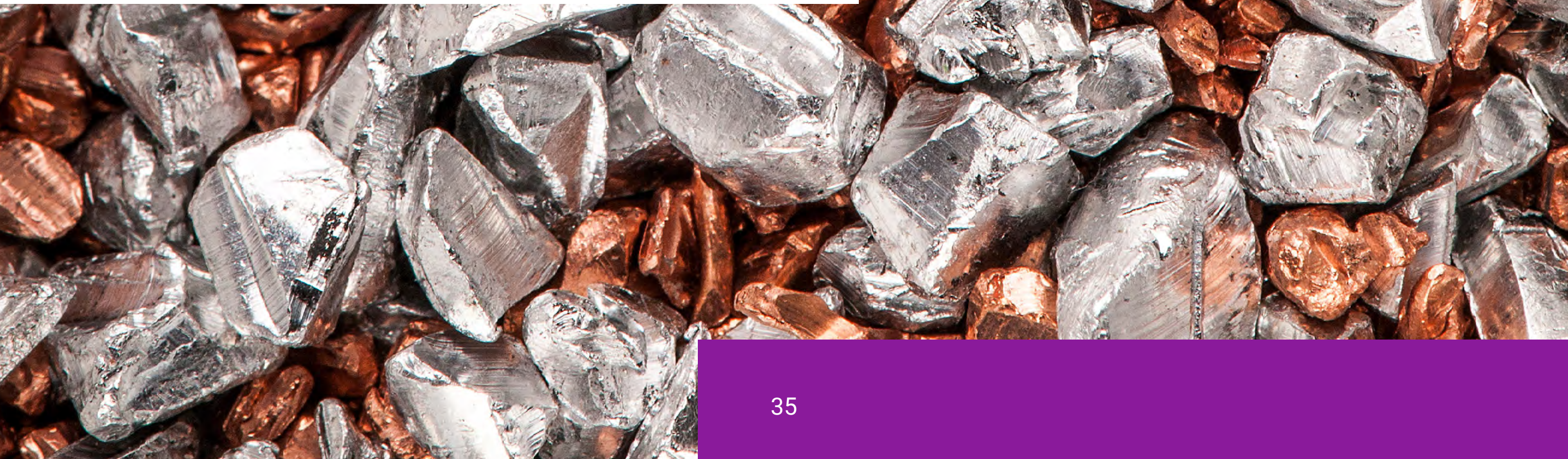
Observations and recommendations

In the UK there is growing activity around innovations that could be applied for recycling by reprocessing and these technologies range from low TRL technologies to mature technologies such as solvent extraction. The challenge is to engineer efficient and robust chemical process solutions that can transform a range of feedstocks into a very similar end product (REE powders for metal/alloy making).

4.7 Magnet manufacturing

Magnet manufacturing is a key part of the circular supply chain in the UK as it enables magnets to be produced from UK recycled REE material. Innovate UK has published a full report on Magnet Manufacturing innovations focussing on opportunities for UK innovations to support UK based magnet manufacturing. The key points are summarised here.

For sintered magnets, manufacturing begins with alloying and strip casting of REE to produce flakes of material. Hydrogen decrepitation takes place on the flakes before jet milling into a powder. The powder is then pressed before being sintered and heat treated. Finally the magnet is machined and coated before being magnetised. The process of machine the magnets during magnet manufacturing however produces waste. There is potential to gather the waste created by the manufacturing process to use as further magnet feedstock material.



Innovations and UK capabilities

As magnet manufacturing is traditionally performed outside of the UK, there is limited capability within the UK at present however organisations such as the University of Birmingham are paving the way for UK based magnet manufacture. HyProMag, a spinout from the University of Birmingham, has developed UK magnet manufacturing capability for primary and recycled REE magnet material and is beginning to scale up the process via a newly established manufacturing plant at Tyseley Energy Park.

