Innovate UK

Rare Earth Permanent Magnet Manufacturing

Innovation Landscape Report

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1. Executive Summary

This Innovation Landscape Report on Rare Earth Permanent Magnet (REPM) Manufacturing 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 Circular Economy, and Rare Earth Permanent Magnet Alternatives.

This report reviews the UK innovation landscape for REPM manufacturing and how it can be leveraged to increase competitiveness and reduce vulnerabilities in the REPM supply chain. Specifically, we examine the current state of magnet manufacturing, identify key innovation areas, assess the UK's capabilities, and map them against its innovation needs to outline challenges and opportunities.

Currently, the primary methods for manufacturing NdFeB magnets, which are the best-performing magnets for applications such as electric vehicle motors and wind turbine generators, are sintering, bonding, and hot deforming. Each method offers unique benefits: sintered magnets provide the highest maximum energy, while bonded and hot-deformed magnets allow for near-net-shape formability.

Innovation in magnet manufacturing focuses on (1) improving coercivity, (2) reducing REE waste, and (3) making the manufacturing processes more efficient. This report identifies 15 critical innovation technology sub-themes, which all try to address one or more of the above problems. However, many of the sub-themes are still at low Technology Readiness Levels (TRLs) and have no active companies in the UK, therefore requiring large capital investment to commercialise.

It is vital for the UK to strategically select the sub-themes in which to invest. Opportunities lie in areas where existing UK organisations are available as commercial partners, examples include technology sub-themes such as bespoke alloy production, optimising hot deformation and bonding, reducing heavy REE content, and automation in sintering and assembly.

In terms of commercialisation support for REPM manufacturing in the UK, additional support outside universities' R&D is needed. The UK has strong capabilities for magnet manufacturing in R&D, with universities such as the University of Birmingham being at the forefront. However, capabilities in other innovation support areas, such as testing facilities, funding for commercialisation, and skills development, are limited.

International benchmarking shows that China currently dominates the REPM manufacturing supply chain and direct competition with China will be very challenging. Therefore, it is critical to consider how to differentiate in the global market.

Eight opportunities to improve the UK's innovation ecosystem for the REPMs manufacturing space were formulated as part of this project, with key recommendations being:

- REPM users should consider end-of-life disassembly in product design. Incorporating a circularity mindset into designing products can reduce reliance on virgin REEs and imported magnets and improves the economies of recycling at a product's end-of-life. This element of recycling as an integral part of magnet manufacturing has the potential for the UK to take a leading position.
- Provide innovator funding to support testing, scaling of technologies, and developing skilled workers. This can build the UK's capacity in magnet manufacturing to address the high barriers to entry, which includes creating the knowledge and capabilities to manufacture at scale. Models could include grant, loan, equity investment, or blended finance models.
- Create an industry-led working group to bring together end-users, corporates, innovators, and academia to provide a voice for the sector. This can create a sector voice that articulates needs and requirements, quantifies demand, supports flow of information, and acts as a point of contact for international collaboration. The secretariat can be hosted by existing organisations such as the Institute of Materials, Minerals and Mining or UK Magnetics Society.
- Increase understanding of the environmental impact of the current REPM supply chain and how that would change by building local capacity. Supporting corporates can help them make better informed decisions and understand key development areas regarding material sourcing to address sustainability requirements from customers, stakeholders, or regulation. This can also support the first opportunity of incentivising end users considering end of life disassembly in product design, for example by having standards and policies to follow.

2. Background context

Permanent magnets can generate and sustain a magnetic field even when subjected to an opposing magnetic field. Today, these magnets play a crucial role in a wide range of applications, including motors, pumps and compressors, wind turbines, electronics, medical devices, satellites and weapon systems, cordless power tools, automobile speakers, robots and lifts, aerospace, etc.

Currently, all the best-performing magnets for electrical machines contain rare earth elements (REEs). NdFeB magnets are the most powerful magnets at room temperature, with a Maximum Energy Product (BH_{max}) exceeding 438kJ/m^3 in commercial products. In comparison, other non-REPMs are significantly less potent: 80kJ/m^3 for Alnico and only 40kJ/m^3 for ferrite magnets (Cui, J. O., 2022).

Therefore, NdFeB magnets are the most popular choice for a wide range of applications. The growing demand and constrained supply of Neodymium (Nd) and Dysprosium (Dy) make these materials critical for industry, especially given their importance in technologies supporting the net zero transition.

Efforts are underway to mitigate the risks relating to REEs, including securing the supply of REEs, reducing waste, recycling, and developing alternatives. Complementary reports covering the Rare Earth Exploration, Extraction, Beneficiation and Concentration, Rare Earth Processing, Rare Earth Circular Economy, and Rare Earth Permanent Magnet Alternatives are available as part of this report series.

Innovation has the potential to reduce production waste and improve the consistency of magnet performance within magnet manufacturing. Additionally, the magnetic properties of permanent magnets are significantly influenced by their microstructure, which in turn is dependent on the manufacturing process. Improving the manufacturing process is a viable near-term approach to addressing the risks relating to REPMs.

There are three primary methods for magnet manufacturing: sintering, bonding, and hot deforming. Sintering is typically favoured since sintered magnets retain full density and offer higher strength, as the (BH_{max}) of the sintered NdFeB magnet can reach above 398kJ/m^3, while that of bonded magnets is generally below 80kJ/m^3. According to the report published by the US Department of Energy, the demand for the sintered segment in NdFeB magnets is dominating the market with a share of 93.3% in 2020 and a predicted 97.1% share in 2030. In contrast, bonded magnets accounted for 6.7% in 2020 and a predicted 2.9% in 2030.

However, sintering is costly and typically results in significant material loss compared to bonding. Bonded magnets and hot deformed magnets, on the other hand, can be formed in a single process without secondary processing and can be made into various complex shapes – a feature referred to as 'net-shape formability' in manufacturing – something often not feasible with sintered magnets.

Figure 1. Common processing route for sintered NdFeB magnets.

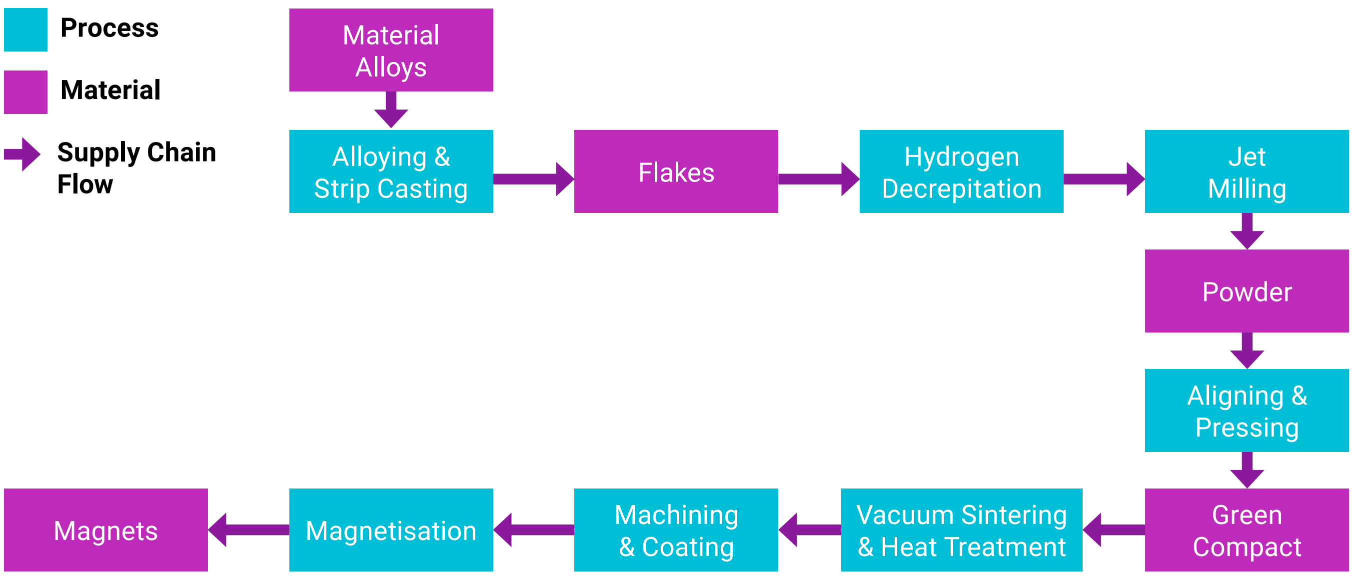


Figure 2. Common processing route for bonded NdFeB magnets (MQ-I Route).

