Innovate UK

CLIMATES Programme: Rare Earth Value Chain

Innovation Landscape Reports Executive Summary

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Published July 2025

1. Foreword

At any given point in human history there are resources that are key to both maintaining and improving socio-economic conditions. Right now, critical minerals are one of these, which is why since 2022 the UK has had a critical minerals strategy and Innovate UK has delivered the CLIMATES programme (Circular critical materials supply chains), utilising £15m of public funding.

The clean energy and digital transition that society is undertaking, and which enables a net zero future, is wholly reliant on critical minerals and materials. From electric vehicles to mobile phones, and renewable energy to medical and defence equipment 21st Century technologies are, and therefore the UK economy is, underpinned by these crucial resources.

Lithium, cobalt, nickel and graphite are needed for batteries; silicon, tin and gallium for semiconductor devices; and rare earth elements for the magnets in electric motors and generators. UK industry is therefore a large consumer and manufacturing supply chain resilience is only maintained by having a secure supply of these materials. Many of the mineral deposits and primary sources of these materials are geographically restricted to few countries and monopolised. Markets are unstable and distorted with significant questions surrounding environmental, social and governance standards.

So as demand for these critical materials continues to increase geopolitics increasingly becomes a major issue for consumer nations such as the UK. In response to these challenges, the Government launched its first ever Critical Minerals Strategy in July 2022, which was further updated in March 2023.

Within this **Innovation is the UK's trump card.** Our world leading research base can play a big part in building supply chain resilience and increasing security of supply for these materials. The CLIMATES programme, launched as part of the strategy refresh, has been focused on enabling businesses to develop innovative solutions, capabilities, and services, to increase UK supply chain resilience and security of supply of rare earth elements (REEs).

Why have we focused on REEs? Firstly, they were identified as one of the most economically vulnerable and at risk of supply disruption by the British Geological Survey; secondly, due to their strategic application in rare earth permanent magnets, fundamental components in electric machines that propel electric vehicles and generate electricity in offshore wind turbines; thirdly, because the UK has a strategic opportunity to exploit the development of secondary materials supply chains through recycling and circular economy approaches to capitalise on an ever growing future feedstock of end-of-life products rich in magnets (and other critical materials).

The CLIMATES programme aims to improve the security of rare earth elements supply for a more prosperous and secure UK through four routes: sourcing extracted materials and processing them, manufacturing magnets in the UK, recycling high-performance magnets as part of a circular economy, and enabling research into the next generation of magnet materials. We have done this through a structured programme of activities categorised into innovation, international, skills, investment, and standards themes.

As part of the innovation theme, we have completed these 5 innovation landscape reports that identify and explore where there are opportunities to direct future R&D funding to commercialise science, engineering and technology boosting our sources of REEs across the entire value chain. From mining and extraction, through mid-stream processing and metallisation, downstream magnet manufacturing, recycling and the circular economy, and possible alternative materials and solutions to reduce or substitute REEs, there are huge opportunities for the UK. And now we must make the most of them.

Bruce Adderley
Innovate UK – Director Make & Use - Net Zero.

2. Introduction

The UK's Critical Minerals Strategy highlights the importance of critical raw materials to the UK economy. The UK criticality assessment identified rare earth elements as being significantly economically vulnerable and at the highest risk of supply chain disruption. Rare earth elements (REEs) are used in high-performance permanent magnets that are key components in electric vehicles, and offshore wind turbines to enable the green energy transition in transport, energy and industry and deliver net zero.

Innovate UK's **'circular critical materials supply chains programme'** (CLIMATES) aligns with the UK Critical Minerals Strategy to create a more resilient and sustainable UK economy, strengthening the supply chain for rare earth permanent magnets (REPMs), whilst positioning the UK as a leader in REE recycling.

The programme promotes business-led innovation in both primary and secondary supply chains to grow domestic capability and increase supply chain resilience. Activities span international collaboration, skills development, investment (public and private), and standards development.

Executive summary purpose

This is a high-level executive summary of the key outputs of five innovation landscape reports commissioned by Innovate UK, which investigated the REE value chain across both primary (mining to magnet) and secondary (end of life to magnet) supply chains, with a focus on UK innovations and innovation opportunities.

The five reports cover the following themes:

- Rare Earth Exploration, Extraction, Beneficiation and Concentration
- Rare Earth Processing
- Rare Earth Permanent Magnet Manufacturing
- Rare Earth Permanent Magnet Alternatives
- Rare Earth Circular Economy

Each report includes:

- An exploration of the current state-of-the-art technology relevant to the theme.
- Identification of the organisations developing technologies and innovations in the UK and a “mapping” of UK capability.
- Consideration and comparison of global and UK technologies and identification of collaboration opportunities.
- The innovations that need to be developed and deployed for the UK to have a competitive advantage in the REE and REPM supply chain.