Relevant Projects

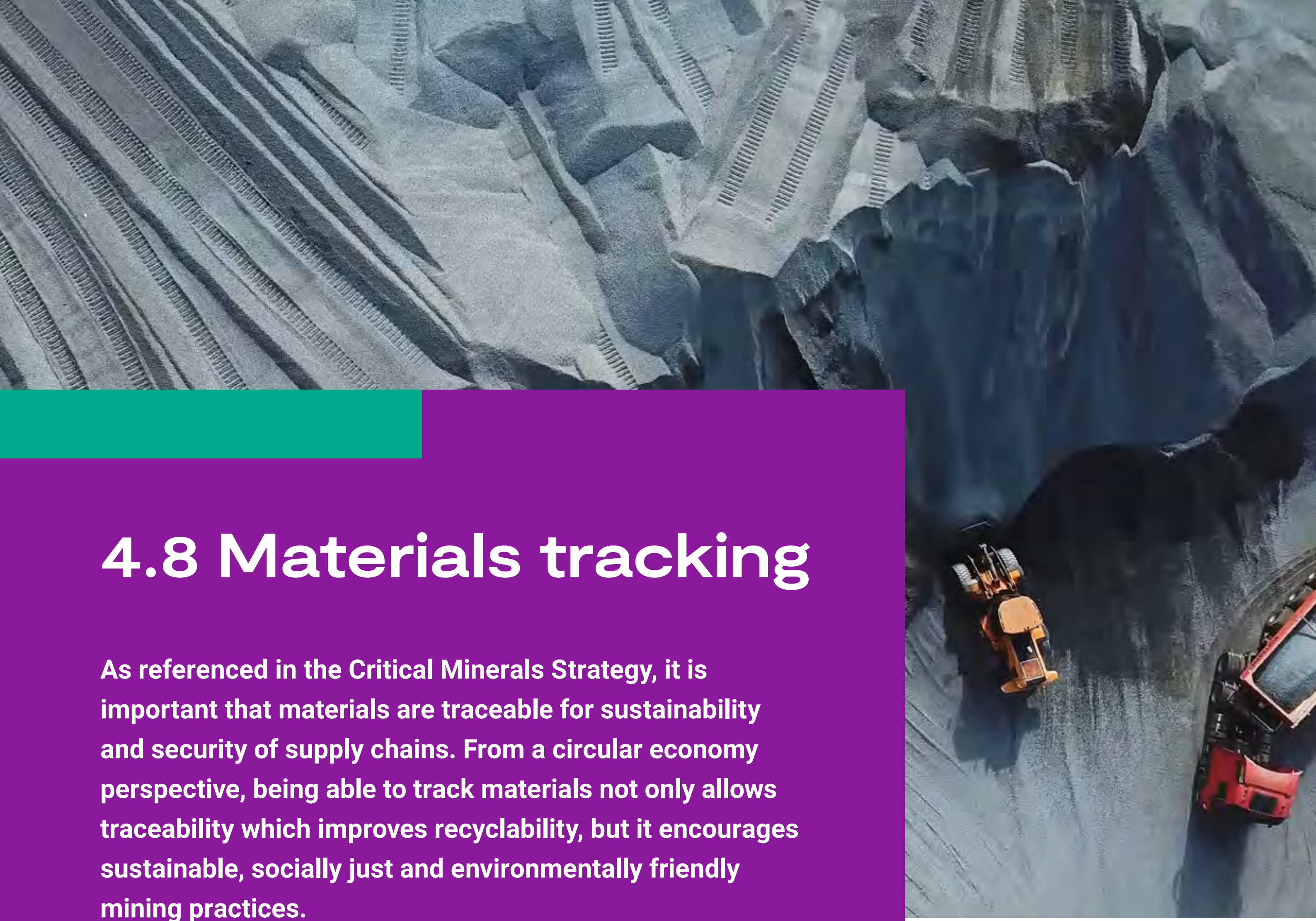
Table 8 – Funded projects related to UK magnet manufacturing