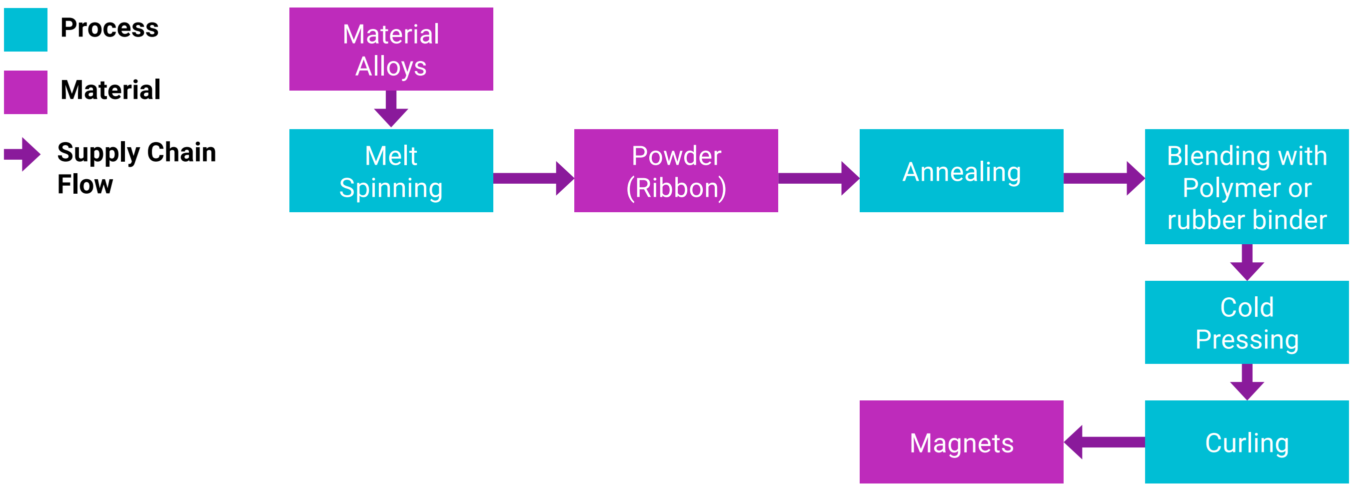
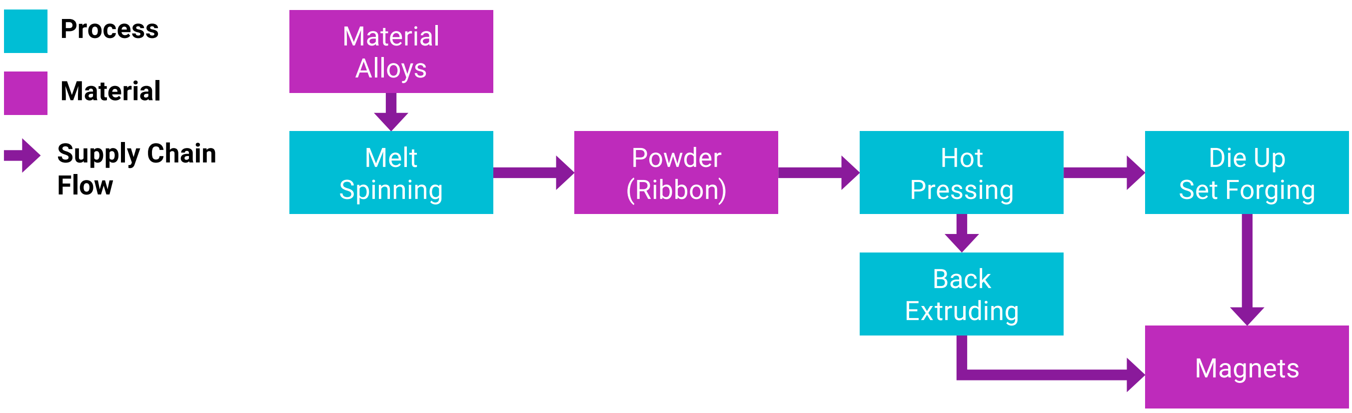


Figure 3. Common processing route for hot-deformed NdFeB magnets (MQ-III Route).



An ideal permanent magnet would have fully aligned grains to give the highest magnetic strength, be fully dense, have high electrical resistivity, have grain sizes below 1 micron to improve coercivity and be manufactured as thin sections with minimal manufacturing losses.

The current magnet manufacturing processes are less than ideal due to waste generation and product variability. In the past 20 years, researchers have explored various manufacturing methods to enhance the magnetic properties and the manufacturing efficiency of permanent magnets. One of the biggest improvements in magnets has been to increase coercivity, which is the magnets' resistance to demagnetisation. This made magnets smaller over time to deliver the same magnetic performance. Traditionally, coercivity has been enhanced in NdFeB magnets by adding HREE, such as dysprosium (Dy) and terbium (Tb). However, Dy and Tb typically have even higher supply chain risk than Nd and Pr as their price volatility is higher and their supply is very geographically concentrated, with China and Myanmar's share of HREE separation almost 100% (U.S. Department of Energy, 2022).

As a result, there are two major ways to improve coercivity with reduced or no HREEs: the first one is using the grain boundary diffusion (GBD) process, and the second one is controlling the magnets' microstructure (Hioki, K., 2021).

Researchers are optimising manufacturing processes to modify the microstructure, developing bespoke alloys, improving the grain boundary phases, and reducing the impurity levels of the materials to increase the coercivity. Much of this coercivity enhancement now has been to reduce

the grain size in the magnets, however this improves coercivity but is difficult to achieve with a reactive powder. Automated systems have the potential to solve this problem. The challenges, current status, and future potential of these methods will be discussed in the next section.

The market demand for REPMs is expanding. It is estimated that the NdFeB market will require around 387,000 tonnes of REPMs by 2030, with average annual growth rates calculated to be 12.5% through 2030. Within the total 387,000 tonnes, 2.9% (11,100 tonnes) will be bonded magnets (U.S. Department of Energy, 2022).

Major market growth drivers include growth in electric vehicles, electric bicycles, drones, wind/tidal energy generators, robotics, and satellites and weapons. However, despite this growing market, the benefits to the UK are currently limited. This is because the supply chain for REPMs is highly concentrated in China, which dominates 94% of magnet manufacturing. Japan holds 5% in the market, and the rest of the world holds less than 1% (Roland Gauß, C. B., 2021).

In fact, Chinese domination can be observed across the entire REE supply chain. Manufacturers outside of China struggle to compete on price with Chinese magnet makers, leading to increasing imports of REPMs as part of assemblies and products for motors and generators.

Securing the REE supply chain in the UK is critical to the economy, and understanding what impact magnet manufacture can bring to the supply chain hence plays a vital role in boosting the market and creating supply chain resilience for a greener economy.

3. Mapping current Magnet Manufacture UK innovation landscape

3.1 Innovation areas and UK innovators

3.1.1 Technology Innovation Areas

The main discoveries of new commercial magnetic materials and advancements in magnets' energy density predominantly took place during the twentieth century. No major new high-performance magnetic material has been introduced since NdFeB in the early 1980s (Cui, J. O., 2022).

Therefore, most current research in magnet manufacturing focuses on developing processes to enhance the properties and manufacturing efficiency of existing magnet materials.

Sintering and bonding are the two primary magnet manufacturing processes. These methods have been utilised for many years and are efficient at producing large quantities of magnets at low unit cost. Each process has its strengths and weaknesses, as shown in Table 1, below.

Table 1 – Comparison of sintering and bonding magnet manufacturing process

Process	Advantages	Disadvantages
Sintering	• High strength. • High coercivity.	• Expensive. • Needs secondary processing. • Large material losses during machining. • Poor dimensional accuracy. • Safety concerns due to the pyrophoric nature of the powder processing. Requires inert handling, which increases cost. • Low electrical resistivity.
Bonding	• Low cost. • No secondary processing is needed. • High electrical resistivity. • Relatively low HREE content. • The starting powders do not require inert handling.	• Lower magnetic performance compared to most sintered magnets • Magnetic powder is isotropic, and the polymer dilutes the magnetic properties.

The current limitations of sintering and bonding highlight the potential and need for advanced manufacturing techniques to increase efficiency, reduce waste, and lower variability in the end products (Cui, J. O., 2022).

Based on the manufacturing process, these innovations can be broadly categorised into metallisation and alloying, magnet manufacturing methods, and automation techniques. There are three innovations focused on magnet manufacturing methods including reducing grain sizes, grain boundary diffusion, and other emerging methods. Beyond that, 15 innovation sub-themes have been identified and will be detailed below.

Some of these emerging technologies are very low TRL and have not been scaled up due to technological challenges, as shown in Table 2, below. Additionally, many of the processing methods, such as spark plasma sintering and shock compaction, are unable to reduce costs and may even increase them. This means that these emerging methods are unlikely to completely replace sintering and bonding in the near future, although they do offer manufacturers a broader range of options.

Table 2 – Innovation areas against TRL

Category	Innovation Sub-Themes	TRL	Coercivity Improvement	Manufacturing Waste Reduction	Magnet processing cost reduction
Metallisation and Alloying	Production of bespoke alloys	4-9	Yes		
	Doping with light rare earths	9		Yes	Yes*
Manufacturing Methods: Reducing Grain Sizes	Innovative jet milling process	4-5	Yes		
	Hot deformation and Extrusion	9	Yes	Yes	Yes*
	Hydrogen Ductilisation Process	2-3	Yes		

Manufacturing Methods: Reducing HREE	Grain Boundary Diffusion	9	Yes	Yes	Yes*
Manufacturing Methods: Other Manufacturing Methods	Laminated magnets to improve electrical resistivity	2-3		Yes	
	Improvements to remanence in bonded magnets	8-9	Yes	Yes	
	Additive Manufacturing	4	(Coercivity has not been improved so far but some exprienments show that some magnetic properties e.g. thermal stability, could be better than traditional bonded magnets)	Yes	Yes*
	Spark plasma sintering	2-3	Yes	Yes	
	Thermomagnetic processing	2-3	Yes		
Automation techniques	Automated Pressing and sintering	9	Yes		
	Automation in magnet assembly to end products	7-8			Yes
	Modelling	1-2	Yes		

* The trade-off between processing costs and material costs depends on current REE prices.

The innovation sub-themes identified are described in the following paragraphs.

Production of bespoke alloys (TRL level 4–9)

The properties of REPMs are largely determined by the microstructure of the final magnets. However, this microstructural control starts at the cast alloy stage. Further R&D is required at this stage to reduce the grain size, produce more uniform alloys, reduce the oxygen content, produce nanostructured alloys and develop light rare earth-containing alloys. The alloys are commonly formed by a strip-casting process for sintered magnets. Nanocrystalline alloys are also produced by melt spinning to produce bonded or extruded magnets.

Doping with light rare earths in sintered and nanocrystalline magnets (TRL 9)

In recent years, much work has been done developing NdFeB magnets containing light rare earths, which are in oversupply. This includes Cerium (Ce) and Lanthanum (La) in both sintered and hot-pressed magnets. Ce and La offer multiple benefits to manufacturing, such as energy reduction and improved throughput (Sims, Z.C. et al., 2022). This has reduced the cost of magnets, but due to their valence state, these elements tend to reduce the magnetic performance of NdFeB magnets.

Innovative jet milling process (TRL 4–5)

In recent years, there has been a large body of work focusing on reducing the grain size of sintered NdFeB magnets, controlling the microstructure and reducing the impurity levels within NdFeB magnets (particularly oxygen) to improve their performances. Innovative approaches to jet milling, for example, adding helium, have been matched up to in-situ sintering of magnets to reduce grain size in the final magnets and to lower the oxygen content, known as press-less sintering (PLP) (Sagawa, M.; Une, Y., 2008). PLP tends to be suitable only for thin magnet sections. It has been suggested that jet milling should be trialled in a wider range of gases to reduce the particle size further.