3. Summary of REE value chain – Needs and opportunities

	Exploration, Extraction, Beneficiation and Concentration	Processing	Permanent Magnet Manufacturing	Permanent Magnet Alternatives	Circular Economy
Innovation landscape overview	Evaluates recent technological advances in the exploration, extraction, processing (beneficiation) and pre-separation of REEs. **Example explored:** • Fertility of REE deposits • Unconventional REE deposits and minerals • REE extraction from waste streams • AI and machine learning • Deep-sea mining and environmental implications • Artisanal mining • REE digital product passports	Covers the technologies used to concentrate and separate mixtures of REEs from primary (mining) or secondary (recycling) sources. It splits the technologies into mature, emerging and novel categories. **Examples explored:** • Solvent extraction • Plasma separation • Chromatography • Ionic liquids/DESs/Ionometallurgy • Ligand-induced selective flocculation • Phytomining • Bioleaching/Biosorption	Reviews the UK's innovation landscape for REPM manufacturing and how competitiveness can be advanced and supply chain vulnerabilities can be reduced. **Examples explored:** • Innovation activities • Metallisation and alloying • Manufacturing • Automation techniques • Capability to commercialise innovation	To reduce reliance on REPMs, the UK could explore alternatives that reduce the need for virgin REEs (but not completely replace them). **Examples explored:** • Substitution • REE-free/reduced designs • New magnetic materials • Reformulation	A circular economy approach can help to secure supply of REEs to produce new REPMs, eliminating the need to rely solely on primary REE supply. **Examples explored:** • Design for disassembly • Direct reuse strategies for REPMs • Collection, sorting and disassembly of REPM-containing products • Recycling via short-loop and long-loop • Materials tracking
Key innovation needs and opportunities	• Enhancing awareness of UK capability and expertise • Facilitation of stakeholder connections and funding TRL progression • Promotion of full value mining and reporting standards	• AI, Digital and Process Control technologies for solvent extraction • New, more environmentally friendly and domestically produced solvents for solvent extraction • Scale-up and commercialisation of emerging and novel techniques for processing of appropriate primary and secondary REE feedstocks, for maximum efficiency, sustainability and quality • Developing the synergies of processing technologies to facilitate innovative processing systems and supply chains in the UK	• Make assembly for REPMs into end products easier • Develop rapid and reconfigurable supply in the UK • Reduction of heavy REEs (HREE) in magnets • Develop REE magnets for the aerospace industry • Workforce development • Stable early-stage financial funding • International collaborations	• Accelerate REE-free magnet research • Create industry-led working group(s) • Development of a UK REE magnet knowledge hub • Investigate environmental impacts • Create small-scale magnet prototyping	• Commercial viability • Competing with primary extraction • Limited technologies for direct recycling in the UK • Lack of UK activity in materials tracking • Design products for disassembly • Raise awareness around the safe handling and storage of magnets • Collaboration across the supply chain

4. Innovation landscape Reports

4.1 Rare Earth Exploration, Extraction, Beneficiation and Concentration

To meet rising demand, mining companies are developing new, challenging REE deposit sites, which bring technical, financial, and environmental, social and governance (ESG) problems to solve. These can motivate UK companies to innovate and develop new technologies for exploration, extraction, beneficiation, and concentration of REEs for subsequent integration into the UK product value chains.

The Innovate UK Rare Earth Exploration, Extraction, Beneficiation and Concentration Innovation Landscape Report evaluates UK technological developments in this field, and highlights innovation opportunities and recommendations. Although the UK's geology contains limited REE deposits, the country has a substantial and capably strong mineral extraction ecosystem.

UK-based REE exploration and mining companies already operate in countries with favourable trade links. The UK itself is home to a strong mining consultancy sector working on REE deposits worldwide, as well as academics and universities with an international reputation in extraction, mining tunnelling, mineralogy, geology, geophysics, and geochemistry. Additionally, the UK has had a modern, mechanised, deep-mining tradition spanning hundreds of years, and as a direct consequence, developed a thriving mining equipment manufacturing industry.

The UK's broad mix of miners, expertise, equipment manufacturers, and technologies has the potential to collaboratively exploit opportunities to enhance the security of REE supplies, minimising the criticality of REEs for UK industry, and enhance the overall value chain for sustainable and environmentally benign, REE-dependant products.

Innovation Opportunities

In situ leaching (solution) mining / Direct in situ mineral extraction

The process involves injecting a chemical reagent into the mineral deposit core, which reacts with the target metal, dissolving it into a solution. The metal salt solution is then pumped to the surface for post-processing beneficiation. Compared to open-cast and underground mining, in situ solution mining potentially offers several important environmental and logistical advantages. Operating directly within the natural ore deposit, the method avoids surface disruption and excavation, as well as reducing the transportation of ore and associated waste (with associated carbon emissions) to a remote processing facility.

Artisanal / small-scale mining

Artisanal and small-scale mining (ASM) is primarily an informal economic sector where workers use their hands, basic tools, and low-tech equipment to extract minerals. Globally, it is estimated that around 40 million people work in the industry, including large numbers of women and children. Working conditions, safety, health, and levels of crime in this industry are mostly unknown. How artisanal mining can contribute to global mineral supply chains and help meet demand for critical metals in a sustainable way, without the associated social and environmental issues, is an important hurdle to be overcome.

Innovation opportunities include:

- Improving the ESG credentials of ASM-extracted REEs.
- Including the development of provenance and ESG compliance traceability technologies (passports).
- The coordinating and regulation of production, pricing and markets for multi-ASM operations (such as an “ASM-Metal-Exchange)”.
- Development of ASM-scale processes.
- Mechanisation and automation of ASM operations to improve the productivity, health and safety of ASM workers.

Extraction of minerals from complex (challenging) REE deposits

These deposits are usually poorly characterised and may lack developed ore concentration (beneficiation) processes such as those used in mainstream ore concentrating processes (grinding followed by froth flotation, magnetic, electrostatic, or gravity separation methods). However, they may contain higher proportions of heavy REEs and offer an opportunity to develop processes and technologies for their economic extraction.