Project Title	Project Partners	Funder	Project Value	Summary
EMPRESS	Materials Nexus, LCM Ltd	Innovate UK CLIMATES	£346K	Using machine learning techniques to design high performing magnets with reduced REEs
Re-REwind (UKRI, 2025)	European Metal Recycling Ltd, HyProMag Ltd, Offshore Renewable Energy Catapult, Magnomatics and University of Birmingham	Innovate UK CLIMATES	£1.5M	Decommissioning and recycling of offshore wind turbines
UK Produced High Energy net-shaped PEMD Magnets by hot forming and the use of recycled materials (UKRI, 2025)	SG Technologies	Innovate UK CLIMATES	£740K	Implementing a new manufacturing method for primary and secondary Ne permanent magnets

Note: For EU projects, only UK partners have been specified

Observations and recommendations

As design for disassembly is key to a viable circular economy, magnets need to be designed in a way that allows them to be removed from products and be in a recyclable condition. Scale up investment is needed to allow those developing magnet manufacturing within the UK to scale to meet the demand of magnets for new products. Opportunities to bring together innovators to work together to articulate the needs of the sector would be of benefit.



4.8 Materials tracking

As referenced in the Critical Minerals Strategy, it is important that materials are traceable for sustainability and security of supply chains. From a circular economy perspective, being able to track materials not only allows traceability which improves recyclability, but it encourages sustainable, socially just and environmentally friendly mining practices.

One way to track materials is by means of a digital passport. A digital passport, or digital product passport (DPP) is a software tool that can be used to manage and track data on a particular product as it makes its way through the supply chain, aiding transparency and improving circularity potential. Such data may include information on the source of the materials, its sustainability credentials, and details on how the product and materials were manufactured. Advantages of tracking data via a DPP include the availability of information in real time, information being accessible to several stakeholders at the same time and easier regulatory auditing. Additionally, it allows those further along the supply chain, including consumers, to track and trace where their product originated, and the sustainability credentials associated with the product components along the supply chain.

DPPs are gradually being introduced in the EU across various sectors. For example, electric vehicle battery products have a requirement to have DPPs implemented by 2027 and there is a requirement for data on materials, carbon footprint, quantity of recycled materials, battery durability and guidance on how the product can be repurposed or recycled (Stretton & Buzeti, 2024., McManus, 2024).

In the context of REE digital materials tracking, means of tracking such as DPPs are key to a transparent and sustainable circular supply chain. The elemental composition of REPMs varies from product to product, and documentation and personnel changes can mean that information on magnet type and grade isn't always available. Similarly, the development of magnets over time to improve performance of the magnet has resulted in contents and concentrations changing over time Information on the grade of the magnet, as well as the chemical composition would enable more efficient remanufacture, reprocessing and recycling of REPMs. In some cases, this would reduce the need for extensive analysis of the chemical composition, prior to recycling, which can be challenging due to the chemical similarity of individual REEs to each other. This is also a known issue when processing primary magnet material as separating REEs from each other is complex (see Innovate UK's Rare Earth Processing report).

Digital product passport innovations may alleviate some of these challenges when recycling REPMs, however, some considerations are needed to encourage adoption of these technologies

- DPPs need to be clear in their purpose, as well as the information they collect.
- Tracking needs to be cost-effective and the risk of increasing the cost of REPM recycling as a result of materials tracking needs to be minimised.
- The supply chain is global, meaning that digital passports need to be able to operate on an international basis. Tracking information throughout the supply chain needs to be a collaborative process internationally, as well as domestically.
- Data security must be a priority. DPPs must be reliable and secure to give the supply chain confidence that there is no risk to commercial data. With regards to data sharing, organisations may be reluctant to share information that may reduce their competitiveness.
- Responsibility needs to be established for the holding and auditing of DPPs, to ensure accuracy and to ensure satisfactory entry of data. Regulations may be needed to ensure a centralised approach.

Global Alliance Battery Passport

The Global Battery Alliance established a framework to enable a battery passport – a digital log containing data and information from mining to product production including a battery's sustainability credentials, its manufacturing process, and its chemical and material contents to improve transparency in the battery supply chain. The Global Battery Alliance has developed battery passport pilots, with the most recent pilot announced in June 2024, to create a minimal viable product of the passport, working with global battery manufacturers.