Hot deformation and Extrusion (TRL 9)

Also known as the hot-deformation process, bulk magnets can be made by hot pressing and then extruding melt-spun ribbons with sub-micron grain size, therefore increasing the coercivity of permanent magnets, as reducing grain size is proven an effective method for enhancing coercivity. As a result, extrusion has the potential to avoid the traditional way of adding HREE. It can also reduce REE content while maintaining high coercivity levels compared to sintered NdFeB magnets. This method also offers a near-net-shape manufacturing solution, meaning that not many assemblies are needed (Hioki, K., 2021).

However, even though extrusion is already TRL 9 and provides many benefits, the manufacturing process is more expensive than sintering and requires a lot of energy for heating. The trade-off between processing costs and material costs depends on current REE prices. Various hot-deformation techniques reported for producing bulk magnets include die-upset and backward extrusion, equal channel angular extrusion (ECAE), torsional extrusion, and friction consolidation and extrusion (FC&E) (Cui, J.O., 2022). Extruded magnets are produced commercially by Daido in Japan and used in the automotive sector.

Hydrogen Ductilisation Process (HyDP) (TRL 2–3)

The aim of the Hydrogen Ductilisation Process (HyDP) is to reduce the risk of processing powders compared to current sintering technology but still form an aligned nanocrystalline magnet. This is achieved by pre-processing solid alloys in hydrogen, making them ductile at room temperature. The alloys can then be pressed at room temperature, producing a nanocrystalline-aligned material when the material is heated to remove the hydrogen. There are some current limitations to this technology, which require further research, such as the porosity in the magnet (Brooks, O. et al, 2018). Additionally, hydrogen is an effective tool in modifying the microstructure of NdFeB magnets and it is also used to produce anisotropic powders for bonded magnets, SPS or new manufacturing methods when processing is carried out at elevated temperatures. Hydrogen is also used to recycle NdFeB magnets (HPMS process). Further work should be carried out to explore the broader use of hydrogen at multiple points in the processing of NdFeB.

Grain Boundary Diffusion (TRL 9)

It has been shown that higher coercivity is only required at the edges of magnets and as such research has focussed on diffusing Dy or Tb into the surface of magnets where the coercivity is required. Grain Boundary Diffusion (GBD) is the process of coating sintered magnets with a thin layer of HREE (Dy or Tb) and then undergoing a special heat treatment. The HREE diffuses along the grain boundaries into the interior of the magnet, wrapping around the NdFeB grains. This method can increase the coercivity of the magnets under hot environments without sacrificing its induction (magnetic strength, denoted as Br). There are multiple methods being proposed to do this, for example, sputtering and screen printing. Traditionally producers mix HREE into the initial grain structure when making the NdFeB powders to increase coercivity, but this method decreases the induction of the magnet as it displaces some Nd. GBD also reduces the total HREE added to the NdFeB magnets compared to traditional methods, meaning that it can potentially decrease manufacturing costs. GBD provides a second option for manufacturers to improve coercivity with reduced or no HREE other than reducing the grain sizes of magnets. Academics have been exploring this technology for over 20 years and multiple methods are being proposed to do this, for example, sputtering and screen printing. There have been some significant advancements recently in coercivity improvements and applications on nanocrystalline and even waste magnets (Liu, Z. et al, 2021). Further R&D in the UK is required in this area to develop new IP (He, J., 2021).

Laminated magnets to improve electrical resistivity in sintered magnets (TRL 2–3)

In recent years, magnets have been cut into thin pieces to reduce eddy current losses, but this can result in large machining losses. The magnets are segmented in the rotor with epoxy, and this breaks up the eddy currents when the motor is spinning quickly. The result is that less heat is generated in the rotor, and therefore, less HREE (Dy and Tb) is required in the magnet to stop them from demagnetising. There has been some work internationally on REPMs on producing laminated magnets where an insulating layer is layered in the green compact powder bed prior to pressing which creates laminated magnets (EE corporation). Further work should be conducted in this area, because if a laminated material could be produced, it would significantly reduce wastage. The University of Birmingham is investigating a possible route to this using the HyDP route, which is mentioned earlier.

Improvements to remanence in bonded magnets (TRL 8–9)

Bonded NdFeB magnets are generally weaker than sintered ones in terms of remanence, which is the magnetisation left behind in a material after an external magnetic field is removed. Researchers are looking to improve the performance of bonded magnets by enhancing the manufacturing process. SG Technologies, the only large-scale magnet manufacturer in the UK, is working on optimising the REE-bonded magnets. The company produces compression moulded magnets with higher remanence and maximum energy product.

Additive Manufacturing (TRL 4)

Additive manufacturing (AM), also known as 3D printing, is a rapidly growing area that enables manufacturers to build objects with precise geometric shapes, usually built layer by layer. This is in contrast to traditional manufacturing, which often requires machining or other techniques to remove surplus material. The ability to create a fully customised magnet opens up possibilities to create tailored magnetic fields which are required for technologies such as medical sensors and e-motors. AM produces little waste compared with sintering, which helps to reduce costs for customised items and lowers supply risks. Based on observations, AM can potentially improve thermal stability and corrosion resistance for the magnets by configuring the structures, which are important traits for REPMs in motors and generators (Cui, J. O., 2022).

However, there are also some significant challenges in using 3D printing of REPMs, so much more work and research is needed in this innovation space, for example, the lack of magnetic feedstock powder specifically designed for 3D printing. Other challenges include the process being slow and expensive, difficulties to scale up for mass production, the small market for high-end customised magnets, and difficulties in producing a uniform microstructure and an anisotropic fully dense magnet (Crozier-Bioud, T. et al, 2023).

Emerging ways to use AM in magnet manufacturing include 3D Printing of Bonded Magnets via Binder-Jet and Extrusion, Directed Energy Deposition (e.g. selective laser melting, laser powder-bed fusion), and Cold Spray. Currently there are more research interests in binder-jet and directed energy deposition for 3D printing REPMs. Recent collaborative research by the University of Oxford, Nottingham, and Loughborough has explored the microstructure and potential of using laser powder-bed fusion.

Spark plasma sintering (SPS) (TRL 2–3)

Spark plasma sintering (SPS), also known as pulsed electric current sintering (PECS) or field-assisted sintering technique (FAST), is a low-voltage, current-activated, and pressure-assisted sintering process (P. Mishra, T. L., 2023). This method can potentially reduce or even eliminate HREE, and is possibly suitable for direct densification of recycling powders made from magnetic scrap (Castle, E. et al). Although near theoretical density of SPS has been achieved (Cui, J. O., 2022), SPS is too expensive and slow to commercialise with the current state of this technology.

Thermomagnetic processing (TRL 2–3)

Thermomagnetic processing is the application of magnetic fields during heat treatment. It has the potential for manipulating microstructures, thus enabling the control of magnetic properties in magnetic materials. This method is typically used in Alnico, but recent experiments showed that NdFeB magnets also respond well to thermomagnetic processing in terms of improving coercivity. Follow-on research is necessary to fully understand the underlying mechanisms behind the observed experimental effects (Cui, J. O., 2022).

Automated Pressing and sintering (TRL 9)

In recent years, there have been large advances in pressing and sintering technologies, including automated aligning presses, new additives to enhance the alignment of powders, automated stacking systems and fully automated multi-stage sintering furnaces. At present, the most advanced equipment is only available in China. The only facility equipped with automated presses for sintered magnets in the UK is located at Tyseley Energy Park in Birmingham. It is being installed by the University of Birmingham alongside its commercial partner HyProMag with funding from Driving the Electric Revolution (DER). Further work is required to develop the pressing and alignment technologies in the UK.

Automation in magnet assembly to end products (TRL 7–8)

Most REPMs are procured in standard bulk specifications, therefore, assembling the magnets onto the end products can be very costly and labour-intensive, as it involves a lot of cutting and fitting of the standard magnets. Many manufacturers are now developing automation techniques to enable a more efficient and cost-effective assembly process.

Modelling (TRL 1–2)

The UK has leading groups investigating the modelling at both an atomistic and micromagnetic level. This includes the Universities of Warwick and Exeter, respectively. This modelling work needs linking through the groups working on microstructural design and manufacturing techniques to develop new magnetic microstructures.

3.1.2 Major UK Activities

Table 3, below, highlights UK-based activities linked to technology sub-themes.

Table 3 – Major UK activities

Sub-themes	UK Activities	TRL (UK)
Production of bespoke alloys	UK corporate Less Common Metals produce strip cast alloys commercially in the UK and the University of Birmingham have 5-10 kg pilot facilities for strip casting and melt spinning. These facilities are used in multiple projects including SCREAM (DER) and EU project REESILIENCE.	8-9
Hot deformation and Extrusion	SG Technologies, the University of Birmingham and ZF Group have a project on making hot-deformed magnets, which is forming nanocrystalline fully dense materials from melt spun ribbons.	4-6
Improvements to remanence in bonded magnets	SG Technologies has been developing commercial high remanence compression bonded NdFeB magnets for motors, which has up to 17% higher remanence and 30% higher maximum energy product.	8-9
Hydrogen Ductilisation Process (HyDP)	Multiple publications and patents from the University of Birmingham on developing this new method for manufacturing REE magnets from a solid alloy.	2-3