REE extraction from non-REE mining waste streams

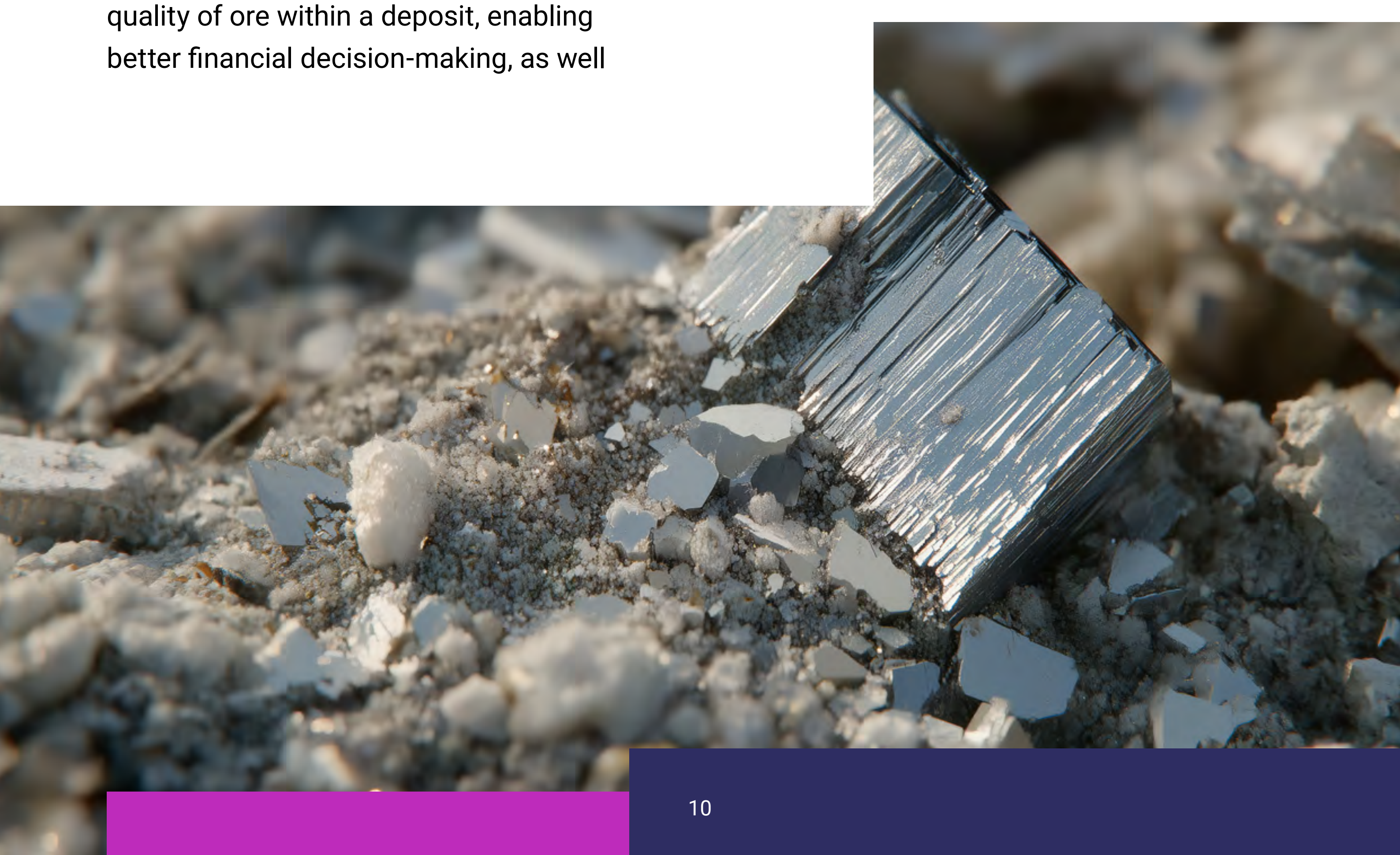
During the extraction of non-REE minerals, there is an opportunity to recover REE from waste by-products. Drainage and sludge from coal and metal acid mines (e.g., Pennsylvania, USA) have been processed to yield high-purity mixed rare earth oxides. Opportunities exist to develop new REE extraction technologies and processes and integrate these into exist ing mining beneficiation processes to yield new sources of REEs.

Application of AI for enhanced mineral exploration and extraction

AI and machine learning might be applied to geological exploration data and satellite imagery to develop predictive models to improve the estimation of the "quality" of potential REE deposit sites. They may also be applied to help estimate the grade and quality of ore within a deposit, enabling better financial decision-making, as well as reducing the time from discovery and testing to a commercially operating mine. The approach may also improve decision-making when considering the selection of recovery of lower-grade ore deposits.

Deep-sea mining environmental implications

Society's negative perception and acceptance of mining in the marine environment would need to be assuaged before this could proceed at a commercial scale. Demonstrations of environmental conservation and protection, reducing the uncertainty of creating ecological disasters will be needed, as well as developing extraction methods and potential in situ beneficiation technologies that have zero ecological impact. Despite these challenges, the UK oil and gas industry has developed considerable experience in sub-sea mineral resource extraction.



Recommendations

REE digital product passports

To ensure the ESG provenance of REE supplies, a “passport” system needs to be developed and implemented globally, containing the records of production and transportation of REE materials. To match the REE material to its origins, a database of extracted mineral chemical/physics data fingerprints needs to be developed to match with extracted mineral ESG credentials. Such data can be linked to a digital product passport (DPP) that is attached to the product shipment.

Promote UK extraction technologies, capabilities, and expertise

Relevant technology developed in the UK is not being adopted by the REE industry. To promote its evaluation, assessment, and potential uptake requires promotional activities such as workshops, conferences, and events that showcase the potential opportunities in using UK technology.

Promotion and awareness of UK capabilities and expertise will assist in developing partnerships with international trade partners, diversifying the international REE supply chain and delivering the UK Critical Minerals Strategy.

Promoting full value mining and reporting standards

Incentivising analysis of all metals present in a deposit would determine potential by-products and identify resources stockpiled in tailings facilities for future processing.

Full-value mining and recovery of critical metals as by-products creates a mineral supply better buffered against the financial risks that ensue from mineral pricing fluctuations, resulting in a more resilient and sustainable supply of critical minerals.

4.2 Rare Earth Processing

REEs from both primary (mining) and secondary (recycling) sources need to be concentrated and separated into finished REE products (e.g. oxides or carbonates) that can be turned into the precursor alloys required for permanent magnet manufacturing and other REE applications.

The Innovate UK Rare Earth Processing Innovation Landscape Report describes the technologies in current use and those that could be adopted in the future to perform these concentration and separation steps.

The report categorises the technologies into three levels of maturity using the technology readiness level (TRL) scale:

- **Mature (TRL 8-9)**
- **Emerging (TRL 3-7)**
- **Novel (TRL 1-3)**

We highlight the UK's strengths based on academic or commercial expertise.

Mature technologies (TRL 8–9)

Solvent extraction (SE) is by far the most used separation technology. SE even continues to be the method of choice for new projects (and is used as part of the process in recycling projects).

Innovation opportunities include:

- **AI, digitalisation, and process control** for enhanced efficiency, selectivity, and reduced waste/downtime.
- **Discovery and implementation of more environmentally friendly solvents** that can be domestically produced.

