Innovate UK

Rare Earth Permanent Magnet Alternatives

Innovation Landscape Report

Contents

Produced by Carbon Limiting Technologies for Innovate UK

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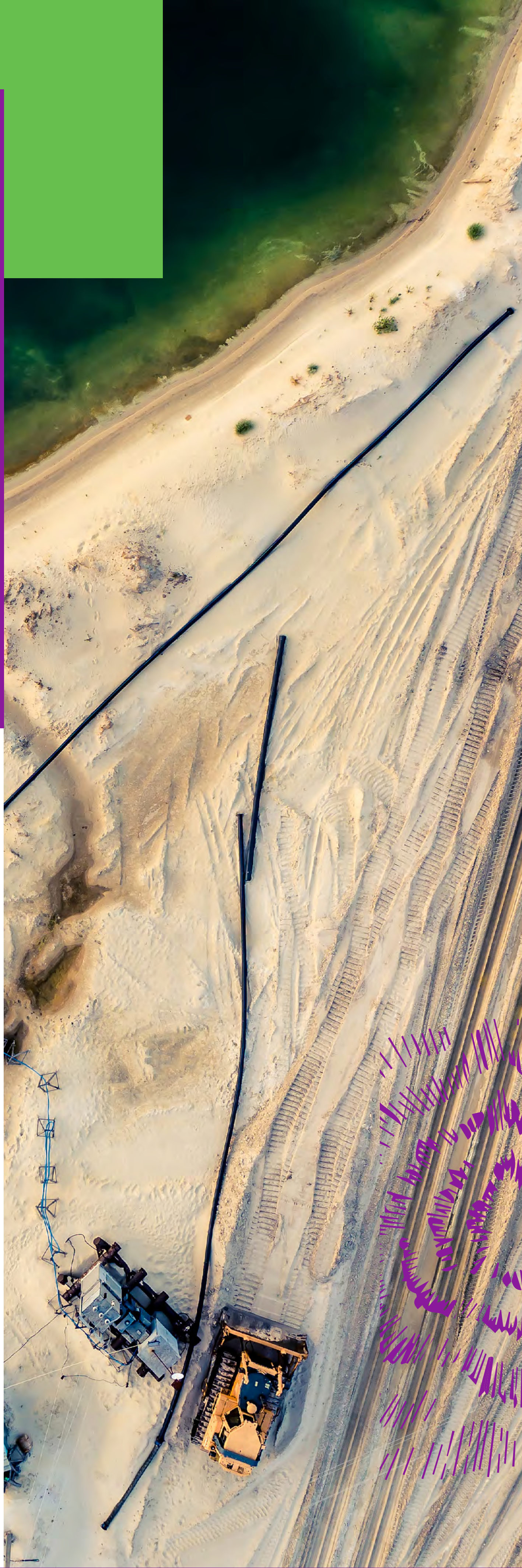
1. Executive Summary

This Innovation Landscape Report on Rare Earth Permanent Magnet Alternatives 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 Manufacturing.

This report aims to summarise the UK opportunity and the current state of the innovations being developed for potential alternatives to rare earth permanent magnets (REPMs).

This includes mapping technologies and capabilities that already exist within the UK, and highlighting gaps that require future innovation support and investment.

REE supply and price uncertainty have prompted concerns over the resilience of the UK's access to REPMs; a key component of many electrical devices, including those crucial to the net zero transition, such as EV motors and wind turbine generators.

One solution to reduce the UK's REPM vulnerability is to increase the use of alternatives to current REPMs. These technologies do not aim to entirely replace the use of REPMs but instead reduce the demand for virgin REE to ease the strain on supply chains. Alternative REPM technology is complementary to, and not a replacement for, pursuing improvements in REE production, recycling or diversification of the supply base. These approaches are discussed in other reports in this series.

Four categories of alternative technologies were identified: new magnetic materials, reformulation, substitution, and REE-free or reduced design.

Many technologies described in this report are early-stage, low technology readiness level (TRL) innovations, such as new magnetic materials and some reformulation approaches. To develop these technologies would require considerable resources and yield only limited results in the distant future, diverting resources from more impactful solutions. This needs to be weighed against supporting high-TRL technologies close to commercialisation that can reduce demand for virgin REEs in the near term, such as REE-free or reduced designs.

The UK currently has a strong environment to support general early-stage innovation, born from a combination of a world leading academic sector and R&D facilities supported by accessible non-dilutive funding, in the form of grants and accelerator programmes, as well as early-stage dilutive funding. However, there was no specific support identified for alternatives to REPMs.

The UK provides limited support for commercialisation of late-stage alternative technologies. The funding required to bridge the gap between seed/series A rounds and commercialisation of a technology is scarce, and large original equipment manufacturers (OEMs) using REPMs are reluctant to collaborate with innovators.

Opportunities to improve the UK's innovation ecosystem in developing and deploying emerging technologies in the alternative to REPM space were formulated with key recommendations being:

- Increase support to innovators, with a focus on skills development and funding to enable commercialisation.
- Create an alternative to REPM research centre to drive development of existing technologies.
- Create an industry-led working group to bring together end-users, corporates, innovators and academia to foster collaboration and provide a voice for the sector in discussions with the UK government.

2. Background context

Currently, the highest performing permanent magnets for electric machines contain (some, but not all) REEs: a group of 17 elements, containing the lanthanides and scandium and yttrium. In the 1980s, it was discovered that combining the REE neodymium with iron and boron (NdFeB) produced a magnet with a maximum energy product (BH_{max}) exceeding 55 MGOe. This is significantly higher than that of non-REPM: 10 MGOe for Alnico and only 5 MGOe for ferrite magnets (Cui, 2022).

Other REEs, such as samarium (for samarium-cobalt, SmCo, magnets) and dysprosium (Dy) are also commonly used in high strength magnets. These magnet types are often selected for their high energy density and coercivity (resistance to demagnetisation) and are used in applications where size and weight are critical. Crucial to the clean energy transition as they are fundamental to the electrification of mobility, they are commonly used in pump motors, robotics, healthcare, and many electrical devices, including satellite and defence systems. Increasingly, they are being used in the automotive industry as more electric vehicles (EVs) are produced, as well as the renewable energy sector in offshore wind turbines.

The growing demand and constrained supply of REE, have prompted concerns over the security of the supply chain and future price volatility, Concerns about the environmental and ethical practices used to extract REEs from the ground also exist. Therefore, complementary efforts are underway to mitigate the supply risks, including diversifying the sources, reducing waste, and developing new methods of manufacture and recycling. There is also a drive to find alternatives to virgin REE used for magnets, including new magnetic materials, substituting REPM for existing magnets, and designing out the use of REEs in end-use applications, such as motors and generators.

Since NdFeB magnets were introduced in the early 1980s, research into new magnetic materials declined as REPMs were found to be sufficient for most applications and significantly more power-dense than any other potential magnetic materials. More recently, interest in alternative materials has increased due to fears of price volatility and supply chain disruption, sparking a renewed wave of research into alternative materials. However, much of this research is still at low technology readiness level (TRL) and largely confined to universities.

End-users of REPMs have been developing technology to optimise NdFeB or SmCo magnets for several decades. This presents a considerable disadvantage to end-use technologies attempting to incorporate non-REPM into their designs for the first time. After proving the concept works, a long process of validation and optimisation is required before solutions can be perceived by the industries using them to be compatible with existing designs. Often, there are negative prejudices over the performance of historically underdeveloped design types, even if the barriers that traditionally held these solutions back have recently been overcome.

This report aims to outline the current innovation landscape for alternatives to REPM in the UK, highlighting the country's current strengths, capabilities, and opportunities in this innovation area.