Additive Manufacturing (AM)	Research paper on the microstructure and magnetic performance of NdFeB magnets manufactured by laser powder-bed fusion (PBF-LB), a class of AM, by a team from the Centre for Additive Manufacturing in University of Nottingham, Atom Probe Group at University of Oxford, and Loughborough Materials. UK corporate Less Common Metals participated in 3DREMAG project that aims to up-scale and introduce to the market a 3D printable NdFeB powder. University of Birmingham have previously worked with partners in the SUSMAGPRO project on 3D printing and metal injection moulding of magnets providing feedstock powders from recycled sources. Warwick Manufacturing Group is currently working with corporate Phoenix Scientific Industries on developing additively manufactured NdFeB powder for eMachine rotor.	4-5
Spark plasma sintering (SPS)	Conference paper on SPS of permanent magnets for next-generation electric vehicle motors, also explored its potential in REE recycling. Research conducted by scholars in Queen Mary, University of London, and University of Birmingham.	2-3
Automated Pressing and sintering	The Magnetic Materials Group at the University of Birmingham have worked on pressing and sintering technologies for NdFeB for 40 years. The University now has pilot facilities for pressing and sintering of NdFeB magnets including fully automated commercial presses at Tyseley Energy Park funded through DER. The facility is capable of producing 100kgs of primary or secondary NdFeB powders using hydrogen as a processing gas. The group has facilities for jet milling, magnetic alignment, isostatic pressing and sintering at 20kg level to produce sintered blocks. As part of the DER research programme the University is building a 100-tonne facility for production of sintered magnets on an automated production line. This includes facilities for automated pressing on commercial presses and inert transfer to sintering system at 50kg level. This is being scaled up by commercial partner Hypromag, with plans to build a large sintering facilities up to 400kg batch sizes in the UK, expected to finish by December 2024. The University has been involved in the EU and UK projects totalling over £70 million in the last 20 years, acting as a UK training centre for manufacturing of magnets.	7
Automation in magnet assembly to end products	AMRC has worked with company Magnomatics on developing automated process to assemble REE magnets into wind turbine generators using robotic arms. It was developed in AMRC's automation lab Factory 2050.	7-8
Modelling	The University of Warwick and Exeter University have modelling at both an atomistic and micromagnetic level.	1-2

3.2 Stakeholder map of the UK

Figure 4, below, shows the stakeholder landscape of REPM manufacture in the UK. It is colour-coded based on the technology themes in which each organisation is involved, such as participating in research projects or hosting events **– Details of their activities can be found in the Supply Chain Database.**

Figure 4. UK Stakeholder Map

Universities

- * University of Birmingham
- University of Sheffield
- University of Nottingham
- University of Loughborough
- University of Warwick
- University of Oxford

RTOs

- AMRC
- MTC
- WMG
- NPL

Government stakeholders and trade organisations

- UK Magnetics Society
- Minor Metal Trade Association
- Critical Minerals Intelligence Centre
- Automotive Transformation Fund (APC)
- CMA

Corporates

- SG Technologies
- *Less Common Metals
- Diffusion Alloys
- Phoenix Scientific Industries
- *Mkango UK
- *Bunting
- Hirst Magnetics

Early-stage Innovators

- *Hypromag

Funding and financing

(Only included investors who have funded REE Magnet Manufacturing companies)

- *CoTec
- EPSRC
- Innovate UK
- National Wealth Fund
- APC

Metallisation and alloying

Magnet Manufacturing methods

Automation techniques

* Note: These organisations have participated in projects related to recycling

There are limited stakeholders that have direct manufacturing capability in the UK, beyond universities, most activities focused on upstream processes, such as alloying and research on microstructures, and downstream processes, such as magnet assembly.

There are few innovators and investors active in the field of magnet manufacturing, reflecting a low level of innovation activity in the industry. Notably, only one UK innovator, HyProMag, has been identified. The company is a spinout from the University of Birmingham and has patented Hydrogen Processing of Magnet Scrap (HPMS) technology, which can extract and demagnetise NdFeB alloy powders from magnets embedded in scrap and redundant equipment. Since it was spun-out in 2018, HyProMag was bought in 2023 by Maginito, a 90% owned subsidiary of UK and Canada listed company Mkango Resources. Recently the company has started building a manufacturing facility that can take primary or secondary materials for REPMs.

Most of the corporates are large multi-national based companies. The map shows corporates which have a UK office. Magnet manufacturing is a high CAPEX industry, and the technologies are relatively mature. Less Common Metals, a company based in Ellesmere Port, is the only company that can produce REE metals and alloys in Europe for the magnet market. Additionally, the UK has several large and medium-sized companies involved in magnet assembly and distribution. However, there is still a gap in magnet manufacturing. SG Technologies, one of the largest producers of polymer-bonded magnets in Europe, is the only magnet manufacturer in the UK REE supply chain. The Rainham-based company produces bonded magnets for components in the automotive industry and has actively participated in R&D projects with stakeholders such as ZF and the University of Birmingham.

To fill in the gap for magnet manufacturing in the UK, the Magnetic Materials group at the University of Birmingham has pilot scale facilities for manufacturing sintered magnets in the School of Metallurgy and Materials. The facility can produce 100kgs of primary or secondary NdFeB powders using hydrogen as a processing gas. The group has facilities for jet milling, magnetic alignment, isostatic pressing and sintering at 20kg level to produce sintered blocks. As part of the DER research programme, the University is building a 100-tonne facility for the production of sintered magnets on an automated production line. This includes facilities for automated pressing on commercial presses and inert transfer to the sintering system at 50kg level. This is being scaled with the University's commercial partner HyProMag, who are installing sintering capability at 400kg batch sizes.

3.3 UK capabilities to commercialise innovation

The UK's capabilities to commercialise innovation for REPM manufacturing are segmented into R&D facilities, testing facilities, funding opportunities, skills development, and manufacturing capabilities. In the UK, most support tends to aim at higher TRLs and there is limited support for developing lower TRL magnet manufacturing technologies. It is also clear that the UK has very limited large scale REPM manufacturing capability at the moment. Although there is some support for the upstream and downstream processes around magnet manufacturing, such as processing and assembling.

Universities are at the forefront of R&D, although mostly emphasising extraction, processing, and recycling of REPMs at higher TRL levels. The University of Birmingham has laboratories for producing bespoke alloys to make both sintered and bonded magnets. They are building a larger sintering facility with their commercial partners, HyProMag and Mkango Resources. The University of Sheffield and the University of Nottingham have also been working on some magnet manufacturing technologies, for example magnets assembly and AM of medical sensors. Despite these, direct support for developing magnet manufacturing methods remains limited, with the only exception being AM that spans across different universities, as many universities have their own 3D printers and the capability to analyse the product's structure.

Testing facilities tailored specifically for REPMs are scarce due to the lack of dedicated magnet manufacturing plants within the UK. Some universities such as the University of Birmingham and the University of Nottingham have magnet testing laboratories. Beyond that, only some RTOs (NPL, WMG) and companies (ZF, Bunting, Less Common Metals) have been identified, with their capabilities mostly in upstream metal testing and downstream assembly. The main UK equipment supplier to measure and characterise magnets is Hirst Magnetic Instruments, who have been providing solutions for 60 years in magnetics and magnetic measurement. Most of their customers are based in China.

There are some relevant funding opportunities in the UK for the magnet supply chain, including grants, accelerators, and early-stage venture capital funds. Although they are mostly aiming at higher TRLs and not directly at magnet manufacturing. UK-based publicly funded investments include the Circular Critical Materials Supply Chains Programme (CLIMATES), delivered by Innovate UK and the Automotive Transformation Fund (ATF), which is managed by the Advanced Propulsion Centre (APC). While these are not always directly targeted at magnet manufacturing, for example, the ATF is focused on funding automotive innovation. Still, they do provide essential financial support for related technological developments. There are also some EU grants which are more relevant to REPM manufacturing, such as REPROMAG, REESILIENCE, SUSMAGPRO, Neohire, and there are many cases where UK stakeholders have joined consortia with other European companies.

In terms of skills development, the presence of relevant accelerators, conferences, events, and research projects contributes to the innovation ecosystem. However, their focus is often not specifically on REPM manufacturing but on the wider REE supply chain or the broader critical minerals industry. Therefore, there are significant skills gaps and lack of training centres for magnet manufacturing in the UK outside universities.

The UK has limited large-scale magnet manufacturing capabilities, with notable exceptions being SG Technologies, the largest bonded magnet manufacturer in Europe, and the University of Birmingham's sintering facility at Tyseley Energy Park, developed in collaboration with HyProMag and Mkango. SG Technologies is actively involved in enhancing bonded and hot-deformed magnets in partnership with the University of Birmingham. HyProMag is planning to scale up the sintering facility at Tyseley Energy Park to handle 400 kg batch sizes, with completion expected by the end of 2024.

