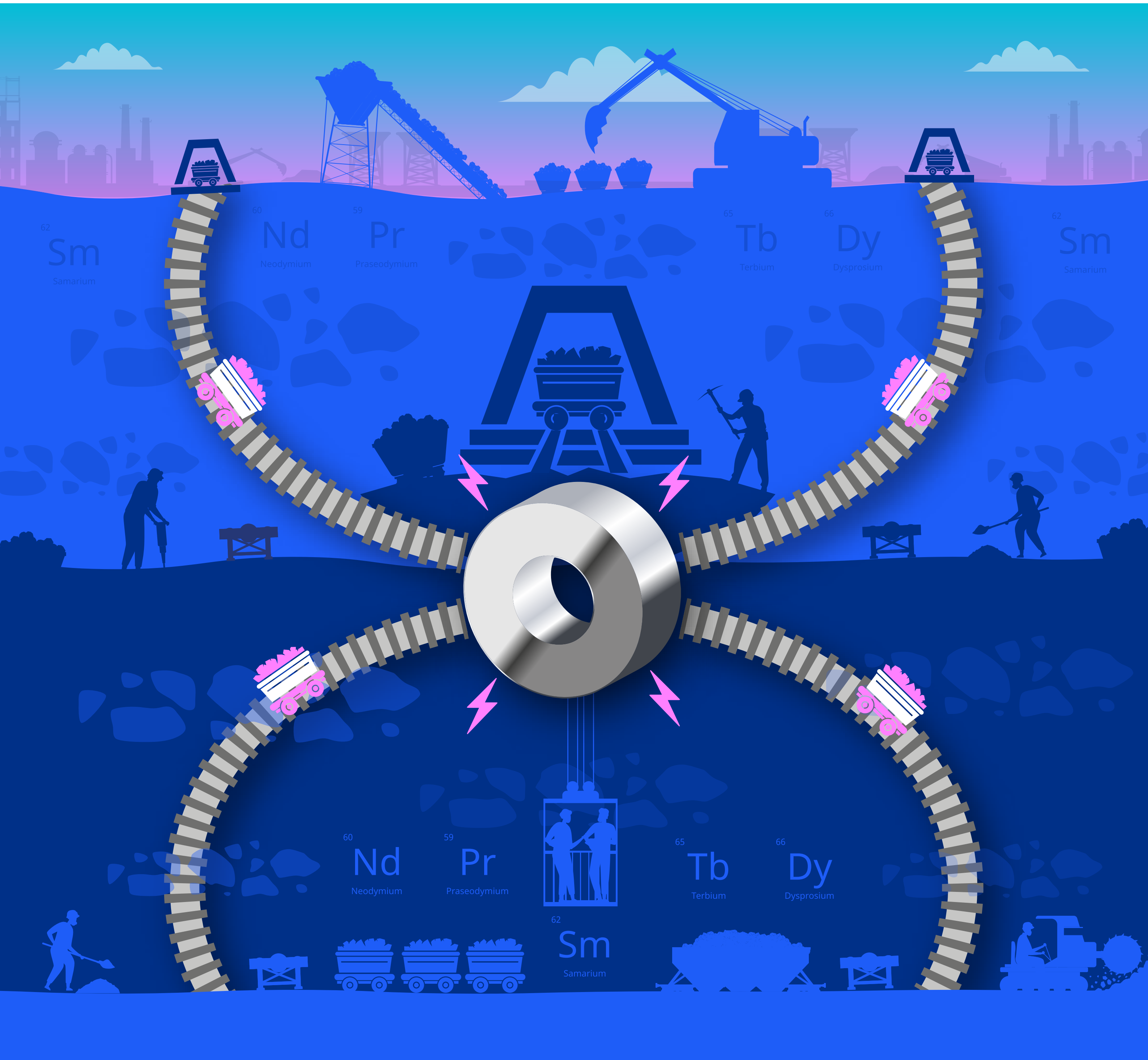
Innovate UK
KTN

UK supply chain opportunity in materials for permanent magnets



Executive Summary

Innovate UK KTN has conducted a review into the UK supply chain opportunity in conjunction with the Driving the Electric Revolution team at UK Research and Innovation (UKRI).

The review aims to highlight:

- The rare-earth market opportunity
- The primary supply opportunity (sourcing materials directly from mines and processing them in the UK)
- The secondary opportunity (magnet recycling)
- The opportunity presented by next generation magnet materials.

The security of a rare-earth material supply is of critical importance to the UK's electrification ambitions which are required to meet the UK government's net zero target. For materials of such strategic importance there are several opportunities that the UK should consider.