3. Mapping the current UK innovation landscape for REE alternatives

For any innovation to displace an incumbent technology, it must have cost and performance parity. In the REE supply chain context, it must not introduce additional complications or transfer a supply chain bottleneck elsewhere. There is also a desire amongst stakeholders interviewed that geopolitical factors should underpin any assessment of new alternatives to REPMs.

There is a desire to reduce price volatility in the REE supply chain to ensure that net zero targets set for the middle of the century are achieved. Due to this time pressure, only technologies already at a higher TRL level, with proven evidence of performance will make a meaningful impact and should be pursued. This should be considered when assessing the applicability of the innovations described in the following section to tackle current REE supply chain concerns.

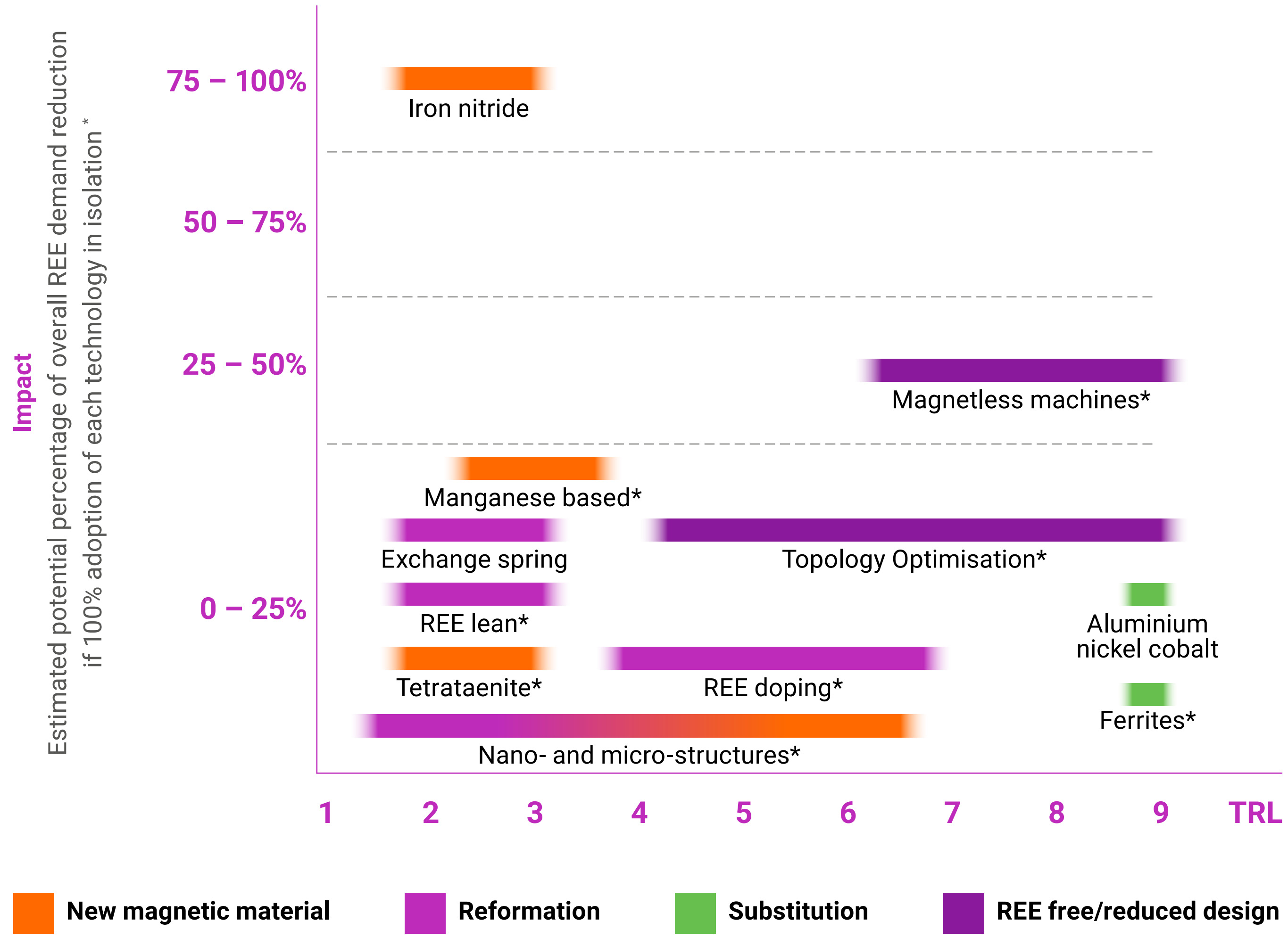
3.1 Innovation areas and UK innovators

3.1.1 Technology innovation areas against TRL

TRLs of the main alternative technologies for REPM and their potential to reduce REE demand can be seen in Figure 1, below.

Impact of technology innovation areas against TRL.

Solutions marked with an asterisk have evidence of activity with the UK.



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

Below is a brief overview of the technology areas, with a detailed description in the next section:

- **New magnetic materials:** novel magnetic materials that can replace or reduce the demand for REPM.
- **Reformulation:** material formulation to reduce REE content in magnets whilst maintaining performance.
- **Substitution:** targeted use of currently available magnets to reduce the demand for REPM.
- **REE free/reduced design:** redesigning or optimising magnet end use case technology to require less or no REPM.

Solutions focused on new magnetic materials or reformulation of magnetic materials are mostly early stage and low TRL. Solutions focused on REE-free/reduced design or substituting REPMs with existing magnet types in end use cases are at a higher TRL, as they have often existed for several decades, despite remaining unoptimized and unfavoured by end-use industries.

The y-axis in Figure 1 indicates the estimated percentage segment of overall REE demand reduction if a technology was fully adopted and achieved its theoretical maximum REE demand reduction potential, in isolation of other implemented technologies. Precision is difficult with such assessments, so solutions are grouped into brackets representing 25% segments. The relative y-position of technologies within the same segment is not indicative of comparative performance. Technologies were located on the y-axis, which was dependent on several factors.

New magnetic materials were located in relation to their theoretical BH_{max}, which indicates whether they will replace REPMs in most situations or act as a gap magnet only to relieve some demand. The higher the BH_{max}, the more demand is relieved and the greater the impact.

Reformulation technologies were located relative to the REE reduction provided with considerations for ease of manufacture.

Substitution technologies were also located by their respective BH_{max}.

Finally, **REE-free/reduced design technologies** were located considering the demand for REPMs from the industries in which these technologies apply and an estimation of the best-case adoption within these industries. The vertical position of each solution is likely an overestimation of the expected impact due to its basis on a theoretical 'best case' scenario, with more variation in error anticipated for lower TRL solutions.

Assessing the estimated impact of these solutions, another concerning story emerges. Most solutions will have a low impact on REE demand for magnets. This is because the BH_{max} of alternative magnets (new magnetic materials, reformulation and substitution technologies) limits the applications in which they can replace REPM, and the broad range of applications REPMs are used for means that any one single REE-free/reduced design technology can only be applied to a specific use case. The only potential high-impact solution is in the early stages and has many technological barriers to overcome before implementation.