Emerging technologies (TRL 3–7)

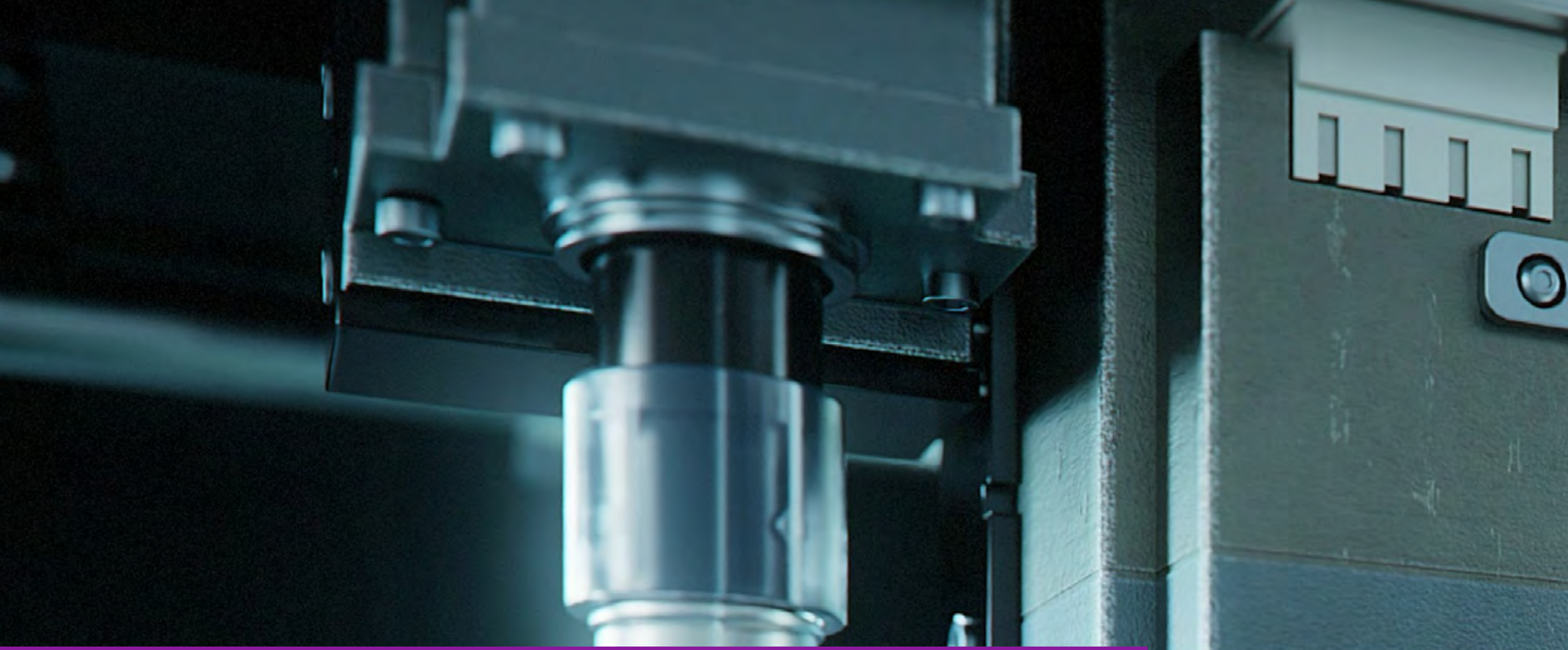
- **Ionic liquids / Deep eutectic solvents (DESs) / Ionometallurgy (TRL 6/7) –** Versatile methods for selectively dissolving and separating REEs (with crossover potential to other critical materials) that are being developed by UK companies. Needs a final investment to enable scale-up.
- **Ligand-induced selective flocculation (TRL 4) –** A highly promising method being developed commercially for a range of CMs by a UK company. Requiring scale-up to demonstrate long-term commercial viability.
- **Plasma separation (TRL 3/4) –** Showing increasing promise for use on REE-bearing materials from both primary and secondary sources, but needs to be validated at scale.
- **Chromatography (TRL 3/4) –** Could be relevant for materials with high REE concentrations, but needs to be validated at scale.

Novel technologies (TRL 1–3)

- **Phytomining (TRL 2/3) –** A highly promising, low-energy footprint method for recovering critical materials from soils. Recently applied to REEs by a UK company with positive initial results. Requires scaling up.
- **Bioleaching / Biosorption (TRL 3) –** A highly versatile, low-footprint approach for recovering critical materials from various sources. There is strong academic expertise in this area, requiring tech transfer to accelerate scale-up and commercialisation.
- **Supramolecular chemistry (TRL 3) –** Academic studies have shown that supramolecular chemistry can be applied to certain mixtures of REEs. It may also be applicable when incorporated into a larger process design.

Innovation opportunity

There is an opportunity to develop a portfolio of technologies to process REEs from both primary and secondary sources, with the technologies matched to the feedstock according to the requirements for selectivity, throughput, purity, energy use, and engineering constraints, and some technologies could even be used in combination to maximise the processing performance.



4.3 Rare Earth Permanent Magnet Manufacturing

The Innovate UK Rare Earth Magnet Manufacturing Innovation Landscape Report reviews REPM manufacturing in the UK and how competitiveness can be advanced and supply chain vulnerabilities reduced.

It assesses the current state of REPM manufacturing, from REE alloying through to either sintering, bonding, or hot deforming of the final magnet, and identifies key innovation areas that could improve performance, reduce waste, and make processes more efficient. Many innovations are still in the early stages and require significant commercial investment to develop them further.

The UK already has strengths in bonded magnet manufacturing, however, in the case of large-scale sintered magnet manufacturing, there remain gaps in capabilities, and innovation support should be considered for this process that typically results in magnets with some of the highest performance characteristics. Innovation in magnet manufacturing technologies such as sintering can result in direct foreign investment in this sector.

Key opportunities to strengthen the UK's innovation ecosystem are discussed, including the design of magnets to permit end-of-life recycling, technology scale-up potential, skills development, and creating an industry-led working group to unite stakeholders. Increasing awareness of the environmental impact of the REPM supply chain and building local capacity are also key steps toward improving sustainability and supporting innovation in the sector.

Innovation opportunities

Make assembly for REPMs into end products easier

There is a need to develop more efficient ways to assemble standard REPMs into end products. This could include innovations like using robotic automation in the assembly of electric drive units (EDUs) and wind turbines.