There is an opportunity in the UK to develop a primary supply chain building on existing strengths in metal refining and the development of breakthrough separation technologies. There is an opportunity for the UK to take a world leading role in the recycling of rare-earth materials by supporting and funding the development of this emerging industry. There is further opportunity to utilise current UK strengths in materials discovery to explore new magnet materials for the future.

The recommendations from this study are:

1. Collaborative Research and Development (CR&D) programme focused on new innovations for the chemical treatment and separation of rare-earth elements, with a particular interest on the development of more sustainable processes than those currently in use.
2. Feasibility studies leading to CR&D funding to explore the development and demonstration of recycling processes for rare-earth materials from a variety of sources.
3. Community building activities to connect the chemical and material sectors to magnet manufacturers and end users to explore, develop and integrate the rare-earth magnet opportunity across the supply chain.
4. Further studies into the development of incentives for Original Equipment Manufacturer (OEM) to support market development in the UK for magnet production and end of life management.
5. Coordination and application of UK research infrastructure to the materials science challenge of creating the next generation of magnet materials, utilising established UK strengths in computational and experimental materials development.

> “There is an opportunity for the UK to take a world leading role in the recycling of rare-earth materials by supporting and funding the development of this industry.”

Dr Matthew Reeves
Innovate UK KTN

Introduction

Permanent magnets are used in a wide variety of consumer and industrial applications, including loudspeakers, automotive drive trains, and wind turbines[1,2]. For high performance applications, which require the highest degree of magnetic energy density, these magnets are alloys of neodymium, iron and boron (other elements, such as dysprosium, are included to boost performance at high temperatures)[3].

Magnet production

The minerals and materials required for permanent magnet production are called the “rare-earths” which, despite their name, are relatively abundant in the earth’s crust[4]. However, they exist as elemental mixtures, and are present at very low concentrations in mineral deposits such as monazite and bastnasite. Hence, it is challenging and energy intensive to produce the pure single-element powder required for magnet production – processing is technically challenging, energy intensive and in most cases acutely harmful to the environment[5,6].

The vast majority of rare-earth production occurs in China (>80%)7, which provides a geopolitical challenge for the West, as evidenced recently by the “rare-earth crisis” of 2010/11. Securing the supply of permanent magnets and the raw materials necessary for their production is a topic of UK strategic importance, given the increasing focus on electrification for energy generation, as well as transport and manufacturing infrastructure[9].

If the UK wants to become a production hotspot for electrical products it would be remiss to ignore such an opportunity to become at least partly self-sufficient in the procurement of critical material components.

Market outlook and opportunity

The global market for rare-earths is projected to grow from $2.8bn to $5.5bn by 2028, with a Compund Annual Growth Rate (CAGR) of 10.0%[10]. The predominant supply of rare-earth materials to the rest of the world is from China (>80%). Outside of this there are currently many projects looking globally (Australia, Malaysia, Canada, USA, South Africa, Burundi, Tanzania, UK, Angola) to source new primary supplies of rare-earths, highlighting the importance of these strategic elements.

Rare-earth metals, unlike other (commodity) metals like copper, gold, and platinum, are not traded on any open exchange. They are traded purely through the negotiation of private contracts. This makes it challenging to ascertain up to date pricing information or to generate price forecasts. It also means that companies need to develop relations with individual mining firms and other actors (for example. states and state-backed enterprises, processing facilities). Large end-users of permanent magnets see the lack of diversity in their rare-earth supply chains as a risk. As a consequence, new and emerging suppliers are sought to ensure supply is robust. Products with 'green' credentials could be of interest but any increased cost would not be viable.

Currently demand for rare-earths in the UK is low, this is due to an under-developed supply chain. However, demand is likely to rise with the move towards electrification. Demand can also be generated by incentivising the onshoring and retainment of manufacturing capability (for example. automotive, wind turbines) that requires a relatively large volume of magnets. Magnet production, and hence magnet material procurement, will be incentivised by this demand.

Collaborating internationally will be very important however it would be very high risk to invest directly into mining projects, due to very high technical, environmental and social risks[11]. An alternative option would be to secure off-take agreements for mining concentrates that can be processed in the UK. Australia and Japan are already exploring this.

The opportunity in the magnet supply chain may look small, in monetary terms, compared to the adjacent opportunities in batteries, green energy generation, for example. However, since magnets are an essential component of many electrical systems, the supply chain opportunity becomes one of strategic importance. If the UK wants to become a production hotspot for electrical products it would be remiss to ignore such an opportunity to become at least partly self-sufficient in the procurement of critical material components[1,8].