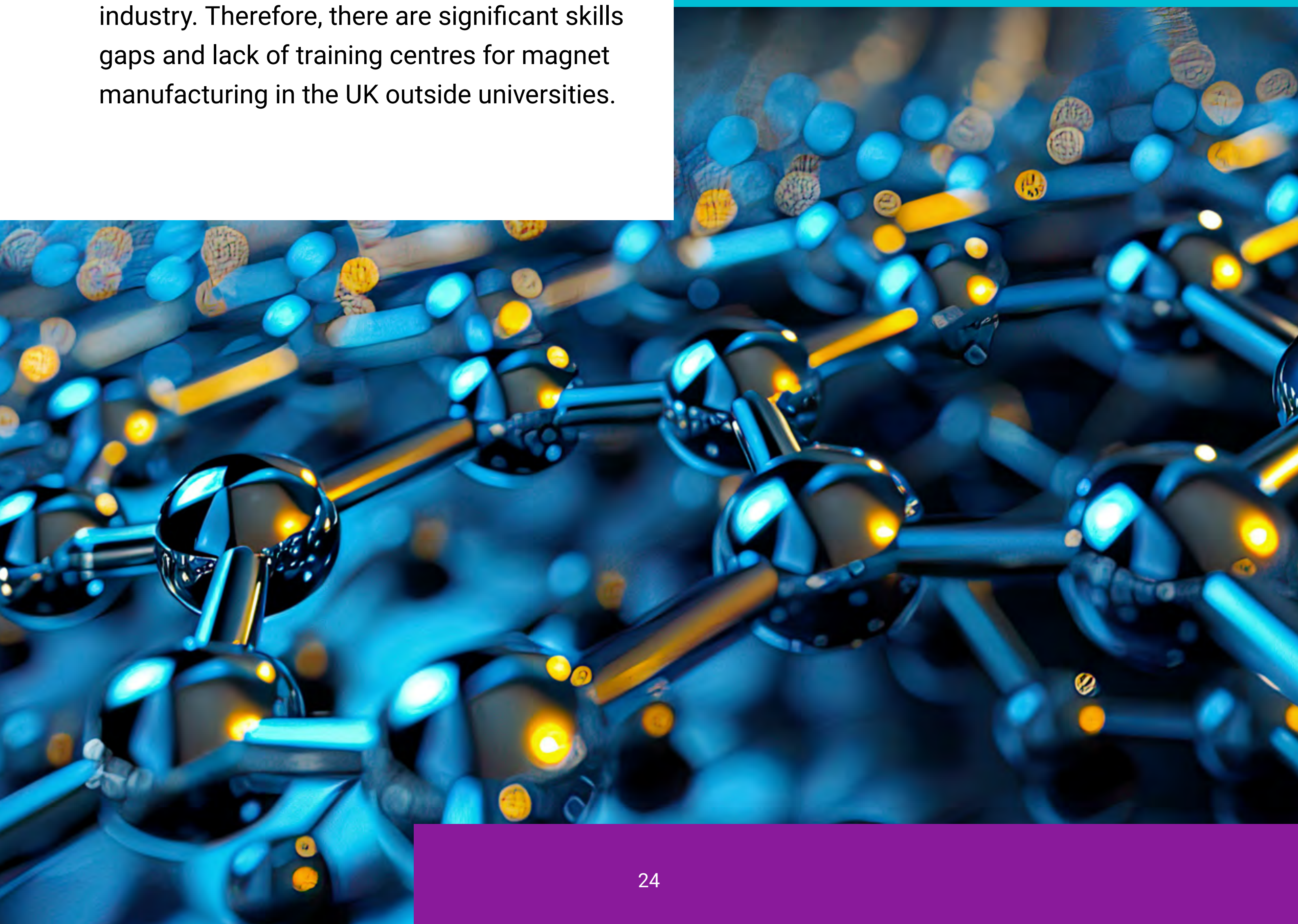


Table 4, below, is a list of UK stakeholders for each capability – Please refer to the Supply Chain Database for more information about their activities.

Table 4 – List of UK stakeholders to each capability

R&D Facilities	Testing Facilities
• **University of Birmingham:** The Magnetic Materials Group; Facilities for automated pressing and sintering from strip casting to manufacturing. • **University of Sheffield, University of Oxford, University of Nottingham, Loughborough University:** 3D printers. Research of AM in NdFeB magnets. • **University of Warwick:** The Superconductivity and Magnetism Group • **AMRC:** Automation Lab • **MTC:** 3D printers; has some magnets sintering research. • **Hypromag/Mkango:** Facility for recycling and manufacturing. Now building a 400kg sintering facility in the Birmingham.	• **University of Birmingham:** The Magnetic Materials Group. • **University of Nottingham:** PEMC centre. • **University of Sheffield:** Royce at University of Sheffield • **MTC:** metal testing and analysis • **AMRC:** Factory 2050 is an automation testing lab, used in the ROBOMAG project to develop automated magnet assembly in wind turbine generators. • **Less Common Metals Laboratory:** test the elemental composition, micro-structural and physical properties of inorganic materials. • **Bunting Laboratory:** Magnetic Separation and Metal Detection. • **Hirst Magnetic Instruments:** providing magnetic measurement • **WMG:** manufacturing centres for testing • **NPL:** Has magnets testing service • **ZF Group:** automotive testing

Funding Opportunities

- **Grants:**

  - Innovate UK (e.g. CLIMATES, DER)
  - APC (Automotive Transformation Fund)
  - Environmental Technologies Fund

- **EU Grants**

  - EIT Raw Materials
  - EU Horizon

- **VC:**

  - ETF Partners
  - CoTec

- **Accelerator:**

  - APC Technology Developer Accelerator Programme

Skill Developments

- **Universities**
- **UK Magnetics Society**
- **APC Technology Developer Accelerator Programme**
- **Minor Metal Trade Association:** REE conferences and events
- **Met4Tech:** Value stream mapping of REE magnets
- **AMRC:** aerospace materials and other high-value manufacturing sectors.
- **The British Geological Survey:** The Critical Minerals Intelligence Centre (CMIC) has database of chemical and metal production in the UK.
- Research group/workshops for rare earth permanent magnets and their applications

Manufacturing Capabilities

- **SG Technologies:** Manufacturing plant for bonded and hot-deformed magnets
- **Tyseley Energy Park:** has pilot facilities for pressing and sintering. Not they are scaling up the automated production line for sintered magnets

4. Assessing UK innovation landscape challenges and needs

4.1 Supply chain and corporate innovation needs assessment

The mapping of innovation needs for the UK REE supply chain in order to boost competitiveness and resilience involved several key steps. Firstly, interviews with end users provided direct insights into the challenges and requirements faced by those involved in the REE supply chain. These interviews helped to highlight specific areas where innovation could significantly impact competitiveness and resilience. Secondly, an analysis of current supply chain gaps was conducted to understand the main innovation needs of end users related to REPM manufacturing. Lastly, these findings were validated through a workshop with UK experts in the REE supply chain and cross-checked with our desk research insights, ensuring alignment with anticipated technological advancements and market demands.

The list of findings is summarised in Table 5, below.

Table 5 – List of innovation needs required by corporates to drive competitiveness and supply chain resilience.

Main innovation needs	Description	Current state
Make assembly for REPMs into end products easier	Develop more efficient ways to assemble standard REPMs onto end products e.g. e-drives and offshore wind generators, such as using robotic automation techniques. Advancing manufacturing methods of REPMs for easier assembly.	Standard design REPMs are directly sourced from China in bulk. Current assembly in electric motors and wind turbine generators are labour-intensive. AMRC has developed automated assembly for REPMs to wind turbine generators using robots.
Develop rapid and reconfigurable manufacturing supply in the UK	Possible ways include building a factory in a box (FIAB), a supply that is rapidly deployable, remotely managed, and flexible. End users also have more customised options for supply.	Standard REPMs are procured without consideration for varying product requirements.
REPMs designed for manufacturing, interchangeability, and disassembly	This can reduce costs in manufacturing and assembly. Ease of disassembly is critical for building a REE recycling supply chain. Examples are standard REPMs in EV motors.	REPMs are not standardised for disassembly and recycling. Disassembly is a challenge in building a circular supply chain.
Reduction of HREE in magnets	To design magnets without HREE due to concerns over the environmental impact of production. Find ways to reduce HREE in the sintering process while increasing coercivity. Potential methods include Grain Boundary Diffusion.	A traditional method to increase coercivity involves adding more HREE (Dy, Tb), which decreases induction (Br).
Production of near net shape thin magnets	Production of cost-effective thin magnets to reduce manufacturing wastes and eddy current losses.	Sintered magnets have to be machined and ground to size with significant losses.

More cost-effective methods for AM of magnets	Explore different AM methods for REPM manufacturing, such as Binder Jet Fusion. Develop new REE powder for 3D printing to support the additive manufacturing industry in the UK.	3D printing REPMs are very expensive. There are not many options for 3D printing REE powder for testing.
Develop REPMs for aerospace industry	The aerospace industry will need higher value and quality magnets, even though the market is smaller than the automotive industry.	The aerospace industry is currently experiencing exponential growth in electrification.

4.2 Assessment of innovator requirements on UK capabilities to commercialise technologies

Commercialising innovation requires a wide range of capabilities from various supporting actors. To map the requirements for commercialising innovation in REPM manufacturing, we interviewed relevant start-ups with different TRL levels, RTOs, and academics to understand their support from the ecosystem, its importance in their development, and what they believe has been missing.

Table 6, below, lists out the capabilities required for innovation, the rationale behind it, and the UK's current state.

Table 6 – List of capabilities required to commercialise innovation for Magnet Manufacture.