Develop a reconfigurable supply chain

There is a growing opportunity to develop a resilient UK REE supply chain that is rapidly deployable, remotely managed, and flexible. e.g. the factory in a box (FIAB) concept.

Reduce the need for heavy REEs (HREEs) in magnets

Due to concerns over the environmental impact of their production, it is aspirational to reduce HREEs, such as dysprosium and terbium, in the sintered magnet whilst maintaining or increasing magnet coercivity. One method under consideration to achieve this includes grain boundary diffusion.

Develop REPMs for the aerospace industry

The aerospace industry is experiencing exponential growth in electrification, creating an opportunity for the UK to develop REE magnetics specifically for this sector.

Recommendations

Support workforce development

To develop a skilled workforce to support the growth and technological advancements in magnet manufacturing.

Enable stable early-stage financial funding

Manufacturing requires high capital investment as well as long-term and guaranteed market stimulus.

Create an innovation ecosystem

Develop an ecosystem that supports innovators to gain access to large-scale enterprises, R&D facilities, testing facilities, grant funding, and IP. Encourage key partners to share facilities (e.g. for prototyping magnets) and create long-term partnerships.

Facilitate international collaborations

To enable UK stakeholders to have international collaborations on research projects and supply chain partnerships.

Promote and support design for disassembly

REE magnet users should consider end-of-life disassembly when designing a product.

Develop skills

Enable opportunities for increased testing and scaling of technologies and for developing skilled workers

Enable collaboration

Create an industry-led working group to bring together end-users, corporates, innovators, and academia to provide a voice for the sector.

Grow knowledge

Increase understanding of the environmental impact of the current REPM supply chain and how that would change by building local capacity. Build up a UK REPM knowledge hub for the sector.

Facilitate prototyping

Develop a small-scale and agile magnet sintering prototyping facility to produce high-value magnets.

Drive research

Develop magnet manufacturing research centres and IP to drive the development of both existing and emerging technologies.

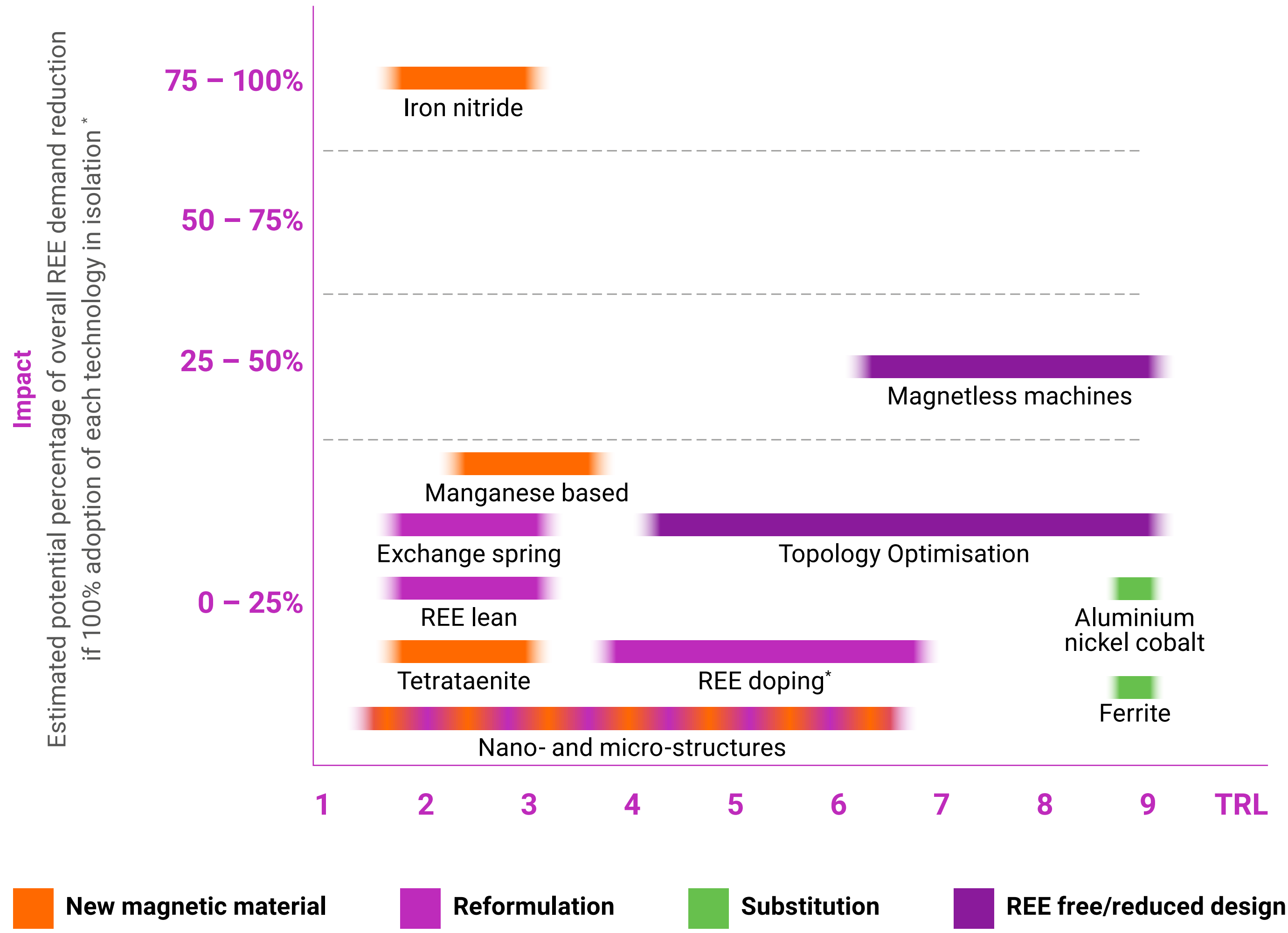
4.4 Rare Earth Permanent Magnet Alternatives

While REPMs dominate the technology landscape in the expansion of the electric vehicle and renewable energy industries, not all applications using permanent magnet electric machines require the higher performance achievable with NdFeB magnets.