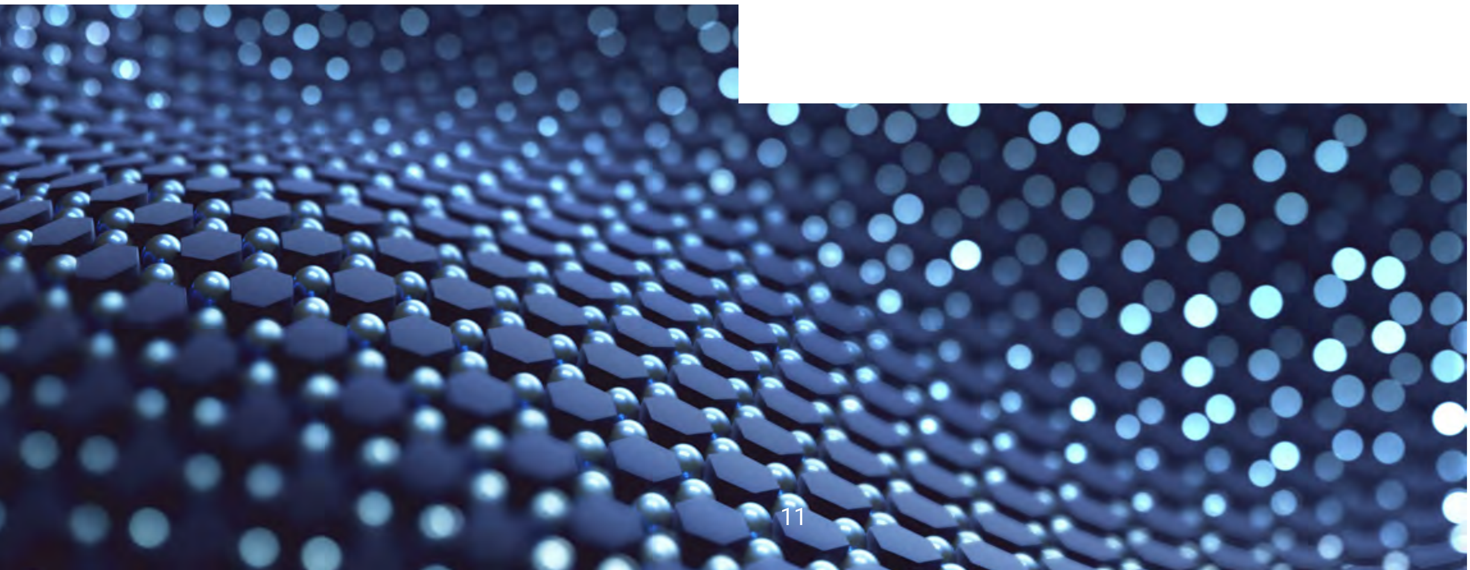
3.1.2 Technology innovation areas

This section explores the main technologies currently being pursued within each innovation area. This is not an exhaustive list of all potential technologies but captures those to which multiple separate research groups and organisations have contributed, or individual organisations have taken beyond TRL 3.

New magnetic materials

The technologies below aim to reduce or replace the demand for REPM by synthesising new magnetic materials with equivalent properties to that of REPMs. These solutions are at a very early stage, with most research being conducted at academic institutions. The commercialisation pathway of these solutions is typically a decade or more, and there is so far little credible evidence they can be scaled cost-effectively or provide the performance theorised.

- **Iron nitride (TRL 2-3):** Iron nitride magnets are a magnet based on iron and nitrogen, both cheap and plentiful materials. The theoretical BH_{max} of 1150kJ/m^3 is far higher than that of current REPM (Niron, 2024), though some academics have expressed doubts to the project team as to whether this is a realistic value. If the theoretical BH_{max} value is achieved, these magnets could replace REPM in all applications, pending an economically viable production process. However, the development of this material is still at an early stage, with the main innovator being Niron Magnets in the US, which has not released much data concerning its progress.
- **Tetrataenite (TRL 2-3):** Tetrataenite is a magnetic material initially discovered in meteorites, formed of iron and nickel, that develops over millions of years as the meteorite cools slowly. In 2022, it was synthesised in the lab for the first time using a phosphorus catalyst in a matter of seconds (Ivanov, 2022). Lab-synthesised tetrataenite has a theoretical BH_{max} of 335kJ/m^3. If the production process is scalable, it can act as a gap magnet. Researchers at the Universities of Cambridge and Warwick are some of the world leaders in this material.
- **Manganese based (TRL 2-4):** This is a family of magnets based on manganese with various combinations of other elements, including manganese bismuth, manganese aluminium (further combined with carbon or gallium) and manganese iron. The BH_{max} of these magnets can range from 55kJ/m^3 to 120kJ/m^3 (Marenkin, 2020), enabling them to function only as a low-level gap magnet. Manganese bismuth has a positive temperature coercivity, making it ideal for high-temperature applications, with recent developments in research discovering methods to make bulk, high-purity powder needed for large-scale manufacture (PNNL, 2024). There has been some research into magnesium aluminium gallium undertaken at the University of Sheffield (Davis-Fowell, 2022).
- **Nanostructures (TRL 1-3):** Control of the nanostructures within a material would enable some materials that were previously not viable as a magnetic material to provide magnetic performance. Examples include nickel graphite (Saini, 2020) and iron cobalt (Frobose, 2024). However, as many of these solutions are in the early stages, it is unclear what the final performance characteristics will be, and no ongoing research has been identified in the UK.



Reformulation

The group of technologies described below aim to reduce the demand for REEs in magnets by altering the magnet's component ingredients, reducing the REE content but maintaining the same or improved performance. These solutions are very early in development, with most research conducted at academic institutions.

- **REE lean/REE doping (TRL 2-7):** REE lean magnets are a family of solutions that introduce non-rare earth elements, or lighter rare-earth elements, such as cerium and yttrium into the magnetic material to reduce the rare-earth content while broadly maintaining the performance. This is also referred to as 'doping'. While these magnets should be able to replace REPM in most applications, they do not provide much of an REE content reduction. There is also current ongoing research at the University of Oxford and the University of Warwick (Staunton, 2024) into a family of REPM called REE1-12 (1-12 refers to the ratio of REE to non-REE atoms), which reduces the REE content compared to the standard REE1-7.
- **Exchange spring magnets (TRL 2-3):** Exchange spring magnets are formed from the combination of a hard and soft magnet broadly maintaining the characteristics and performance of both. The REPM content could theoretically be reduced to 10%, although this has yet to be proven. Such magnets have so far only been produced as nanoparticles (Lopez-Ortega, 2014), with difficulties noted in the alignment and magnetisation of these particles, presenting a barrier to manufacture at scale. While this type of magnet was discovered in 1991 (Kneller, 1991), research has been scattered and without substantial progression outside of academia.
- **Microstructures (TRL 1-7):** Control of the microstructure of magnetic materials can increase the performance characteristics of that material or reduce the content (specifically heavy REE) used. This would allow for magnetic material to reach closer to their theoretical BH_{max}, enabling less magnetic material to be used or empowering gap magnets to relieve more REPM demand. Examples of these techniques include grain boundary diffusion and hot deformation – processes being developed at the University of Birmingham.

Substitution

The technologies below aim to reduce the demand for REPMs by substituting REPMs for other existing magnets. Existing non-REPMs cannot replace REPMs entirely, but through greater use in less power-dense-critical applications can relieve some demand, allowing REPMs to be used in scenarios where there are no existing alternatives. These alternative magnets have historically not been used in these applications because REPMss are the more accessible and better understood option. These solutions are mostly at a later TRL stage and are commercially available now.