Innovations and UK capability

Distributed ledger technologies such as blockchains are being developed for materials tracking within circular economy materials supply chains. Blockchains are chronologically ordered blocks of data and information that are compiled as a decentralised distributed ledger – a note in time that can be assessed by all parties in the blockchain. The technology is immutable with trust built in as part of the cryptographically secure design. A digital tag can be incorporated into a product and linked to the blockchain, resulting in a traceable system.

Often associated with the finance sector, blockchain is the underlying technology of crypto currency, but blockchain has applications beyond finance in particular for sectors that have environmental, social and governance considerations. There are many examples of blockchain technologies being used to track traceability and transparency in the food industry and in the UK. As an example, the Food Standards Agency has published a series of reports on use of blockchain for food standards, trust and governance (Pearson et al, 2021).

Tracking to support food safety was also being explored via an award from the UKRI Legacy Challenge Fund (Ledger Insights, 2021).

In the automotive industry, blockchains are being developed to ensure complex supply chains are compliant, traceable and efficient. The XCEED project by Renault and IBM, as well as other partners, aims to track compliance across the entire, enabling full transparency in Renault's supply chain (Renault Group, n.d.).

UK activity in materials tracking specifically for REEs is an underdeveloped area. UK based Minviro are part of Horizon Europe project CSyARES, and are collaborating with REIA and Circularise to develop a blockchain for tracking the sustainability credentials of REEs.

Relevant Projects **Table 9 –** Projects relevant to materials tracking of REE.

Project Title	Project Partners	Funder	Project Value	Summary
Circular System for Assessing Rare Earth Sustainability (CSyARES) (UKRI, 2025)	Minviro	Horizon Europe	£157K (UK costs)	Creating a blockchain technology that tracks and measures sustainability
CE-RISE Circular Economy Resource Information System (CE-RISE, 2023)	REPIC, ANSYS	EU Funded	€7.7M (total cost)	Developing digital product passports for critical raw materials within ICT, printers, solar panels, batteries and heating systems

Note: For EU projects, only UK partners have been specified

Observations and recommendations

Findings from this work highlighted that the circular REE supply chain needs materials tracking, but UK the position in this area is underdeveloped. It is recommended to create opportunities to bring the UK REE community together such as a roundtable discussion with innovators across the supply chain to discuss what a materials tracking system should look like for the REE magnet supply chain and the best way to implement a DPP for the REPM supply chain. Building upon similar concepts in related industries such as the Global Alliance Battery Passport project would enable the REE community to incorporate shared learning and potentially best practices as determined by other industries.

5. Conclusions

The UK has witnessed increasing interest and activity in relation to innovations in the REE circular economy from EoL products. Drivers of this growing sector include the lack of control of international supply chains and pricing for these critical materials needed for net zero technologies and the development of these technologies in a more environmentally friendly and sustainable manner.

While there are many opportunities for the UK to develop a secondary supply chain for REEs, there are several barriers across the supply chain that need to be overcome to enable a successful circular economy. The supply chain is still in its infancy and despite these barriers, the supply chain for recycled magnets is making real progress, enabled by programmes such as Innovate UK's CLIMATES programme.

With continued investment and support, a circular economy for REEs within the UK presents an economic opportunity that can be achieved through further investment and support for the UK research community across the supply chain from recovery of magnets from EoL products to the manufacturing of new REPMs from the secondary supply.

References

León, M.A. and Daphne, T. (2023) The rare earth problem: Sustainable sourcing and supply chain challenges, Circularise. Available at: **https://www.circularise.com/blogs/the-rare-earth-problem-sustainable-sourcing-and-supply-chain-challenges** (Accessed: 14 April 2025).

Ellen MacArthur Foundation. (no date) Circular economy introduction, Ellen MacArthur Foundation. Available at: **https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview** (Accessed: 14 April 2025).