These applications could use REE-free magnets, and this provides an opportunity to explore alternatives that can reduce our reliance on REEs.

Technology innovation areas

Focus and support should be provided to technologies as higher level TRLs as early-stage technologies are too far from commercialisation.



* **Note:** Relative position of solutions within % brackets are not indicative of comparative impact.

Extract from Alternative Innovation Landscape Report – summary of alternative technologies, impact and TRL.

Four alternative strategies were identified:

1. **Magnet Replacement –** Replacing REPMs with non-REE magnets (e.g. aluminium nickel cobalt, ferrites) where the performance requirement permits.
2. **REE-free/reduced designs –** Performing an engineering topology redesign or optimising the electric vehicle traction motor (for example) to achieve the necessary level of performance while using fewer REPMs.
3. **Design new magnetic materials –** Novel magnetic materials that can replicate or outperform REPMs e.g. iron nitride, tetrataenite, manganese-based, nanostructured magnets.
4. **NdFeB reformulation –** Material formulation to reduce REE content in magnets whilst maintaining performance e.g. REE lean/ REE doping magnets, exchange spring magnets, microstructured magnets.

“1 and 2” are potentially high TRL alternatives that remain relatively unexplored by the UK electric motor industry and “4” at an early-stage, low TRL level requiring longer-term investment.

Innovation capability needs

The UK has strong capabilities in knowledge and skills, particularly around computational materials science.

The gap analysis extracts below overlay findings from an innovator mapping exercise with the sector innovation needs assessment to pinpoint where the UK has strength in an innovation area.

The RAG status (orange, purple, green) visualises the UK’s strength in each technology theme against the innovation needs they satisfy to highlight potential innovation opportunities.

UK gap analysis – capability gap to commercialise innovation

The UK has good general early-stage capabilities to support innovation but suffers from a lack of commercialisation funding, domestic supply chain, and end-user collaboration.

Requirements for Innovation	R&D Facilities	Testing Facilities	Funding Opportunities	Skills Development
Knowledge & Skills	Average	Strong	Strong	Strong
Computational & Simulation	Average	Average	Strong	Strong
Synthesis & Testing	Average	Average	Strong	Strong
Non-dilutive Support	Strong	Strong	Average	Strong
Early stage Dilutive Funding	N/A	N/A	Average	N/A
Commercialisation Funding	N/A	N/A	Weak	N/A
UK REE Magnet Supply Chain	Strong	Weak	Weak	Weak
End User Collaboration	Weak	Strong	Weak	Weak

N/A Capability is not relevant for the specific requirement to innovate

Average Findings indicate UK capabilities partially meet requirements to innovate

Weak Findings indicate UK capabilities do not meet requirements to innovate

Strong Findings indicate UK capabilities meet requirements to innovate

UK gap analysis – innovation opportunities

REE free/reduced design technologies present the best innovation opportunity in the UK.

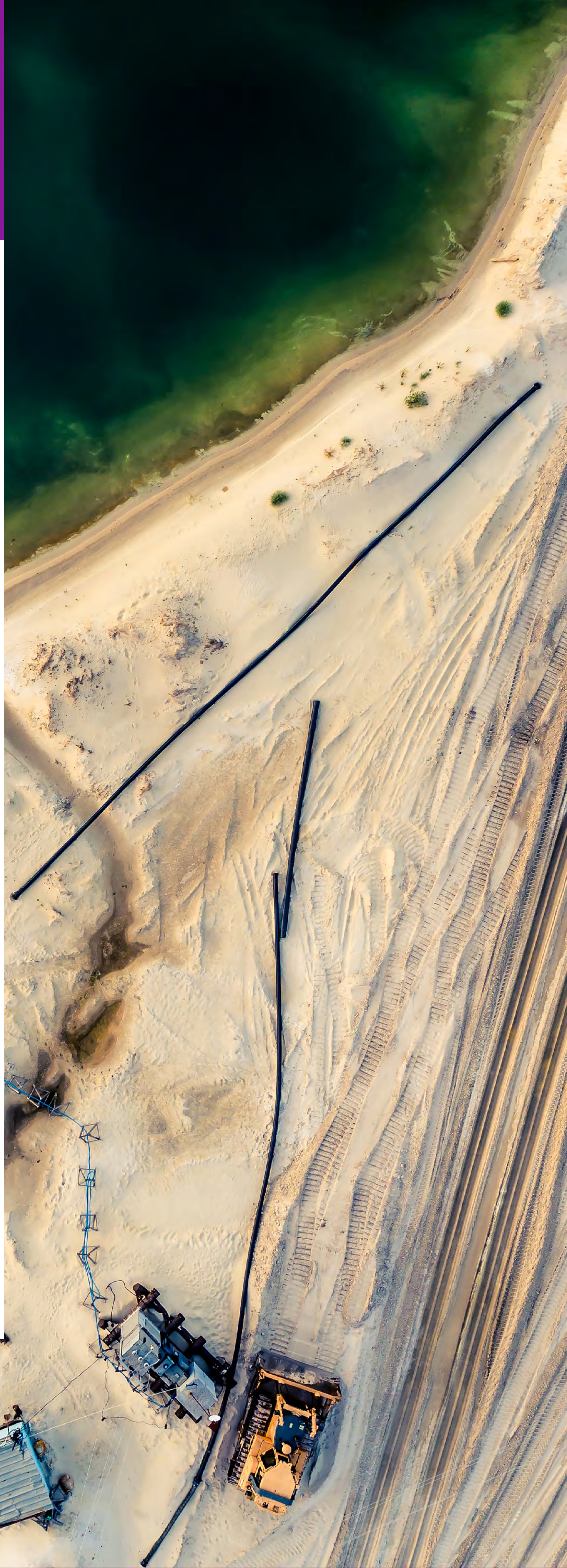
Innovation Need						
Develop magnets that can compete with no or reduced REE content	Iron nitride (Weak)	Tetrataenite (Strong)	Manganese based (Strong)	Nano and micro structures (Strong)	REE lean REE doping (Strong)	Exchange spring magnets (Weak)
Computational & Simulation	Magnetless machines (Strong)	Topology Optimisation (Average)				
Synthesis & Testing	Alnico (Weak)	Ferrite (Average / Strong)				