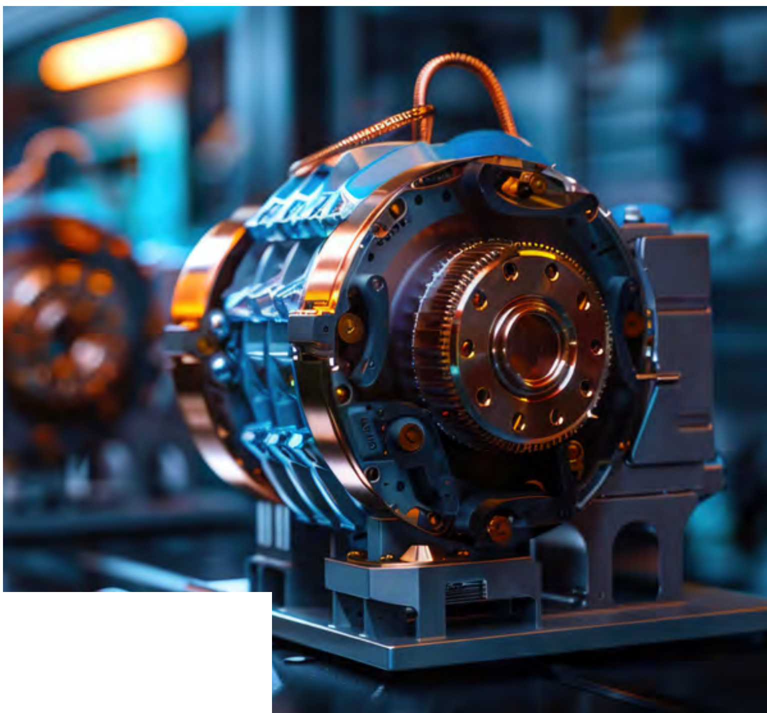
- **Aluminium nickel cobalt (TRL 9):** Aluminium nickel cobalt magnets, referred to as alnico, are a widely commercialised family of magnets primarily composed of iron alloys, alongside the addition of the elements which give the material its name. With a BH_{max} of 50kJ/m^3 (Arnold, 2024), alnico magnets are currently widely used in microphones and loudspeakers, alongside other industrial applications where weight and size are not key drivers.
- **Ferrite (TRL 9):** Ferrite magnets are widely commercialised ceramic magnets derived from iron oxides. With a BH_{max} of 40kJ/m^3. They are used in most low-level magnetic applications and are favoured for inductors, transformers, and electromagnets due to their high electrical resistance, which reduces eddy currents. There is current research in the UK to create end-use cases designed for ferrite magnets, as described below, that will enable the reduction of REPM use.

REE free/reduced design

The technologies below aim to reduce the demand for REPMs by redesigning the end-use case in which these magnets are used. This can be achieved by optimising and designing the technology for a substitution magnet or by replacing the need for magnets entirely. These solutions are mostly later TRL stages and are being pursued primarily by industries which use REPMs, such as motors in EVs or generators in the wind industry. Compared to other alternative technologies, there is a comparatively large amount of activity within the UK automotive industry focussing on these solutions.

- **Magnetless machines (TRL 6-9):** Magnetless machines can exist in several topologies, such as induction motors, synchronous reluctance machines or switched reluctance machines. Induction motors typically present good peak power and torque density over short periods but can prove challenging to manage thermally and typically have lower efficiency than permanent magnet motors. Because of these reasons, they have not traditionally been favoured for applications where weight and size are key, such as the automotive, wind and robotics industries. However, they have found use by some OEMs, notably Tesla (Tesla, 2023), and advancements in design may enable more uptake in larger EV types. Reluctance machines were not favoured for EVs as they have historically proven difficult to control and produce more noise and vibration than are acceptable. However, recent advancements, such as those by Advanced Electric Machines, have overcome these difficulties, creating a cheaper motor that is easier to recycle.
- **Topology optimisation (TRL 4-9):** Electric machines have mostly been optimised to use REPMs. New topologies being explored allow for the reduced use of REPMs, or are being optimised for less powerful magnetic materials with similar performance outcomes, although this does result in increased size and weight. Examples include axial flux machines; a design being pioneered by companies such as YASA motors and Greenspur (who are also replacing the REPM with ferrite). Research into new topology types is also under way at the University of Sheffield.

While electric machines (motors and generators) are the most common use of REPMs, they are also used in electronics, medical equipment such as MRI scanners, and speaker systems. REE-free/reduced solutions can also be applied to these applications but are too disparate to be categorised. One example of a UK innovator in this space is Warwick Acoustics, which has developed REPM-free speakers.



Adjacent approaches

There is an additional family of solutions to reducing REPM demand that are worth considering but do not fall directly within the scope of this report. This includes adjacent technologies such as lightweighting of EVs, which can reduce the demand for REEs in motors by reducing the size of motors required. Similarly, new business models such as shared ownership of vehicles reduces the overall demand for REPMs significantly by reducing the number of cars requiring REPMs, as do increased uptake in alternative modes of transport such as cycling and the use of public transport.

Furthermore, design approaches in any end application that allow for the easy disassembly and extraction of REPMs for recycling promote a circular economy that further reduces demand for REPMs. This is not an exhaustive list of adjacent approaches but provides examples of how thinking around the need for use of REPMs can reduce REE demand as well as the adoption of alternative technologies.

3.2 Stakeholder map of the UK

Figure 2: Map of UK stakeholders with interest in alternatives to REPM.

Universities

- University of York
- University of Oxford
- University of Cambridge
- University of Leeds
- University of Warwick
- University of Birmingham
- University of Nottingham
- University of Sheffield

RTOs

- Offshore Renewable Energy Catapult
- Warwick Manufacturing Group
- Driving the Electric Revolution Industrialisation Centres
- The MTC

Government stakeholders and trade organisations

- UKRI Engineering & Physical Sciences Research Council

Automotive Corporates

- Turntide
- Ford
- Ricardo
- JLR

Early-stage Innovators

- Warwick Acoustics
- Geolithical
- Advanced Electric Machines
- GreenSpur
- Materials Nexus

Investors & financing

Non-exhaustive list of investors who have funded REE alternative companies

- Carbon13
- Ada Ventures
- MD One Ventures
- Turquoise Capital
- North Star
- Syndicate Room
- Par Equity
- Legal & General Capital
- Barclays
- Green Angel Syndicate
- APC
- Innovate UK

New magnetic material | Substitution | Neutral

Reformulation | REE free/reduced design

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

Figure 2, above, shows the stakeholder landscape of alternatives to REPM in the UK. As with Figure 1, it is colour coded based on the technology themes in which each organisation is involved. Details of their activities can be found in the Supply Chain Database.

As is clear from Figure 2, the UK has the largest activity in REE-free/reduced design, with academic institutions primarily focussing on early TRL level solutions such as new magnetic materials and reformulation. Few stakeholders have focussed on substitution solutions.

The UK has a thriving university sector. The research conducted at these institutions focuses on the discovery of new magnetic materials and reformulation of existing magnet types, as these are the earliest-stage solutions. However, much of the research is conducted ad hoc, with no academic centres containing dedicated faculties or facilities to the study of REPM alternatives.

Most of the RTOs in the stakeholder map are closely linked to end-use industries, such as automotive and wind. For this reason, it is not surprising to see that RTOs have engaged exclusively in REE-free/reduced design solutions that focus on end-use applications prevalent in their respective industries.

Similarly, as there is a limited REPM supply chain within the UK upstream of distribution and end-users, most corporates and early-stage innovators are focused on REE-free/reduced design. R&D of new magnetic materials and reformulation requires expertise and facilities that only exist in academia in the UK. However, corporates and innovators typically come from an industrial background, where they have identified a specific problem that a REPM-free/reduced design can solve. These stakeholders do not view themselves as part of a REPM ecosystem but tend to define themselves by the vertical industry in which they work.

As the UK has a good general funding landscape to provide finance to innovation, there has been support provided for all the early-stage innovators identified, both from grant programmes and venture capital (VC) funds. However, there are no recognised specific VC funds targeted at the REE supply chain, and most grant funding successfully received were either not directly related to the REE supply chain or were for one-off projects.