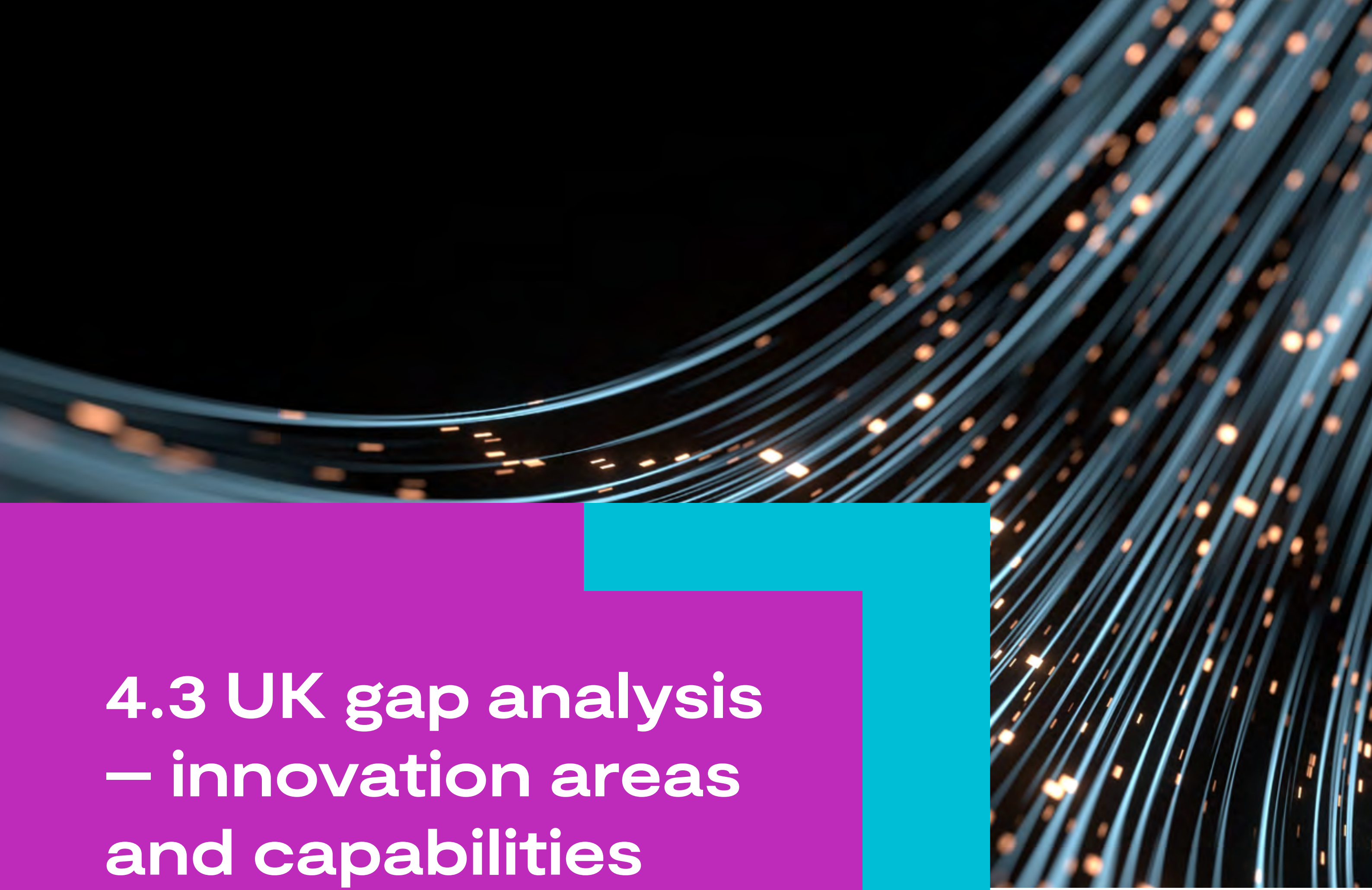
Capabilities required to innovate	Description	Current state
Workforce development	To ensure a skilled workforce that can support growth and technological advancements in magnet manufacturing. An holistic education plan from undergrad to postdoc is required to develop skilled workforce. To increase tech transfer between industry and research institutions.	Significant talent gap in the UK market for magnet manufacturing due to lack of investment and lower cost supplies from China. Limited training courses available on REPMs. Universities acting as training centres but needs to be expanded to apprenticeship level.
Stable early-stage financial funding	Manufacturing requires high capital investment as well as long-term and guaranteed market stimulus.	Almost no VC has focused on magnet manufacturing. UK research funding is limited and tends to focus on higher TRL work.
Policies and regulations	Customers will not switch suppliers unless they need to, such as recycling requirements, subsidies, taxation, etc.	No incentives for end users to source magnets from outside China.
Innovation ecosystem	To support innovators to gain access to corporates, R&D facilities, testing facilities, grant funding, IP, etc. To encourage key partners to share facilities (e.g. for prototype magnets) and create long-term partnerships.	Almost no UK innovators in this sector and few knowledge transfers between stakeholders. Most IP is held in Japan and China, so the UK needs to understand the IP landscape in the supply chain and find its own stand. It is difficult and expensive for researchers to access testing facilities in industry.
International collaborations	To give UK stakeholders access to international collaborations on research projects and supply chain partnerships.	Most REE-related global activities are based in the US and Asia. The UK is not a current leader in these collaborations.

Addressing the talent and financial gaps in the sector stand out as fundamental needs to support innovation. There is a notable shortage of engineers to drive the necessary innovation forward. Access to stable early-stage financial funding is critical, particularly given the high capital investments required for manufacturing. The lack of focused venture capital investment and grant funding opportunities in magnet manufacturing within the UK makes it a risky field in which to innovate.

There are large technology research centres on permanent magnets in the countries which have significant magnet manufacturing including NIMS (Japan), Baotou research institute of rare earths (China) and the Fraunhofer institute (Germany). These are all very large-scale investments for sustaining their magnet industries. At present the UK funds available in this space are often short term (IUK CLIMATES programme), only focussed at higher TRL level (APC and ATF funds) or there are no targeted funds in the area (EPSRC).

Policy and regulation support is also crucial since cost efficiency is the main driver for REPM end user's decision-making processes. The current market landscape offers few incentives for these customers to switch their suppliers away from Chinese manufacturers.

Lastly, the REPM manufacturing supply chain is highly specialised and modular, but also concentrated in China; this means that in the UK, collaborations between companies are required to foster enough resources to innovate and to build a resilient supply chain. A supportive innovation ecosystem allows ventures to access resources which may be difficult for them to build from scratch, such as R&D facilities and testing facilities, while also attracting more financial interest. Additionally, with most magnet manufacturers outside of China located in the US, Japan, and a few in the EU, bi- or multi-lateral funding calls for international collaboration are essential for pooling resources and expertise.



4.3 UK gap analysis — innovation areas and capabilities

4.3.1 Gap analysis for UK innovation

Interviews were conducted to identify innovation opportunities and capabilities needed for corporates and the wider ecosystem.

The gap analysis in Table 7, below, overlays findings from the innovator mapping with the sector innovation needs assessment to pinpoint innovation opportunities.

Table 7 shows a matrix with rows representing the innovation areas discussed in the earlier technology innovation landscape, and the columns representing innovation needs. The three matrices represent three categories: Metallisation and Alloying, Magnet Manufacturing Methods, and Automation techniques. These innovation tech themes were first assessed to determine if they can support the innovation needs, if yes then the cell is coloured with RAG status (Red, Amber, Green) to visualise the UK's strength in these innovation themes to highlight potential innovation opportunities, if the technology themes do not address the innovation needs then the cell is annotated with N/A. The details of these assessments are discussed in section 4.3.2.

Table 7 – Gap Analysis for UK Innovation

N/A Innovation theme cannot address the innovation need

Weak UK has no companies/innovators activities or research activities relevant for this technology area

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

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

* A star in a red cell indicates that there are no companies identified in the UK that can address the innovation need currently.

Metallisation and Alloying

Innovation needs	Production of bespoke alloys	Doping with light rare earths
Make assembly for REE magnets into end products easier		
REE magnets designed for manufacturing, interchangeability, and disassembly		
Develop rapid and reconfigurable supply in the UK		
Reduction of HREE in magnets		
Production of near net shape thin magnets		
Most cost-effective methods for AM of magnets		
Develop REE magnets for aerospace industry		

Manufacturing Methods - Reducing Grain sizes

Innovation needs	Innovative jet milling process	Hot deformation and extrusion	HyDP
Make assembly for REE magnets into end products easier			
REE magnets designed for manufacturing, interchangeability, and disassembly			
Develop rapid and reconfigurable supply in the UK			
Reduction of HREE in magnets			
Production of near net shape thin magnets			
Most cost-effective methods for AM of magnets			
Develop REE magnets for aerospace industry			

Manufacturing Methods - Reducing HREE

Innovation needs	Grain boundary diffusion
Make assembly for REE magnets into end products easier	
REE magnets designed for manufacturing, interchangeability, and disassembly	
Develop rapid and reconfigurable supply in the UK	
Reduction of HREE in magnets	
Production of near net shape thin magnets	
Most cost-effective methods for AM of magnets	
Develop REE magnets for aerospace industry	

Manufacturing Methods - Other Manufacturing Methods

Innovation needs	Laminated magnets for electrical resistivity	Improving bonded magnets	Additive manufacturing	Spark plasma sintering	Thermomagnetic processing
Make assembly for REE magnets into end products easier					
REE magnets designed for manufacturing, interchangeability, and disassembly					
Develop rapid and reconfigurable supply in the UK					
Reduction of HREE in magnets					
Production of near net shape thin magnets					
Most cost-effective methods for AM of magnets					
Develop REE magnets for aerospace industry					

Automation Techniques

Innovation needs	Automated pressing and sintering	Automation in magnet assembly to end products	Modelling
Make assembly for REE magnets into end products easier			
REE magnets designed for manufacturing, interchangeability, and disassembly			
Develop rapid and reconfigurable supply in the UK			
Reduction of HREE in magnets			
Production of near net shape thin magnets			
Most cost-effective methods for AM of magnets			
Develop REE magnets for aerospace industry			

For metallisation and alloying, the UK has reasonable strength in the production of bespoke alloys. This sub-theme addresses almost all innovation needs except for assembly and has UK company Less Common Metals already actively working with UK universities on it.

For magnet manufacturing methods, the UK has some strength in specific sub-themes. Hot deformation and improving remanence in bonded magnets can address all innovation needs and the UK has both research and industrial activities, except for developing cost-effective AM. Grain boundary diffusion cannot address innovation needs in assembly, production of near net-shape magnets and developing cost effective methods for AM of magnets, but it has relatively more activities in both research and industry. And AM can address all innovation needs. SG Technologies is the largest bonded magnets manufacturer in Europe and has the capability to support these innovations.

It is worth noting that automation techniques address many of the sector's innovation needs. There are some opportunities within the automated pressing and sintering and automation in assembly. The UK has strong R&D capabilities and facilities that can be leveraged to accelerate innovation in this space.

4.3.2 Gap analysis rationale

Table 8 below details the assessment of how each technology sub-themes address the innovation needs, as well as relevant UK stakeholders.

Table 8 – Innovation Needs and Technology Sub-themes

N/A Innovation theme cannot address the innovation need

Weak UK has no companies/innovators activities or research activities relevant for this technology area

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

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

* A star in a red cell indicates that there are no companies identified in the UK that can address the innovation need currently.