Riversimple (2023) Innovation. Available at: **https://www.riversimple.com/innovation/** (Accessed: 14 April 2025).

Barrie, J. and Schröder, P. (2024) A global roadmap for an Inclusive Circular Economy, Circular Economy. Available at: **https://circulareconomy.earth/publications/a-global-roadmap-for-an-inclusive-circular-economy** (Accessed: 14 April 2025).

European Commission. (no date) Waste framework directive. Environment. Available at: **https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en** (Accessed: 14 April 2025).

European Commission. (no date) Ecodesign for Sustainable Products Regulation. European Commission. Available at: **https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en** (Accessed: 14 April 2025).

European Commission. (no date) Circular economy action plan. Environment. Available at: **https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en** (Accessed: 14 April 2025).

Department for Environment, Food & Rural Affairs. (2020) Circular Economy Package Policy statement. GOV.UK. Available at: **https://www.gov.uk/government/publications/circular-economy-package-policy-statement/circular-economy-package-policy-statement** (Accessed: 14 April 2025).

UKRI National Interdisciplinary Circular Economy Research. (2022) What is the circular economy?. CE Hub. Available at: **https://ce-hub.org/** (Accessed: 14 April 2025).

Zorpette, G. (2023) The magnet that made the modern world, IEEE Spectrum. Available at: **https://spectrum.ieee.org/the-men-who-made-the-magnet-that-made-the-modern-world** (Accessed: 14 April 2025).

Department for Energy Security and Net Zero. (2021) Industrial decarbonisation strategy, GOV.UK. Available at: **https://www.gov.uk/government/publications/industrial-decarbonisation-strategy** (Accessed: 14 April 2025).

Yang, Y. et al. (2016) 'Ree recovery from end-of-life NDFEB permanent magnet scrap: A critical review', Journal of Sustainable Metallurgy, 3(1), pp. 122–149. doi:10.1007/s40831-016-0090-4.

National Grid. (2023) Can wind turbine blades be recycled? | What happens to old wind turbine blades?. National Grid Group. Available at: **https://www.nationalgrid.com/stories/energy-explained/can-wind-turbine-blades-be-recycled** (Accessed: 14 April 2025).

Kumari, A., Sinha, M.K., Paramanik, S. and Sahu S.K. (2018) 'Recovery of rare earths from spent ndfeb magnets of wind turbine: Leaching and kinetic aspects', Waste Management, 75, pp. 486–498. doi:10.1016/j.wasman.2018.01.033.

National Grid (2022) What happens to old electric car batteries?. National Grid Group. Available at: **https://www.nationalgrid.com/stories/journey-to-net-zero-stories/what-happens-old-electric-car-batteries**

Vikas, H., Sahu, A. and Sharma, N. (2020) 'Life cycle costing of MRI machine at a tertiary care teaching hospital', Indian Journal of Radiology and Imaging, 30(2), p. 190. doi:10.4103/ijri.ijri_54_19.

Liang, T.-O., Koh, Y.H., Qiu, T., Li, E., Yu, W. and Haung, S.Y. (2022) 'High-performance permanent magnet array design by a fast genetic algorithm (ga)-based optimization for low-field portable MRI', Journal of Magnetic Resonance, 345, p. 107309. doi:10.1016/j.jmr.2022.107309.

OECD. (2020) Magnetic Resonance Imaging (MRI) units, Available at: **https://www.oecd.org/en/data/indicators/magnetic-resonance-imaging-mri-units.html** (Accessed: 14 April 2025).

Ramprasad, C., Gwenzi, W., Chaukura, N., Azelee, N.I.W., Rajapaksha, A.U., Naushad,M. and Rangabhashiyam, S. (2022) 'Strategies and options for the sustainable recovery of rare earth elements from Electrical and Electronic Waste', Chemical Engineering Journal, 442, p. 135992. doi:10.1016/j.cej.2022.135992.

Piperidou, N. and Hindocha, S. (2023) The 2035 UK Battery Recycling Industry Vision. Innovate UK. Available at: **https://iuk-business-connect.org.uk/wp-content/uploads/2023/05/UK-Battery-Recycling-Vision-to-2035-Report-Official.pdf.** (Accessed: 21st April 2025).