3.3 UK capabilities to commercialise innovation

The UK's capabilities to commercialise innovation for alternatives to REPM are segmented into key areas: R&D facilities, testing facilities, funding opportunities and skills development.

In the UK, there is limited specific support for alternatives to REPMs. However, general innovation support and capabilities within end-use industry verticals provide an adequate ecosystem for some solution types to commercialise, especially REE-free/reduced design.

UK universities lead R&D, primarily in extracting, processing, and recycling REPMs, but lack dedicated centres for alternative solutions. However, they are well-equipped with generalist facilities for computational modelling and small-scale prototyping of new magnetic materials. R&D for REE-free/reduced designs is shared between universities and end-users, who also conduct in-house research. Both have the necessary computational and engineering capabilities for development and testing

Testing facilities tailored **specifically** for alternatives to REPMs do not exist in the UK. Innovators instead turn to university facilities or those of larger companies for their testing needs. Some innovators interviewed use university labs to synthesise and validate the performance of any magnetic materials they discover. Innovators working with REE-free/reduced design solutions can access the testing facilities of end-user companies, who use them for their internal R&D. However, this can be prohibitively expensive for early-stage innovators. RTOs aligned with end user industries such as the Offshore Renewable Energy (ORE) Catapult, Warwick Manufacturing Group and the MTC work with innovators to provide access to testing facilities alongside funding to support this.

There are some relevant funding opportunities in the UK for alternatives to REPM, including grants, accelerators, and early-stage venture capital funds. While these are not always directly targeted at alternatives to REPMs, for example, they focus on funding automotive innovation, but they do provide essential financial support for related technological developments. There are also some EU grants more relevant to alternatives to REPMs, such as EU Horizon grants, and there are cases where UK stakeholders have joined consortia with other European companies.

Regarding skills development, the presence of relevant accelerators, conferences, events, and research projects contributes to the innovation ecosystem. However, their focus is not specifically on alternatives to REPM but on the wider REE supply chain or the broader critical materials industry.

Below in Table 1 is a list of UK stakeholders for each capability – **for more information on their activities, please refer to the Supply Chain Database.**

List of UK stakeholders

R&D Facilities

- **University of Cambridge:** Department of Materials Science and Metallurgy
- **University of Warwick:** Computational modelling facilities
- **University of Sheffield:** General facilities, participated in SoSRARE project
- **University of Leeds:** General facilities, participated in SoSRARE project
- **University of York:** Simulation and pulse-laser deposition facilities. Participated in SusMat0 project
- **University of Nottingham:** General facilities
- **University of Oxford:** General facilities

Testing Facilities

- **ORE Catapult:** National Renewable Energy Centre (Blyth) and Levenmouth Demonstration Offshore Wind Turbine (Fife)
- **WMG:** Advanced Materials Manufacturing Centre
- **DER-IC:** **t**esting facilities for electric motors
- **End users:** Large end users and OEMs in the auto and wind industry have their own in-house testing facilities

Funding Opportunities

Multiple sources of funding available to innovators and corporates, such as grants, accelerators, and early-stage VCs.

- Innovate UK
- Advanced Propulsion Centre (APC)
  - Technology Developer Accelerator Programme (TDAP)
  - Automotive Transformation Fund (ATF)
- EIT Raw Materials
- EU Horizon
- Environmental Technologies Fund
- Angel VC (e.g. Cambridge Capital Group, Molten Ventures
- Carbon13 accelerator (Venture builder Cambridge)

Skill Development

The UK has relevant accelerators, conferences, events, research project.

Most are not directly focused on alternatives to REE magnets.

- **APC TDAP:** Transport technology accelerator
- **Minor Metal Trade Association:** REE conferences and events
- **MetTech:** Value stream mapping of REE magnets
- **AMRC:** Manufacturing and aerospace materials and other high-value manufacturing sectors.
- **DER-IC:** Knowledge base and facilities for electric motor manufacturing

4. Assessing UK innovation landscape challenges and needs

4.1 Supply chain and corporate innovation needs assessment

Interviews with end-users provided direct insights into the challenges and requirements faced by those in the REE supply chain. These highlighted specific areas where innovation could significantly impact competitiveness and resilience. An analysis of current supply chain gaps was conducted to understand where new developments are most needed. These findings were cross-checked with our desk research insights, ensuring alignment with anticipated technological advancements and market demands.

While most end-users are aware of supply chain concerns with REPMs, it was often not at the top of their priority list. Only one unifying innovation need presented itself from interviews: reducing the amount of REPMs used, driven by concerns over future price volatility.

REPMs are mainly utilised due to their high performance characteristics (BH_{max}, coercivity) and they outperform many possible alternatives within current end-use technology. They are also better understood, more accessible and cheaper for the same performance than gap and non-gap magnet alternatives.

These factors present three possible innovation pathways to reduce REE demand. These are laid out in Table 2 in the 'Innovation needs' column, with the current state of innovation activity in the UK summarised for each need.

Table 2: List of innovation needs required by corporates to drive competitiveness and supply chain resilience.

Main innovation driver		Innovation needs	Current state
REE use reduction due to end-user concerns over future price volatility.	1	To develop magnets that can compete with REE performance with no (new magnetic materials) or reduced REE (reformulation) content.	All new magnetic material or reformulation research is at an early stage, with some research being conducted in the UK, primarily by universities.
	2	Redesigning end-use technology to reduce or eliminate REE content (REE-free/reduced design).	End-users, particularly in the automotive industry, are actively conducting R&D in this area, and publicly stating their aims to reduce REE dependency. There are also several external innovators focused on this category of solutions.
	3	To make current alternative magnets better understood/more accessible/cheaper for the same performance (Substitution).	While some substitution solutions overlap with REE-free design, there is little being done to educate about, or use, other currently available alternatives to reduce demand on REE.

Each technology theme focuses on solving a different innovation need, as indicated within the 'Innovation needs' column of Table 2. For each need, consideration should be given to the time to market, cost-effectiveness and scalability of any solution.

Technologies that are more than a decade away from commercialisation cost significantly more and have similar choke points in their supply chain to REEs, are considered not beneficial. Similarly, technology that adds complexity to other aspects of the supply chain (such as during manufacture, assembly, or disposal) should be avoided. Technologies whose entire supply chain could be contained in the UK or Europe would be preferred, as this mitigates the geopolitical risks.