Metallisation and Alloying

Innovation needs	Production of bespoke alloys	Doping with light rare earths
Make assembly for REE magnets into end products easier		
REE magnets designed for manufacturing, interchangeability, and disassembly	- Bespoke alloys allows more optimised microstructures, enhancing the performances and ease of manufacturing - LCM is active in this sector	- Ce and La offer multiple benefits to manufacturing, such as energy reduction and improved throughput - No activities identified
Develop rapid and reconfigurable supply in the UK	- Producing bespoke alloys in the UK provides more options and flexibility for manufacturing - LCM is active in this sector	- Ce and La are currently in oversupply, therefore does not face similar constraints as Nd and Dy - No activities identified
Reduction of HREE in magnets	- Reducing grain sizes in alloy's microstructure can increase coercivity, which potentially reduces need for HREE - LCM is active in this sector	- Theoretically has the potential to HREE content by substituting the magnets with the light REE - No activities identified
Production of near net shape thin magnets		
Most cost-effective methods for AM of magnets	- There is a potential to develop cheaper alloys for 3D printing powders. Developing powder specifically for 3D printing can also support R&D in AM of magnets - LCM participated in 3DREMAG to develop 3D printable powder	- Light REE are generally more abundant and cheaper than Ny and other HREE - No activities identified
Develop REE magnets for aerospace industry	- Aerospace has higher performance requirements so producing premium bespoke alloys can potentially support the industry needs - No activities identified	- Doping with lower REE can lower the cost for manufacturing, although currently they tend to reduce the magnetic performance - No activities identified

Manufacturing Methods - Reducing Grain sizes

Innovation needs	Innovative jet milling process	Hot deformation and extrusion	HyDP
Make assembly for REE magnets into end products easier		- It has near-net-shape formability, therefore easier to assemble onto end products - SG Tech is working with ZF and University of Birmingham on this topic	
REE magnets designed for manufacturing, interchangeability, and disassembly		- It has near-net-shape formability, therefore does not need machining compared to sintered magnets - SG Tech is working with ZF and University of Birmingham on this topic	- HyDP reduces the risk of processing powders - University of Birmingham is researching this topic
Develop rapid and reconfigurable supply in the UK	- It provides better control to the microstructures and impurity levels, hence better control and options for supply in the UK - Has pilot scale facilities in the University of Birmingham	- Provides a cheaper and different option compared to sintered magnets - SG Tech has manufacturing plant in the UK	- Enabling safer, easier and more efficient manufacturing - University of Birmingham is researching this topic
Reduction of HREE in magnets	- Can reduce grain sizes in magnets to increase coercivity, which potentially reduces need for HREE - Has pilot scale facilities in the University of Birmingham	- Can reduce grain sizes in magnets to increase coercivity, which potentially reduces need for HREE - SG Tech is working with ZF and University of Birmingham on this topic	- Enabling laminated magnets to improve electrical resistivity in magnets, less HREE is required to stop them from demagnetising - University of Birmingham is researching this topic
Production of near net shape thin magnets		- It has near-net-shape formability - SG Tech is working with ZF and University of Birmingham on this topic	

Most cost-effective methods for AM of magnets			
Develop REE magnets for aerospace industry	- This improve magnetic performances, which is a requirement in aerospace - No activities identified	- There are opportunities to explore different types of magnets in aerospace - No activities identified	- There is potential to explore how to make high performance magnets more efficiently and safer during manufacturing - No activities identified*

Manufacturing Methods - Reducing HREE

Innovation needs	Grain boundary diffusion
Make assembly for REE magnets into end products easier	
REE magnets designed for manufacturing, interchangeability, and disassembly	- Able to reduce costs by using HREE and enhance magnetic performances after sintering, and even after machining, although there are currently no limitations such as time and uniformity - University of Birmingham is researching this field. Bunting makes and sell magnets using GBD
Develop rapid and reconfigurable supply in the UK	- Enabling production of NdFeB magnets with enhanced heat resistance, offering an alternative to SmCo magnets, which are becoming more expensive due to rising Co costs - Bunting makes and sell magnets using GBD
Reduction of HREE in magnets	- By concentrating HREE only at the grain boundaries, the approach maintains Br and BHmax unchanged while reducing HREE use in production - University of Birmingham is researching this field. Bunting makes and sell magnets using GBD
Production of near net shape thin magnets	
Most cost-effective methods for AM of magnets	
Develop REE magnets for aerospace industry	- This method produces magnets with smaller, thinner, and have higher heat resistance. These are all important traits for aerospace - No activities identified

Manufacturing Methods - Other Manufacturing Methods

Innovation needs	Laminated magnets for electrical resistivity	Improving bonded magnets
Make assembly for REE magnets into end products easier		- Bonded magnets can be easily shaped into complex and precise forms, therefore easier to assemble onto end products - SG Tech is one of the largest bonded magnet manufacturer in Europe
REE magnets designed for manufacturing, interchangeability, and disassembly	- Improving design for laminated magnets can boost production efficiency and manufacturing accuracy, even reducing machining losses - University of Birmingham is researching this topic	- Can be produced through simpler and more flexible processes than sintered magnets. No secondary processing is needed - SG Tech is one of the largest bonded magnets manufacturer in Europe
Develop rapid and reconfigurable supply in the UK	- This allows for modularity in production, enabling manufacturers to quickly adjust and scale operations. There is also potential to significantly reduce wastage by innovating in this area - University of Birmingham is researching this topic	- Bonded magnets provides a cheaper, higher electrical resistivity option than sintered magnets. 5G Tec is already active in this area so there is existing supply in the UK - SG Tech is already manufacturing in the UK
Reduction of HREE in magnets	- This allows less heat generated in the rotor, therefore less HREE is required in the magnet to stop them from demagnetising - University of Birmingham is researching this topic	- The binder material in bonded magnets reduces heat generated in the rotor therefore less HREE is required to prevent demagnetising - SG Tech is already manufacturing in the UK
Production of near net shape thin magnets		- It has near net shape formability, so does not require secondary processing - SG Tech is already manufacturing in the UK
Most cost-effective methods for AM of magnets		
Develop REE magnets for aerospace industry	- This method significantly reduces eddy current losses for magnets in high-efficiency motors, therefore an important trait for the aerospace industry - No activities identified*	- Bonded magnets has high electrical resistivity. SG Tec is working on improving remanence so there are some potential for aerospace - No activities identified

Manufacturing Methods - Other Manufacturing Methods

Innovation needs	Additive manufacturing	Spark plasma sintering	Thermomagnetic processing
Make assembly for REE magnets into end products easier	- Magnets can be easily shaped into complex and precise forms, therefore easier for assembly - LCM and Scientific Industries had been developing 3D printing powder for REE magnets for more effective manufacturing outcomes. While some RTOs and universities has 3D printers and has worked on related research to create more precise and complex shapes, e.g. WMG, University of Nottingham		
REE magnets designed for manufacturing, interchangeability, and disassembly	- Can easily make magnets into different shapes based on the requirements for ease of manufacturing, interchangeability, and disassembly - LCM and Phoenix Scientific Industries' research on 3D printing powder for REE magnets could make it easier to additively manufacture REE magnets		
Develop rapid and reconfigurable supply in the UK	- AM has a lot of flexibility in terms of product specifications (e.g. size, shapes, magnetic fields) and volume and fills in the gap for premium and customised magnets. - LCM and Phoenix Scientific Industries had been developing 3D printing powder for REE magnets to enable local capacity. While some RTOs and universities has 3D printers and has worked on related research to create REE magnets with better quality e.g. WMG, University of Nottingham	- This method is possible for direct densification of recycling powders made from magnetic scraps, therefore can work with the circular UK recycling industry - There are studies on this method at the University of Birmingham and Queen Mary University	

Reduction of HREE in magnets	- There are already research showing that using laser-based powder bed fusion can manufacture HREE free magnets, - A research from the University of Nottingham studied the overall microstructure of 3D printed NdFeB magnets. Although most research of HREE free 3D printed magnets are conducted in Europe	- This method can potentially reduce or even eliminate HREE - There are studies on this method at the University of Birmingham and Queen Mary University	- Thermomagnetic processing has the potential to control the microstructures of magnets, therefore has the potential to lower the HREE content - No activities identified*
Production of near net shape thin magnets	- AM enables manufacturers to build objects with precise geometic shapes - LCM and Phoenix Scientific Industries had been developing 3D printing powder for REE magnets to enable local capacity. While some RTOs and universities has 3D printers and has worked on related research to create REE magnets with better quality e.g. WMG, University of Nottingham		
More cost-effective methods for AM of magnets	- Developing specialised powders and exploring different AM methods for REE magnet manufacturing, such as Binder Jet Fusion could lower the cost for AM - LCM and Phoenix Scientific Industries had been developing 3D printing powder to optimise AM for REE magnets		
Develop REE magnets for aerospace industry	- AM can produce magnets with customised shapes and potentially improve magnetic performances such as thermal stability and corrosion resistance by configuring the structures, these can be useful in the aerospace industry. - No activities identified		- This tech has the potential to enable the control of magnetic properties in magnetic materials, therefore can be explored for using in the aerospace industry - No activities identified*

Automation techniques

Innovation needs	Automated pressing and sintering	Automation in magnet assembly to end products	Modelling
Make assembly for REE magnets into end products easier	- Automating the pressing and sintering process can increase and enable more complex design for assembly - The only facility equipped with automated presses for sintered magnets in the UK is at Tyseley Energy Park, installed by the University of Birmingham and Hypromag	- Automating the assembly process such as using robotic arms enables quicker and more precise assembly than the original labour-intensive process - AMRC has developed automated process to assemble REE magnets into wind turbine generators using robotic arms for Magnomatics	
REE magnets designed for manufacturing, interchangeability, and disassembly	- Tech such as automated aligning presses can reduce the complexity and labour for manufacturing - There are facility at Tyseley Energy Park, which also works on disassembling magnets	- Automation ensures consistent quality and precision, and can be programmed to produce magnets to exact specifications for interchangeability - AMRC has developed automated process to assemble REE magnets into wind turbine generators using robotic arms for Magnomatics	- Modelling materials at micromagnetic level can potentially explore materials that are easier to manufacture - The University of Warwick and Exeter University have modelling at both an atomistic and micromagnetic level, although still very low TRL
Develop rapid and reconfigurable supply in the UK	- Automation allows more efficiency and flexibility in manufacturing - University of Birmingham is developing this at the facility at Tyseley Energy Park, the facilities are scaling up in 2024	- This speeds up production, and is easier for scaling up - A lot of magnets assembly activity is already taking place in the UK e.g. Bunting	- Modelling can accelerate R&D in materials and potentially enables a faster and more flexible supply chain - The University of Warwick and Exeter University have modelling at both an atomistic and micromagnetic level, although still very low TRL

Reduction of HREE in magnets	- This can enhance the alignment of powders therefore potentially reduces HREE content - University of Birmingham has facility for jet milling and magnetic alignment		- Modelling can support R&D in controlling microstructures hence reducing HREE content - The University of Warwick and Exeter University have modelling at both an atomistic and micromagnetic level, although still very low TRL
Production of near net shape thin magnets			
More cost-effective methods for AM of magnets			- Modelling the magnetic properties can explore optimising magnetic materials and processes for AM - No activities identified
Develop REE magnets for aerospace industry	- These innovations potentially increase precision, supporting the complexity required in aerospace - No activities identified	- Automation in assembly allows more precision which is critical for the aerospace industry - No activities identified	- There are some potential to enhance magnetic properties and accelerate R&D for the aerospace industry - No activities identified

4.3.3 Gap analysis of UK capabilities to commercialise technologies

To capture capability gaps within the UK's ecosystem in respect of commercialising technologies, analysis has been conducted on current UK capabilities alongside the required capabilities for innovation. Table 9, below, shows our findings with the rows representing current UK capabilities and the columns representing requirements for innovation. If the UK capability can address the requirement for innovation, it will then be coloured with the RAG status (Red, Amber, Green) to visualise the extent to which the UK has the capability to support each requirement for commercialisation, if the capability is irrelevant in addressing the requirement it is shown as N/A in the cell. These findings were validated through interviews and workshops with key stakeholders.