Weak Has no companies, innovators or research activity for this technology area

Average UK has research activity for this technology area, but no companies or innovators

Strong UK has both companies and innovators relevant for this technology area

Innovation Opportunities



Opportunities identified to address capability needs include:

- **Accelerate REE-free magnet research using AI –** UK research centres with strengths in AI for materials discovery could focus on alternatives to REE magnets, using existing infrastructure to reduce costs and promote long-term development.
- **Development of a UK REE magnet knowledge hub –** Building a knowledge base to support innovation in the sector. However, the success of this hub depends on companies sharing data, which may be difficult.
- **Investigate environmental impacts –** Determine the effects of using REEs in magnets and how alternative technologies could reduce these impacts.
- **Create small-scale magnet prototyping facilities –** Develop to support the production of customised REE-free magnets for motor designs, bridging the gap between research and large-scale production.

4.5 Rare Earth Circular Economy

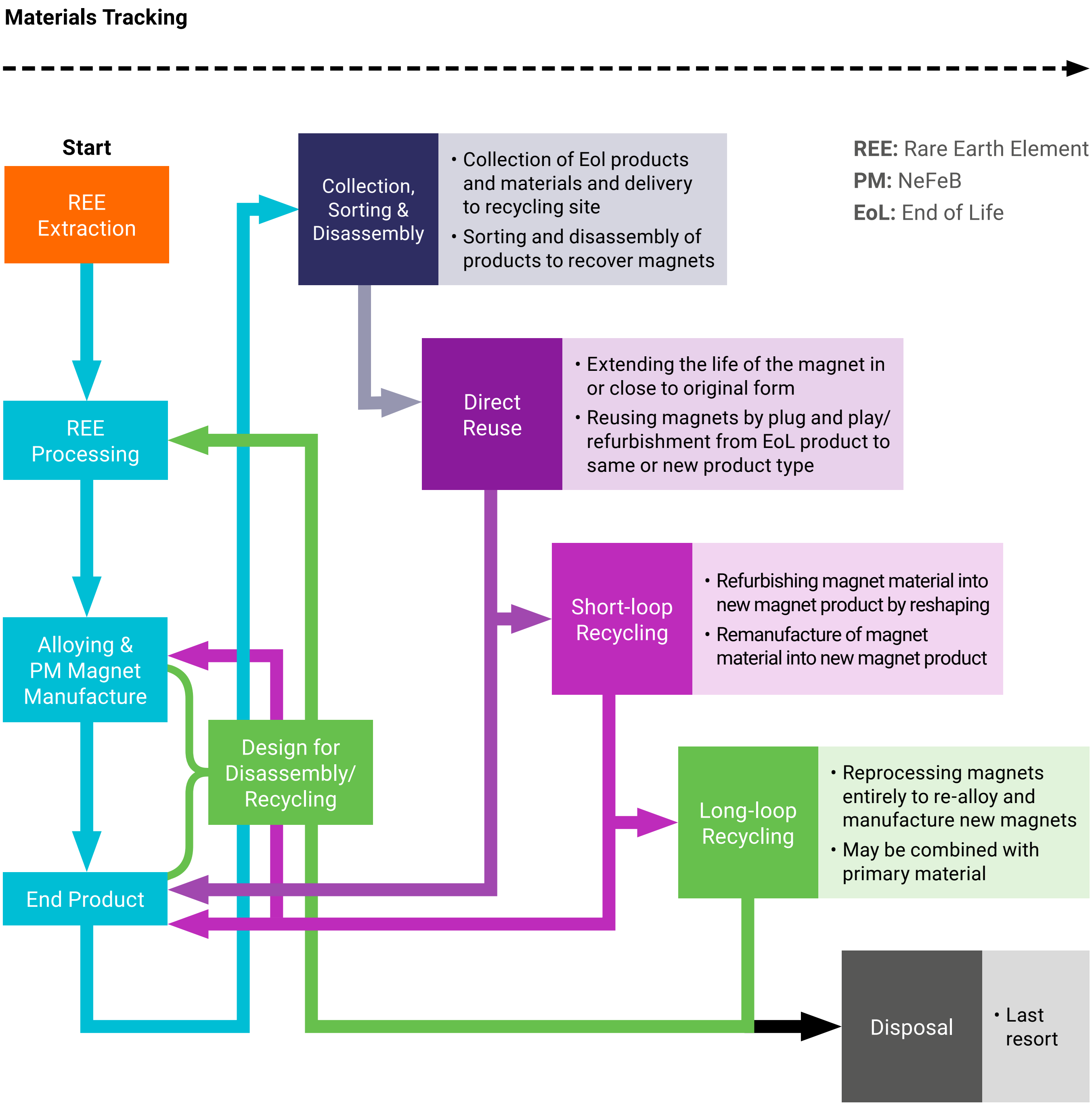
A circular economy approach is critical to enable a secure UK supply of REEs and increase supply chain resilience, reducing the need to rely solely on overseas primary REE supply and de-risking geopolitical factors.

Recycling end-of-life (EoL) products to recover REE magnetic materials for subsequent reuse and remanufacturing into new magnet products may be a viable circularity approach.

Many nations, including the UK, are looking to implement a secondary supply chain by exploring the potential of recycling REE permanent magnets.

Circular supply chains – what is possible?

REE: Developing A Circular Economy



Report Extract: An idealistic circular rare earth permanent magnet supply chain

Key considerations in developing a REE circular supply chain

Design for disassembly

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

Direct reuse strategies for permanent magnets

Involves the removal of permanent magnets from EoL products (e.g. electric vehicle drive motors or decommissioned wind turbines) and placing them directly into new products with minimal modification.

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, however, the diversity of waste streams that contain REE permanent magnets adds logistical complexity and makes sorting and disassembly challenging.

Recycling via remanufacture (Short-loop recycling)

Recycling by remanufacture / short-loop is the process of recovering REE permanent magnets from EoL products and remanufacturing the magnet material alloys into a new sintered magnet.