Global Battery Alliance (2025) Establishing a sustainable and responsible battery value chain - global battery alliance, GBA. Available at: **https://www.globalbattery.org/** (Accessed: 14 April 2025).

Piperidou, N. and Hindocha, S. (2023) The 2035 UK Battery Recycling Industry Vision. Innovate UK. Available at: **https://iuk-business-connect.org.uk/wp-content/uploads/2023/05/UK-Battery-Recycling-Vision-to-2035-Report-Official.pdf.** (Accessed: 21st April 2025).

Liu, S.-L., Fan, H.R., Liu, Xmn Meng, J., Butcher, A.R., Yann, L., Yang, K.F. and Liu, X.C.. (2023) 'Global Rare Earth Elements Projects: New Developments and supply chains', Ore Geology Reviews, 157, p. 105428. doi:10.1016/j.oregeorev.2023.105428.

IEA. (no date) Executive summary – the role of critical minerals in Clean Energy Transitions – analysis, IEA. Available at: **https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary** (Accessed: 14 April 2025).

Onstad, E. (2023) Focus: Mine waste finds new life as source of rare earth. Reuters. Available at: **https://www.reuters.com/business/sustainable-business/mine-waste-finds-new-life-source-rare-earths-2023-04-04/** (Accessed: 14 April 2025).

Goodenough, K.M., Schilling, J., Jonsson, E., Kalvig, P., Charles, N., Tuduri, J., Deady, E.A., Sadeghi, M., Schillerup, H., Müller, A. and Bertrand, G. (2016) Europe's rare earth element resource potential: An overview of REE metallogenetic provinces and their geodynamic setting. Ore Geology Reviews, 72, pp.838-856..

Kinnunen, P., Karhu, M., Yli-Rantala, E., Kivikytö-Reponen, P. and Mäkien, J. (2022) 'A review of circular economy strategies for mine tailings,' Cleaner Engineering and Technology, 8, p. 100499. **https://doi.org/10.1016/j.clet.2022.100499.**

UKRI. (2025) 'REEMAG - Closing the loop on REE for MAGnets'. UK Research & Innovation. Available at: **https://gtr.ukri.org/projects?ref=10082398** (Accessed: 21st April 2025).

UKRI. (2025) 'Mine to Magnets – Securing a Supply of Rare Earth Elements from Volcanic Tuffs for UK Magnet Manufacture'. UK Research & Innovation. Available at: **https://gtr.ukri.org/projects?ref=10078460#/tabOverview.** (Accessed: 21st April 2025).

UKRI. (2025) 'ReREE: Establishing feasibility of a novel process to recover rare earth elements from mining tailings for re-entry into a UK supply chain'. UK Innovation & Research. Available at: **https://gtr.ukri.org/projects?ref=10082225.** (Accessed: 21st April 2025).

Rotate. (no date) 'Rotate Project'. Available at: **https://rotateproject.eu/#what.** (Accessed: 21st April 2025).

Rademaker, J.H., Kleijn, R. and Yang, Y. (2013) 'Recycling as a Strategy against Rare Earth Element Criticality: A Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling,' Environmental Science & Technology, 47(18), pp. 10129–10136. **https://doi.org/10.1021/es305007w.**

Catapult. (no date) 'Offshore renewable Energy | Innovation Centre | ORE Cataplut'. UK Research & Innovation. Available at: **https://ore.catapult.org.uk/?orecatapultreports=end-of-life-materials-mapping-for-offshore-wind-in-scotland.** (Accessed: 21st April 2025).

UKRI. (2025) 'Polarising designs: Redesigning neodymium magnets (NDM) for the circular economy'. UK Innovation & Research. Available at: **https://gtr.ukri.org/projects?ref=131388.** (Accessed: 21st April 2025).