Table 9 – Gap analysis of UK capabilities to commercialise technologies

N/A If the capability is not relevant for the specific requirements to innovate

Average Findings indicate that UK capabilities do partially meet requirements to innovate

Weak Findings indicate UK capabilities do not currently meet requirements to innovate

Strong Findings indicate that UK capabilities do meet requirements to innovate

Main UK capabilities to support magnet manufacturing

Requirements for innovation	R&D facilities	Testing facilities	Funding opportunities	Skills development	Manufacturing capabilites
Workforce development	Average	Average	Weak	Average	Weak
Stable early-stage financial funding	N/A	N/A	Average	N/A	N/A
Innovation ecosystem	Strong	Average	Average	Average	Average
Policies and regulations	N/A	N/A	Average	N/A	Weak
International collaborations	Strong	Weak	Weak	Strong	Average

This analysis shows that the UK has strength in early-stage capabilities to support R&D activities but lacks a skilled workforce. UK universities are capable of training talents, but before that happens the industry needs to show stronger demand signals for a skilled workforce and the universities receiving additional resources for training. Testing facilities also appear to be limited for innovating magnet manufacturing technologies. The UKs funding landscape should be strengthened for REPMs to support the long timescales required to commercialise innovation in this space. Finally, enhancing manufacturing capabilities in the UK is crucial for fostering manufacturing innovation. This initiative not only helps develop a skilled workforce for REE manufacturing but also strengthens the entire REPM manufacturing value chain. Improved manufacturing capabilities can contribute to building a more comprehensive innovation ecosystem, shaping effective policies and regulations, and promoting international collaborations.

4.4 Benchmarking against global innovation

To provide practical recommendations, the UK's ecosystem was benchmarked against global innovation. This will demonstrate where the UK has an opportunity to lead the market and where the UK faces challenges as other geographies are more active or are market leaders. The findings are detailed in Table 10, below.

Table 10 – UK and global main innovators and TRLs

Technology theme	Technology readiness level of UK innovators or research	Technology readiness level of leading non-UK innovators and research	Opportunities and challenges for the UK to become a market leader
Metallisation and Alloying	LCM (TRL 8-9) University of Birmingham (TRL 8)	Tennessee's Oak Ridge National Laboratory, US (ORNL) (TRL 4-9) Zhejiang University, China (TRL 4-8) Zhong Ke San Huan, China (TRL 7-9) NIMS, Japan (TRL 7-9) Baotou research institute of rare earths, China (TRL7-9)	**Opportunity – High in bespoke alloying:** LCM and University of Birmingham has strong knowledge in production of bespoke alloys. **Challenge:** Most patents are in Japan and emerging in China. China has already commercialised light REPMs.
Manufacturing Methods: Reducing Grain Sizes	University of Birmingham (TRL 2-9) Hypromag & Mkango (TRL 4-5) SGTec & ZF (TRL 5-7)	Tohoku University, Japan (TRL 8-9) Daido Electronics, Japan (TRL 9) Tokyo University of Science, Japan (TRL 9) CISRI-NIMTE, China (TRL 9) Baotou research institute of rare earths, China (TRL7-9)	**Opportunity – High in extrusion:** SGTec is already engaging in an innovation project with the University of Birmingham on developing hot deformed extruded magnets. It has been demonstrated in Japan that hot deformed magnets can be used in EVs. University of Birmingham and HyProMag are working on the HyDP process and already have jet milling facilities. **Challenge:** Daido is already making hot deformed magnets commercially for automotives (Daido, 2022).
Manufacturing Methods: Reducing HREE	University of Birmingham (TRL 7) Hypromag & Mkango (TRL 7) Bunting (TRL 7)	South China University of Technology, China (TRL 7) Shin-Etsu Rare Earth Magnet, China (TRL 7) Yunsheng Magnetics, China (TRL 7)	**Opportunity – High in recycling:** Grain boundary diffusion can be explored alongside magnet recycling. **Challenge:** Most research activities are based in Japan and China

Manufacturing Methods: Other Manufacturing Methods	Queen Mary University of London & University of Birmingham (TRL 2-4) SGTec (TRL 9)	Fraunhofer institute, Germany (TRL 4-7) Tennessee's Oak Ridge National Laboratory, US (ORNL) (TRL 4-9) Ames National Laboratory, US (TRL 3,4) Iowa State University, US (TRL 3,4)	**Opportunity – High in bonding & AM:** UK has many 3D printing facilities in universities and academics in this area, and China has yet to focus on AM. SGTec has developed high performance bonded magnets. **Challenge:** US ORNL is currently one of the leaders in AM, and this tech still faces many technical limitations such as scaling up. Other manufacturing methods have many technological limitations to commercialise.
Automation techniques	University of Sheffield & AMRC (TRL 6-7) Hypromag & Mkango (TRL 6-7) AMRC (TRL 7-8) University of Exeter (TRL 1-2) University of Warwick (TRL 1-2)	Jožef Stefan Institute, Slovenia (TRL3,4) University of Ljubljana, Slovenia (TRL3,4) Jiangxi College of Applied Technology, China (TRL3,4) Baotou research institute of rare earths, China (TRL7-9)	**Opportunity – High:** It is worth looking at how the UK can develop automated assembly for magnets. Tyseley Energy Park has automated presses for sintered magnets. AMRC has automation research capability. **Challenge:** At present the most advanced equipment is only available in China.

5. Conclusions

This Conclusions section will discuss opportunities to address innovation and capability gaps to allow the UK to maximise the potential of REPM manufacturing.

A description of the potential benefits and challenges of the opportunities is detailed below.

REPM users should consider end of life disassembly in product design.

- **Benefits:** Incorporating a circularity mindset into designing products can reduce reliance on virgin REEs and imported magnets and improves economies of recycling at a product's end-of-life. This element of recycling as an integral part of magnet manufacturing has scope for the UK to take a leading position.
- **Challenges:** Ensuring quality control of the new products will be critical given the current complexity in design and the supply chain.

Innovator funding to support testing and scaling of technologies and developing skilled workers.

- **Benefits:** This can build the UK's capacity in magnet manufacturing to address high barriers to entry, which includes creating the knowledge and capabilities to manufacture at scale. Models could include grant, loan, equity investment, or blended finance models.
- **Challenges:** How to manage risks for funding support requires full assessment of the landscape. The viability of scaling technologies competitively within the UK should be considered, given the lack of domestic raw materials and high energy costs compared to other geographies.

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

- **Benefits:** This can create a sector voice that articulates needs and requirements, quantifies demand, supports flow of information, and acts as a point of contact for international collaboration. The secretariat could be hosted by existing organisations such as the Institute of Materials, Minerals and Mining or UK Magnetics Society.
- **Challenges:** Some existing UK organisations are already doing this, but there is a lack of formal structure. Another challenge is how to strategically find partners for international collaboration. Possible criteria for UK partners include looking for countries with similar R&D capabilities, more natural resources, and cheaper energy prices than the UK to build magnet manufacturing and research capability.

Increase understanding of the environmental impact of the current REPM supply chain and how that would change by building local capacity.

- **Benefits:** Supporting corporates can help them make better informed decisions and understand key development areas regarding material sourcing to address sustainability requirements from customers, stakeholders, or regulation. This can also support the first opportunity of incentivising end-users considering end of life disassembly in product design, for example building standards and policies.
- **Challenges:** Expertise in environmental impact and magnet manufacturing often do not overlap, and collaboration is needed to address this challenge.

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

- **Benefits:** Having UK based sintering prototyping facility can enable: (1) Production of value-added magnets (e.g. with HREE) in the UK, (2) development of necessary engineering know-how to build and operate larger factories, (3) trial of new magnet formulations, (4) test manufacturing technologies enabling novel topologies, and (5) supporting the R&D and testing for UK's magnet recycling value chain.
- **Challenges:** The energy price in the UK is very high for magnet manufacturing, which is an energy-intensive process, and sufficient funding, access to suitable skills, and mechanisms to overcome the perceived risk around building this capability will be a challenge.

Support development of magnet manufacturing research centres and IP to drive development of existing technologies and emerging technologies.

- **Benefits:** This can utilise and enhance the UK's R&D capability. Academics seeking to develop leading edge competence will need strategic support from their university to build up capabilities, pursue multi-year funding opportunities, and operate as coordinators. Understanding the REE IP landscape can also support innovators to develop practical manufacturing strategies.
- **Challenges:** It will be costly to set up and maintain research centres, as well as having enough skilled workers for it.

Build up a UK REPM knowledge hub for the sector.

- **Benefits:** This hub could work closely with government departments and lobby for legislation to strategically support UK magnet and motor manufacturing. This enables (1) knowledge support for design engineers to choose fit for purpose magnets, (2) the ability to articulate and disseminate sector requirements and potential direction, and (3) the ability to gauge potential demand for different types of magnets for different industries and applications. This could be supported by the above working group.
- **Challenges:** The UK is lagging globally in this sector in terms of general knowledge, so bringing in international talents should be considered.

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