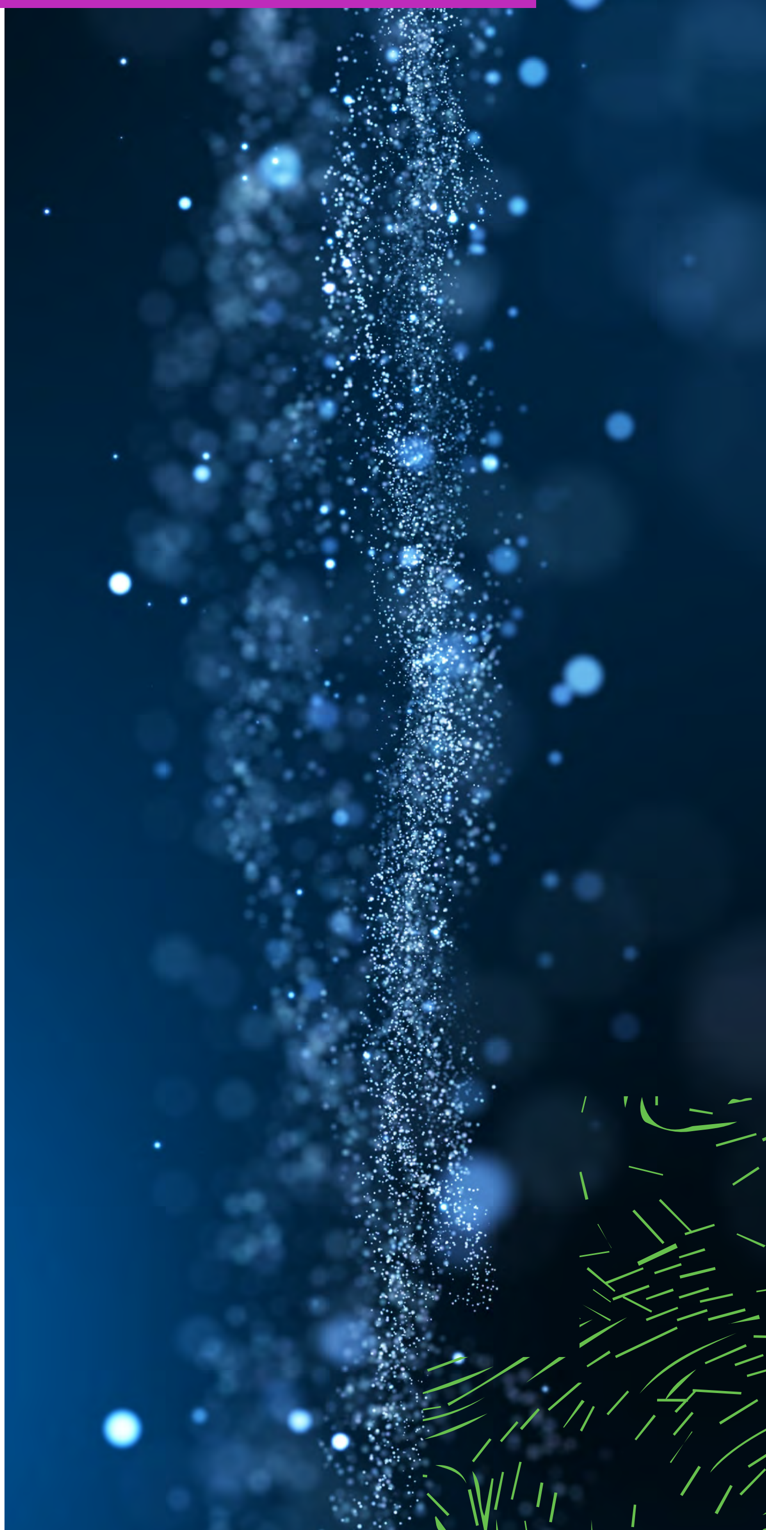
The alignment of technology theme and innovation need is expanded below:

1. To reduce the need for REEs within magnets because they have the highest performance characteristics, new magnetic materials must be developed or existing REPMs must be reformulated to contain a lower concentration of REEs without reducing their performance characteristics. Many of these solutions are at early stages, are far away from commercialisation and have little credible evidence of scalable performance.

2. To reduce the use of REPMs because they outperform alternatives within the current end-use case technologies (motors and generators), these can be redesigned to reduce or eliminate the need for REPMs. Activity in this space is primarily driven by stakeholders who view themselves as within the 'vertical' of the end-use case technology. These verticals include the automotive, wind, pump and robotic industries, with most REPM demand from the automotive and wind industries (IEA, 2022). Of these end-use verticals, the automotive industry is the most active in driving innovation forward. Several OEMs have declared their intention to reduce their REE dependency and there are more innovators focussed on REE-free/reduced design from the automotive industry than any other.

3. To reduce the use of REPMs because they are better understood, generally more accessible, and are currently cheaper for the same performance than alternatives, awareness needs to be raised of viable alternatives as well as of the potential for future price volatility with REPMs. While some substitution solutions overlap with REE-free design, there is little being done to educate about, or use, other currently available alternatives to reduce demand for REEs, and there are not many advocates in the UK for this. The notable exception is Geolithical, who are pushing for an increased use of strontium ferrite magnets.

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 alternatives to REPMs, relevant start-ups across varying TRLs and academics were interviewed to understand their support from the ecosystem, its importance in the development of innovation, and what they believe has been missing.

Table 3, below, lists the capabilities required for innovation in alternatives to REPM, a description of each capability and the UK's current state against this capability.

The capabilities in this table have been laid out approximately in the chronological order an innovation would experience them from inception to full commercialisation. This order is the same as what would be expected for any hardware technology innovation.

The capabilities available in the UK are sufficient to support low TRL technologies. However, the UK often does not have the capabilities to support later stage, higher TRL technologies, presenting a barrier to the commercialisation of alternatives to REPM. The notable exception to this is REE-free/reduced design in the automotive industry.

List of capabilities required to commercialise innovation for alternatives to REPM.

Capabilities required to innovate	Description	Current state
Knowledge and skills	Expert academic knowledge at research institutes enables the research and development of low TRL solutions, which can lead to spin out innovations. The right skills capabilities allow for the design, manufacture and testing of solutions.	• Reasonable academic activity in new magnetic material and reformulation. • Good knowledge of REE-free/reduced design in the automotive industry. • Academic funding to support research has recently declined. • More skills required to manufacture and test technologies.
Computational and simulation	Simulation can increase the discovery of new magnetic materials as well as aid the development of REE-free design.	• Universities have world leading computational facilities available. • Material Nexus uses bespoke software to accelerate discovery.
Synthesis and testing	New materials and designs must be synthesised and tested to validate their performance.	• No specific facilities are dedicated to REE alternatives, but university labs have general capabilities. • End user testing available via the ORE catapult, APC, DER-IC etc.
Non-dilutive support	Grant funding and accelerators support early-stage innovators.	UK has good generalist early-stage innovation support, with all innovators identified having accessed relevant grant funding and several participating in accelerators.
Early-stage dilutive funding	Early-stage dilutive funding provides capital to develop solutions.	Venture capital willing to provide funding to promising early-stage innovators.
Commercialisation funding	Commercialisation funding provides capital to scale solutions to full commercialisation.	Funding to bridge the gap between a seed/ series A round and commercialisation at scale is scarce.
UK REPM supply chain	A UK-based REPM supply chain would encourage more innovators and researchers and would provide a domestic market into which to sell solutions.	There is a limited UK REPM supply chain before distributors and end-users.
End user collaboration	To ensure solutions are aligned with end user needs and to provide access to real world testing through pilots.	• End-users are currently not that active in collaborating with innovators, especially in the wind industry. • Some end-users have supported research projects at universities.

Knowledge and skills: There is access to world-leading knowledge across many disciplines. Few academics are solely focussed on alternatives to REPMs and there are no departments or faculties identified that actively foster concentrated hubs of this type of knowledge. Furthermore, in recent years, it has become increasingly difficult to access academic-focused funding for this research. There is also a resource constraint on skills required to synthesise, manufacture, assemble and test solutions.

Computational and testing: The UK has world-leading computational facilities and adequate testing facilities, although it can be prohibitively expensive for innovators to access these without financial or grant support to do so. Furthermore, OEMs often want to repeat testing conducted on external facilities before adopting technologies, slowing the commercialisation progress.

Non-dilutive support and funding: The UK innovation ecosystem is well supported by grants and accelerators, though very few were found to directly target alternatives to REPMs as their primary aim. General grants, critical mineral grants or grants and accelerators targeted at the end-user verticals all provide non-dilutive support to innovators focused on alternatives to REPMs. Similarly, there are active venture capital firms willing to invest in innovators in this space, but none were identified that were focussed exclusively on sourcing deals even in this innovation area. Further to this, a distinct lack of funding that bridges the gap between seed/series A rounds and commercialisation has been identified, a comment repeatedly heard during interviews and workshops.