European Commission. (no date) 'Training Network for the Design and Recycling of Rare-Earth Permanent Magnet Motors and Generators in Hybrid and Full Electric Vehicles'. Available at: **https://cordis.europa.eu/project/id/674973.** (Accessed: 21st April 2025).

European Commission. (no date) 'Novel concept of a low cost, high power density and highly efficient recyclable motor for next generation mass produced electric vehicles'. Available at: **https://cordis.europa.eu/project/id/101096306.** (Accessed: 21st April 2025).

SMART. (no date) 'Centre for SMART - Sustainable Manufacturing and Recycling Technologies'. Available at: **https://www.centreforsmart.co.uk/.** (Accessed: 21st April 2025).

Burkhardt, Carlo & Ortiz, Francisco & Daoud, Kaies & Björnfot, Tomas & Ahrentorp, Fredrik & Blomgren, Jakob & Walton, Allan. (2023) Automated High-Speed Approaches for the Extraction of Permanent Magnets from Hard Disk Drive Components for the Circular Economy. 10.13140/RG.2.2.31642.21449.

Advanced Manufacturing Research Centre. (no date) 'Automation and Robotics', University of Sheffield. Available at: **https://www.amrc.co.uk/capabilities/automation-and-robotics.** (Accessed: 21st April 2025).

Advanced Manufacturing Research Centre. (no date) 'Automation and Robotics', University of Sheffield. Available at: **https://www.amrc.co.uk/capabilities/automation-and-robotics.** (Accessed: 21st April 2025).

University of Birmingham. (2024) '£34.6M awarded to host National Hub for a robotics-enabled sustainable future for manufacturing'. Available at: **https://www.birmingham.ac.uk/news/2024/34.6m-awarded-to-host-national-hub-for-a-robotics-enabled-sustainable-future-for-manufacturing**

UKRI. (2025) 'Robotic disassembly technology as a key enabler of autonomous remanufacturing'. UK Research & Innovation. Available at: **https://gtr.ukri.org/projects?ref=EP%2FN018524%2F1.** (Accessed: 21st April 2025).

UKRI. (2025) 'Re-REwind'. UK Research & Innovation. Available at: **https://gtr.ukri.org/projects?ref=10078341#/tabOverview.** (Accessed: 21st April 2025).

UKRI. (2025) '(RE4REE) Magtec Repurposed Magnets from Reuse, Reduce, and Reconditioning for REE Circular Economy'. UK Research & Innovation. Available at: **https://gtr.ukri.org/projects?ref=10084047.** (Accessed: 21st April 2025).

UKRI. (2025) 'REAP - Rare-Earth Extraction from Audio Products'. UK Research & Innovation. UK Research & Innovation. UK Research & Innovation. Available at: **https://gtr.ukri.org/projects?ref=75835.** (Accessed: 21st April 2025).

Magnomatics. (2021) Project ROBOMAG. Available at: **https://www.magnomatics.com/post/project-robomag.** (Accessed 21st April 2025)

Yang, Y., Walton, A., Sheridan, R., Güth, K., Gauß, R., Gutfleisch, O., Buchert, M., Steenari, B.M., Van Gerven, T., Jones, P.T. and Binnermans, K. (2016) 'REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review,' Journal of Sustainable Metallurgy, 3(1), pp. 122–149. **https://doi.org/10.1007/s40831-016-0090-4**.

Magnet Sales. (no date) 'Recycling'. Available at: **https://magnetsales.co.uk/services/recycling/#:~:text=We%20offer%20several%20recycling%20options,the%20magnets%20into%20alternative%20dimensions.** (Accessed: 21st April 2025).