UK Opportunities
Chemical processing and refining of primary supply

Minerals are extracted from mines and undergo many physical and chemical steps to become purified single rare-earth containing compounds (usually oxides or salts)[6,11,12]. The opportunity here is to improve or revolutionise the chemical separation process, which is the stage that carries the most environmental and financial risk. There are several methods available for the separation of rare-earths however most if not all are not ready for deployment at commercial scale. These include biosorption and other biological/biotechnological and agronomical techniques[12–14], ordered mesoporous materials (OMMs)[15], precipitation techniques, ionic liquids, adsorption and hydrometallurgical techniques, amongst others[5,12].

Environmental social governance (ESG) is becoming increasingly important for OEMs. As OEMs clean up their supply chain, the harms embedded in the procurement of permanent magnets will become a drag on their overall ESG performance. If improvements for the separation processes can be made, the material produced through such a supply chain could become very attractive to OEMs.

Magnet production would benefit greatly from an "integrated supply chain" – This is an approach which has been utilised in China to exploit their natural geology. However, it is a challenge in most regions as it requires significant effort, trust and governmental support to coordinate. Alternative ways to integrate the supply chain could be explored within the UK, for example establishing and fostering closer relationships between the chemical and material sectors as well as end-users, or locating new facilities within established industrial clusters.

There is an opportunity in the UK to develop this primary supply chain, with strengths in metal refining and development of new chemical technologies within university chemistry departments and scale up facilities like Centre for Process Innovation (CPI). Existing players and universities developing innovative separation techniques should be supported and developed through CR&D and scale up funding. Support should also be provided for UK firms trying to establish off-take agreements from foreign mines, and this should be coordinated with process development to match up materials specifications to processing methods.

> "Magnet production would benefit greatly from an integrated supply chain."

Recycling of rare-earth products for secondary supply

Currently, less than 1% of magnets are recycled[16]. Economic factors currently favour production of magnets from primary material sources over recycled materials[17]. However, as demand for rare earths increases and the amount of second-hand magnetic material available also increases, recycling becomes a more viable opportunity[18–20].

Developing a secondary supply chain could provide security of supply to the UK which, as previously discussed, is currently a risk for many end users. In addition, the utilisation of recycled rare earth metals back into different magnet materials and products will enable the circular economy, reduce the requirement for virgin material and the environmental impact of final products.

The challenges associated with the recycling of magnets include collection and variable magnet composition, developing and demonstrating new technologies for the recycling of rare earth magnets, and unfavourable economics for recycled rare earth materials.

There are several UK based companies in adjacent industries (PGM refining and battery recycling) that have technology that could be applied to rare earth magnet recycling. When developing new recycling technologies, it will be important to establish the requirements of the rare earth products so that they can be utilised in downstream sectors. Novel processes will need to produce cost effective products with equivalent or increased performance to those currently produced from virgin material. To engage with companies in these adjacent industries funding is required for feasibility studies to test processes. Funding for collaborative research and innovation to support the development of new supply chain relationships is also needed.

The collection of used rare-earth magnets is a challenge. Many consumer electronics e.g. hard drives and speakers utilise permanent rare earth magnets. As these consumer goods reach their end of life it can be difficult to predict how they will be disposed of. This makes it challenging to collect products to sort and recycle the components. In addition, generally speaking, the magnets are embedded within complex products with multiple components which makes it challenging to segregate the valuable rare earth materials. Different products may also have magnets of different compositions which have varying process requirements. The introduction of a UK wide common waste disposal route for these products would enable industry to access materials for recycling, this applies not just to consumer electronics but also to power trains and drives which are used in electric vehicles. The move to electrification may drive the development of a recycling industry for rare earth materials as the end-of-life vehicle directive will apply.

Continued

There are opportunities for recycling permanent magnets beyond consumer products. One significant industrial use of rare-earth permanent magnets is in direct drive generators for offshore wind turbine applications[21]. Wind turbines tend to have a lifespan of 25 to 30 years and a 15 MW turbine with a direct drive generator contains nine tonnes of permanent magnet. These rare-earth magnets would provide a large volume of material of a known composition for recycling processes. There are opportunities to explore new business models with industrial users of rare-earth materials for example rental agreements, which would enable a recycling industry.

Currently the cost associated with collection and recycling of rare-earth materials is not economically viable. There are different incentives that could assist with altering this market dynamic, this could include ensuring producer responsibility for end-of-life approaches or establishing a required amount of recycled content in new magnets[17]. Understanding the impact of different approaches to this requires further investigation.

It is worth considering that support for a UK based rare-earth recycling sector could encourage and further seed a rare-earth permanent magnet manufacturing sector, with access to a local supply of sustainable material providing a point of difference in the market. In turn a UK based magnet manufacturing sector could seed the recycling industry with manufacturing waste and off-take agreements for specific products.