UK-based REPM supply chain: A main concern for driving forward innovation of alternatives to REPMs in the UK is the limited onshore supply chain. There is less incentive to innovate within the REE supply chain when it is limited domestically until the end-use of magnets. Whilst there are end-users, and, ultimately, they would be the final customer of any alternative REPM innovation, there is a loss of exposure to knowledge and potential partners with no domestic market. Many innovators would also be likely to sell overseas and could relocate to a more central hub of the REE supply chain.

End-user collaboration: Another concern is the lack of willingness for end users to collaborate with both each other and external innovators to focus on promoting innovation in alternatives to REPMs. They are rarely present in consortium projects, though have supported some research work at universities. There is a caution around sharing data from the end-use industries that is preventing alignment of innovators and end-users, and which can also complicate the process of testing and trials of solutions.

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 players. The gap analysis in Table 4, below, overlays findings from the innovator mapping with the sector innovation needs assessment to pinpoint where the UK has strength in an innovation area. These findings were also tested and validated through an on-line workshop held on 3rd July 2024.

The RAG status (Red, Amber, Green) visualises the UK's strength in each technology theme against the innovation needs they satisfy to highlight potential innovation opportunities.

Gap analysis for UK innovation.

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

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

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

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

Overall, the UK has weak capabilities in innovation of alternatives to REPMs. However, certain technology types in REE-free/reduced design have high potential for innovation to be commercialised and reduce UK reliance on the REE supply chain.

The UK has limited strength in developing new magnetic materials and reformulation of REPMs. These all come from academic institutions. As discussed, these solutions are all early stage and are not likely to be commercialised within at least the next decade. Further to this, there is little interest from end-users in pursuing or supporting these innovations.

The UK has reasonable strength in REE-free/reduced design. This is a result of an active automotive industry in this space and a high knowledge base amongst a small number of individuals. These solutions are near commercialisation and pose a good opportunity for the UK to become a world leader in exporting this technology if the appropriate investment and support are provided.

The UK has limited strength in substitution. There has been a small amount of research in academia, and through REE-free/reduced design, an uptick of interest in ferrite in electric machines. However, there is limited knowledge concerning the capabilities of substitution magnets and limited economic advantage to be gained from pursuing these solutions.

4.3.2 Gap analysis of UK capabilities to commercialise technologies

Table 5, below, displays UK capabilities against requirements for innovation. The RAG status (Red, Amber, Green) visualises the extent to which the UK has the capability to support each requirement for commercialisation. N/A annotates where there is no interaction between requirement and capability. These findings were validated through interviews and workshops with key stakeholders.

Gap analysis of UK capabilities to commercialise technologies.

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

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

Average Findings indicate UK capabilities partially meet requirements to innovate

Weak Findings indicate UK capabilities do not meet requirements to innovate

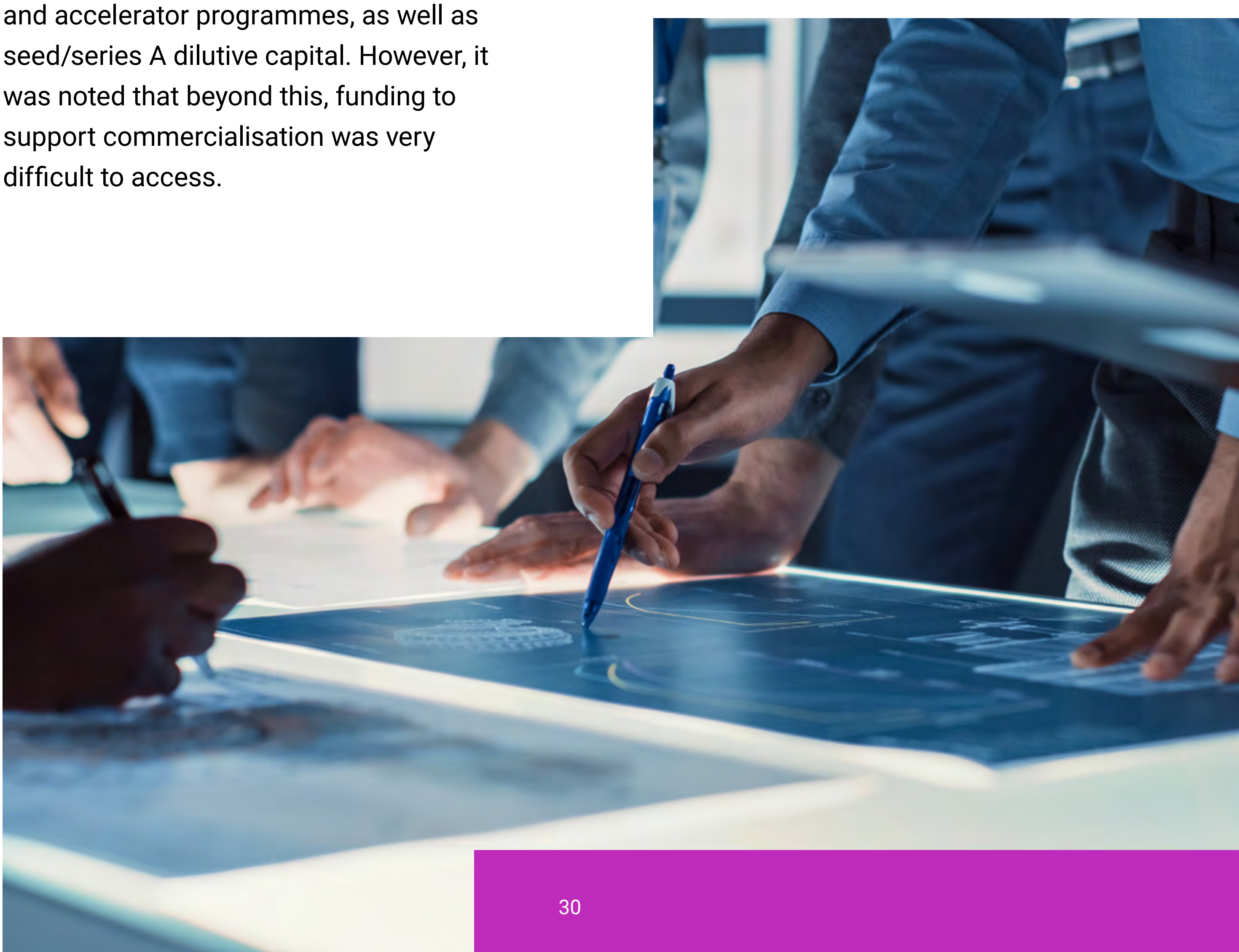
Strong Findings indicate UK capabilities meet requirements to innovate

The UK has reasonable (non-alternatives to REE focussed) early-stage support for innovation. Good capabilities are found in R&D facilities and testing facilities for the early stages of an innovation pathway. However, there is a lack of funding to access these facilities on a regular basis, as well as the skills of both innovators and facility personnel to fully support all activities. It was also noted that while funding for academics used to be easy to access, this has become more difficult in recent years. This could prevent new technology from being spun out of universities to begin the commercialisation journey and threaten the development of low TRL solutions, particularly new magnetic materials and reformulation.

A theme that emerged from interviews was the good state of early-stage support, both from non-dilutive sources such as grants and accelerator programmes, as well as seed/series A dilutive capital. However, it was noted that beyond this, funding to support commercialisation was very difficult to access.