Bacchetta, G., Luca, S., Rado, C. and Genevrier, S. (2022) Short-loop recycling of sintered NdFeB magnets by hydrogen decrepitation. In World PM2022 Congress and Exhibition, EPMA. p.p. 5370650

Institute of Materials, Minerals & Mining. (2022) 'An overview of electric pulse treatment of ores and applications in mineral processing'. Available at: **https://www.iom3.org/resource/an-overview-of-electric-pulse-treatment-of-ores-and-applications-in-mineral-processing.html.** (Accessed: 21st April 2025)

European Commission. (2024) 'High Voltage Pulse Fragmentation Technology to recycle fibre-reinforced composites'. Available at: **https://cordis.europa.eu/project/id/323454/reporting.** (Accessed: 21st April 2025)

UKRI. (2025) 'RaRE – Rare-Earth Recycling for E-Machines'. UK Research & Innovation. Available at: **https://gtr.ukri.org/projects?ref=105397.** (Accessed: 21st April 2025)

REEsilience. (no date) 'REEsilence: Home'. Available at: **https://REEilience.eu/.** (Accessed: 21st April 2025).

European Commission. (no date) 'Resilient and sustainable critical raw materials REE supply chains for the e-mobility and renewable energy ecosystems and strategic sectors'. Available at: **https://cordis.europa.eu/project/id/101058598.** (Accessed: 21st April 2025)

Scream. (no date) 'Scream UK - Home'. Available at: **https://scream-uk.com/.** (Accessed: 21st April 2025).

UKRI. (2025) 'SCREAM - Secure Critical Rare Earth Magnets for the UK'. UK Research & Innovation. Available at: **https://gtr.ukri.org/projects?ref=10008116.** (Accessed: 21st April 2025)

European Commission. (no date) 'Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy (SUSMAGPRO)'. Available at: **https://cordis.europa.eu/project/id/821114.** (Accessed: 21st April 2025)

European Commission. (no date) 'Rare Earth Magnet Recovery for Environmental and Resource Protection'. Available at: **https://cordis.europa.eu/project/id/310240.** (Accessed: 21st April 2025).

UKRI. (2025) 'UK Produced High Energy net-shaped PEMD Magnets by hot forming and the use of recycled materials'. Available at: **https://gtr.ukri.org/projects?ref=10062183.** (Accessed: 21st April 2025)

Stretton, C. and Buzeti, Z. (2024) Digital Product Passports (DPP): What, how, and why?, Circularise. Available at: **https://www.circularise.com/blogs/digital-product-passports-dpp-what-how-and-why** (Accessed: 21 April 2025).

McManus, S. (2024) Could product passports revolutionise the way we shop? BBC News. Available at: **https://www.bbc.co.uk/news/business-68283317** (Accessed: 21 April 2025).

Pearson, S., Brewer, S., Godsiff, P. and Maull, R. (2021) ‘Food Data Trust: A framework for sharing’. Food Standards Agency. Available at: **https://www.food.gov.uk/research/cutting-edge-regulator/food-data-trust-a-framework-for-information-sharing** (Accessed 21st April 2025)

Ledger Insights. (2021) ‘Lloyds Register, IBM in UK blockchain food consortium’. Available at: **https://www.ledgerinsights.com/lloyds-register-ibm-in-uk-blockchain-food-traceability-consortium/.** (Accessed: 21st April 2025).

Renault Group. (no date) ‘XCEED, the new blockchain solution for the certification of vehicle compliance is moving a step further in Europe’. Available at: **https://media.renaultgroup.com/xceed-the-new-blockchain-solution-for-the-certification-of-vehicle-compliance-is-moving-a-step-further-in-europe/.** (Accessed: 21st April 2025).

UKRI. (2025) ‘CSyARES - Toward a Circular System for Assessing Rare Earth Sustainability - Year 2’. Available at: **https://gtr.ukri.org/projects?ref=10088224.** (Accessed: 21st April 2025).

CE-RISE. (2023) ‘CE-RISE | Circular Economy Resource Information System’. Available at: **https://ce-rise.eu.** (Accessed: 21st April 2025).

European Commission. (no date) ‘Circular Economy Resource Information System’. Available at: **https://cordis.europa.eu/project/id/101092281**. (Accessed: 21st April 2025).

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Visit the Circular Critical Materials Supply Chains programme page
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03003 214357 • support@iuk.ukri.org • @innovateuk

Innovate UK, Polaris House, North Star Avenue, Swindon, SN2 1FL