> “There are opportunities to explore new business models with industrial users of rare-earth materials”

There is an opportunity for the UK to take a world leading role in the recycling of rare earth materials by providing support and funding for the development of a new industry. Establishing this industry could provide security of supply for rare earth materials for the UK and would have the added benefit of providing more sustainable materials for a magnet manufacturing supply chain in the UK.

Next Generation magnet materials

The best available permanent magnets currently are based on alloys of neodymium and ferromagnetic cobalt or iron (Nd-Fe-B). This design paradigm was discovered in 1982 and has since undergone various improvements (for example the improvement of production processes and the inclusion of small amounts of other elements to improve performance characteristics for example Dysprosium)[3]. The first rare-earth magnets were invented in the 1960s, which used alloys of samarium and cobalt (Sm-Co). Crises in the supply of cobalt in the 1970s created problems for manufacturers of Sm-Co and other magnets based on cobalt (for example. the "alnicos", Al-Ni-Co-Fe), which in turn resulted in the shift to Nd-Fe-B[22]. These magnets also suffered their own supply crisis in 2010, hence the incentive to look at new magnet material prospects.

What Nd-Fe-B, Sm-Co and Al-Ni-Co-Fe all have in common from a material standpoint is a high magnetic energy density (required for the efficient conversion of electrical energy into motion) high global shape anisotropy (so that the material can be moulded into any shape and be able to retain its magnetisation), and a high value of coercivity (required so that the magnet sufficiently resists its demagnetisation field over time)[22]. The materials are stable at high temperatures (experienced both in applications and during processing) and are based on elements that are geologically abundant. Attempts to formulate new magnets have resulted in materials that underperform in at least one key area[3,22].

Given the economic, environmental, and technical complexities around rare-earth extraction, it would be wise to consider the possibility of a new "gap magnet material" emerging through research over the next few years or decades. The gap to bridge is between the best performing Nd-Fe-B magnet (energy density ~500 kJ $^{m-3}$) and the best performing rare-earth free magnet Ba-Fe-O (~50 kJ $^{m-3}$), whilst requiring a high coercivity and a Curie temperature in excess of 550K for any practical purpose.

This problem lends itself well to computational material screening (to identify candidate alloys) and high throughput experimentation (to make samples of the alloys and measure their magnetic and physical properties). The rapid development of machine learning, experimental robotics and the advent of quantum computing add to the array of tools at our disposal[23–25].

The UK has significant capability in this area. High performance computing apparatus, high throughput experimentation infrastructure and expertise, academic expertise in materials science for magnetic materials and magnetics testing and diagnostics expertise are all located within universities, research organisations and companies across the UK.

The UK has an opportunity to connect multiple skilled disciplines to address the challenge. The recommendation is to engage stakeholders in this area to explore the possibility of directing research infrastructure towards this materials science challenge.
This would involve an in-depth assessment of the capability, an exploration of the mechanisms (funding and otherwise) that would enable this, and dissemination of the strategic opportunity such research would present.

Recommendations & Acknowledgements

Recommendations

1. Collaborative Research and Development (CR&D) programme focusing on new innovations for the chemical treatment and separation of REEs, with a particular interest on the development of more sustainable processes than those currently in use.

2. Feasibility studies leading to CR&D funding to explore the development and demonstration of recycling processes for rare-earth materials from a variety of sources.

3. Community building activities to connect the chemical and material sectors to magnet manufacturers and end users to explore, develop and integrate the rare-earth magnet opportunity across the supply chain.

4. Further studies into the development of incentives for OEMs to support market development in the UK for magnet production and end of life management.

5. Coordination and application of UK research infrastructure to the materials science challenge of creating the next generation of magnet materials, utilising established UK strengths in computational and experimental materials development.

Acknowledgements and Additional Resources

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Reaching net zero by 2050 will not be possible without the supply of power electronics, machines and drives (PEMD) on a large scale. The Driving the Electric Revolution challenge at UK Research and Innovation is investing £80 million to:

- Leverage the UK's world leading research capability in PEMD to help industry create the supply chains necessary to manufacture the PEMD products developed here.
- Identify gaps in the supply chains and help industry fill them.
- Ensure cooperation and collaboration so we don't duplicate effort, waste time and can reuse solutions across all sectors.
- Help fill the skills gap by retraining, upskilling and repurposing engineers from traditional internal combustion businesses into PEMD supply chains.

To find our more, visit: https://www.ukri.org/what-we-offer/our-main-funds/industrial-strategy-challenge-fund/future-of-mobility/driving-the-electric-revolution-challenge/

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