Recycling via reprocessing (Long-loop recycling)

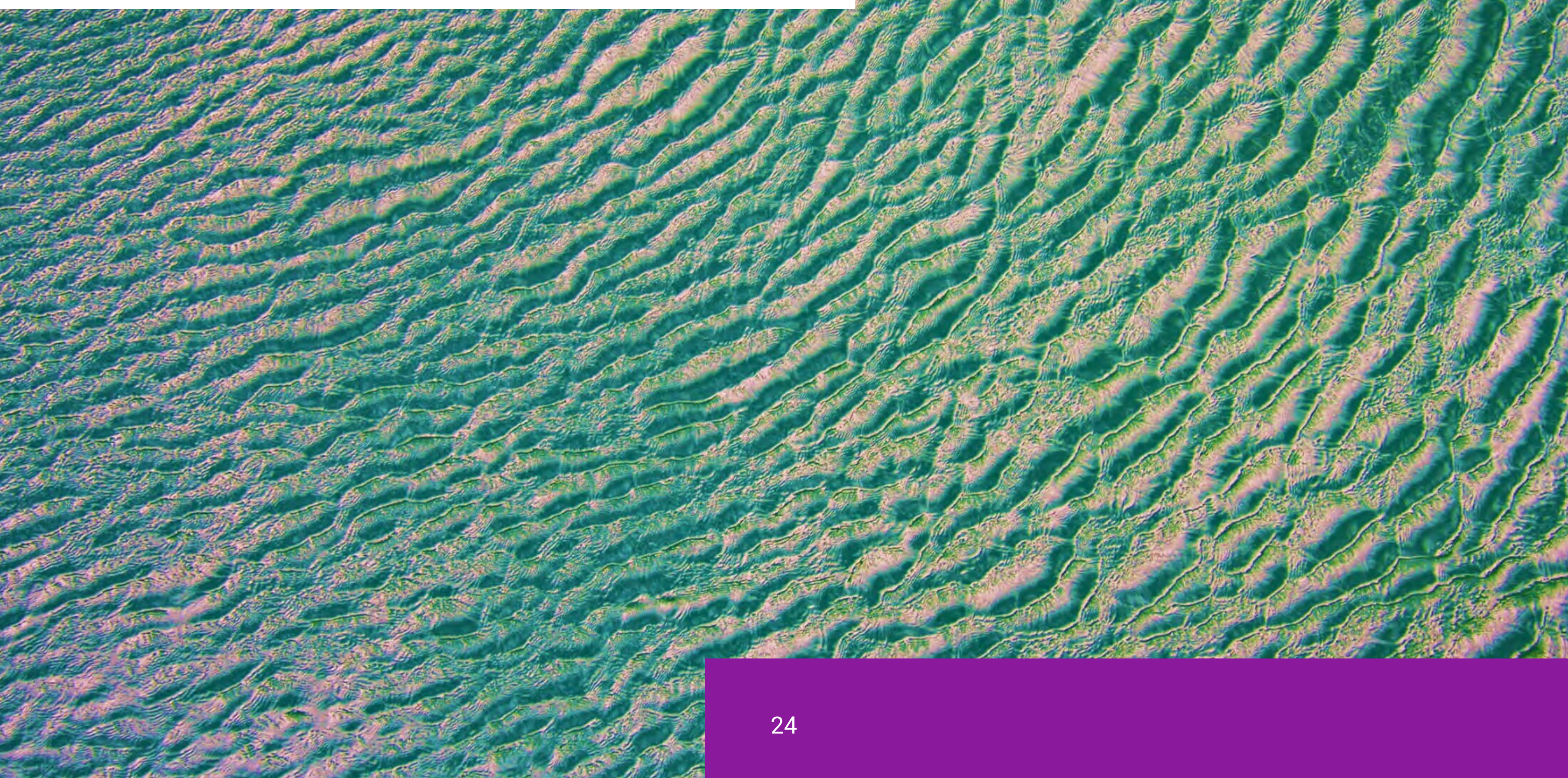
This involves taking REE permanent magnets and reprocessing the material back to individual REEs for subsequent re-alloying and then manufacturing new sintered magnets with this alloy.

Materials tracking

Tracking materials allows traceability which improves recyclability and encourages sustainable mining practices.

Barriers to the development of a circular approach

- **Lack of incentives –** Manufacturers may be happy to manufacture magnets with existing supplies of magnet alloys made from REE elements extracted from virgin REE ores.
- **Commercial viability –** Includes the capital requirements needed to scale processes and infrastructure.
- **Regulation and legislation –** This is needed to provide clarity to allow organisations to recycle and reprocess in a compliant manner.
- **Financial –** There is competition with the supply of REEs/alloys from virgin ores, which can be at substantially lower cost to purchase than recycled REE materials.
- **Timing –** Larger magnets have long lead times for recirculation. (e.g. wind turbines – 35 years).
- 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.
- **Little evidence was found of UK activity in materials tracking** for REEs.



Opportunities for the REE value chain to promote circularity

- **Design products for disassembly** at EoL at the earliest possible stage, for example, through collaboration between product designers and recyclers.
- **Collaborate with organisations developing robotic disassembly** for related circular economies, enabling cost-effective recovery of REPMs from EoL products.
- **Through careful design, magnets can be reused or repurposed.** New mechanical and glue-based fixings to prevent damage during recovery from motors and generators 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.** There is a need for evidence of longevity and that old magnets can be reused as they are without a drop in performance, in order to reassure product manufacturers that magnets can be reused.
- **Raise awareness around the safe handling and storage of magnets** and the innovations that can effectively demagnetise large quantities of magnets in a timely and safe manner.
- **Collaborate with innovators across the supply chain** to discuss what a materials tracking system should look like for the REPM supply.
- **Recycling companies could 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, to catalyse the circular supply of secondary REEs in the UK.
- **Develop a national waste collection pathway** for the recovery and collection of magnets and magnet-containing products.

Innovate UK

Further information, including links to the Innovation Landscape Reports, can be found on the Circular Critical Materials Supply Chains (CLIMATES) programme website:

iuk-business-connect.org.uk/programme/circular-critical-materials-supply-chains/

ukri.org/councils/innovate-uk

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