Capabilities required for commercialisation of alternatives to REPMs technologies are severely lacking in the UK. There is a limited UK-based supply chain for REPMs and therefore limited capabilities. There are low levels of collaboration between end-users and innovators. Some projects are conducted collaboratively, however, there is little data shared and concerns about protecting IP and competitive advantage can often limit innovation potential.

If it is the desire of the UK to improve capabilities to commercialise alternatives to REPMs, significant government intervention is required, in the form of long-term support and investment.



4.4 Benchmarking against global innovation

To provide practical recommendations, the UK's innovation ecosystem was benchmarked against global equivalents. This demonstrates 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 6, below.

Main UK and global 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
New magnetic materials	• University of Cambridge and Warwick, Tetrataenite, TRL 2-3 • University of Sheffield, Manganese, TRL 3-4	• Niron, Iron nitride, TRL 2-3 • North Eastern University, Austrian Academy of Science, Tetrataenite, TRL 2-3 • Various American and European papers, nanostructures, TRL 1-2	• **Opportunity:** Collaborative world leading research in tetrataenite • **Challenge:** US leading in iron nitride, and no UK presence in other materials. However, low TRLs are likely to prevent commercialisation of solutions over meaningful timeframes.
Reformulation	• University of Warwick and Oxford, REE1-12, TRL 2-3 • University of Birmingham, Grain boundary diffusion, TRL 7	South China University of Technology; Shin-Etsu Rare Earth Magnet; Yunsheng Magnetics, Grain boundary diffusion, TRL 7	• **Opportunity:** Some competitive capabilities in REE1-12 and grain boundary diffusion • **Challenge:** Strong competition from China and Japan
Substitution	N/A – there is limited innovation in substitution	N/A – there is limited innovation in substitution	• **Opportunity:** Limited for the UK. However, there is a possibility of creating domestic capabilities in parts of the ferrite supply chain • **Challenge:** UK domestic supply is small compared to US, Chinese and Japanese markets
REE free/ reduced design	• Advanced Electric Machines, Reluctance Machines, TRL 7-9 • GreenSpur, Axial Flux Machines, TRL 5 • Warwick acoustics, REE-free/reduced design, TRL 7-9 • University of Sheffield, various topologies, TRL 3-5	Several OEMs, including Tesla, Renault, Mercedes, Audi and Hitachi, various topologies, TRL 7-9	• **Opportunity:** World leading innovators in REE-free/ reduced designs with high TRL products in an active auto industry • **Challenge:** Selling UK innovations to large non-UK OEMs conducting their own research into this space

5. Conclusions

Potential opportunities that enable the UK to capitalise on, or to bolster, its current capabilities in alternatives to REPM can be found below, in Table 7. These were compiled from desk research and interviews and aim to target one or more identified gaps.

Opportunities for the UK

	Opportunities for the UK alternatives to REPM	Potential outcome/impact
1	Increase innovator funding to support testing, scaling and commercialisation of technologies and developing skilled workers.	Clear focus on building UK capacity in alternatives to REE which includes building the necessary knowledge and capabilities to test and manufacture. Models could include grant, loan, equity investment, or blended finance models.
2	Support development of alternatives to REPM research centres to drive development of existing technologies and emerging technologies.	Academics seeking to develop leading edge competence will need strategic support from their university to build up capabilities, go after multi-year funding opportunities, and operate as coordinators.
3	Create an industry-led working group bringing together end-users, corporates, innovators, and academia to provide a voice for the sector.	Helps create a sector voice that articulates needs and requirements, quantifies demand (and hence scale of problem), 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.
4	Implement regulations that incentivise a reduction in virgin REE content in magnets over time.	Clarity on a target of virgin REE reduction would incentivise end-users to invest in alternative technologies or recycling to reduce virgin REE demand.
5	Build up a UK alternative to REPM knowledge hub for the sector.	Includes (1) sharing knowledge on alternative magnets and technologies, (2) articulation and dissemination of sector requirements and potential direction, and (3) knowledge support for motor engineers to choose fit for purpose magnets with focus on reducing REE content. This could be supported by the above working group.
6	Increase understanding of the environmental impact of the current REPM supply chain and how that would change by using less REE content in magnets or less REPM.	Supporting corporates to make more informed decisions regarding material sourcing to address sustainability requirements from customers, stakeholders, or regulation.
7	Develop small scale and agile magnet sintering prototyping facility to produce bespoke magnets for REE-free/reduced motor designs.	Increase the speed in which new motor topologies can be tested to accelerate REE-free/reduced designs.

While these opportunities are focussed specifically on the innovation space for alternatives to REPMs in the UK, many would be enhanced by integrating with opportunities targeted at the wider REPM supply chain. With finite funding, maximising the impact of opportunities is imperative, whereas competing for limited resources will divert attention from key areas and stall progress.

With this perspective, it is worth considering whether early-stage technologies that are more than a decade away from commercialisation are a viable solution to be pursued or an unhelpful distraction of time and capital. Focus should be placed on supporting technologies that are at a higher TRL level and closer to market to maximise impact.

While the scope of this report dictates that identified opportunities target alternatives to REPMs, opening them up to include, be accessible to, and benefit the wider REPM ecosystem would be encouraged.

These opportunities were presented to a workshop of 20 expert stakeholders from across the supply chain for validation and feedback. Participants were asked to rank the opportunities from one (best) to seven (worst). The opportunities in this report are presented in order of this ranking exercise.

The numerical output of this scoring (a mean average of rank provided by each attendee) can be viewed in Table 8.

Ranking scores for each opportunity

Innovator funding	Research centre	Working group	Regulated virgin REE reduction	Knowledge hub	Environmental impact benchmark	Bespoke manufacturing plant
2.75	3.00	4.17	4.33	4.45	4.54	4.67

Opportunity 1 and 2 were both favoured by the majority of stakeholders present. However, there is little distinction in preference of the remaining opportunities presented. An interesting observation is that some opportunities received a polarised ranking, obtaining only the highest or the lowest ranks, with the ranking score received broadly determined by the position in the supply chain within which the attendee who gave that score sits.

A more in-depth discussion of the benefits and challenges associated with each opportunity can be found below:

1. Increase innovator funding to support testing, scaling and commercialisation of technologies and developing skilled workers.

To maximise the impact of this opportunity, the additional funding focus should be defined by two streams: one targeting the development of skills and knowledge and the second providing specific commercialisation support. This should increase the numbers of skilled workers able to develop and scale innovations and aid later stage innovations to make the step from R&D to a commercialised product. This would ideally be a government led initiative. It could prove challenges to mobilise the capital necessary and funding could be allocated to solutions that ultimately do not make it to market.

2. Support development of alternatives to REPM research centres to drive development of existing technologies and emerging technologies.

As previously mentioned, to maximise impact, an alternative to REPM research centre should focus on high TRL solutions; therefore championing REE-free/reduced designs and substitution. This would require significant, continued funding to provide long term, strategic development of solutions. To mitigate some of the upfront capital required, building on existing facilities that already exist with the necessary operational infrastructure would be encouraged. These would be suitable research organisations with the appropriate capabilities, such as the DER-IC.

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

This would provide a cross-industry consensus and a strategic focus to direct further innovation actions. The aim should be on providing a long term and stable vision for industry, irrespective of political cycles. However, to be successful, it would require participation from all of the main stakeholders and there are concerns over securing engagement with large OEMs who have already set their own internal strategies. A strong link and backing from the government would support the working group in achieving its aims.

4. Implement regulations that incentivise a reduction in virgin REE content in magnets over time.

While this opportunity would undeniably drive a change from end-users, it would have to be part of a wider European legislation otherwise there is a risk of ostracising the UK from the European market and disincentivising companies to remain in the UK. There was also broad concern in the workshop over unintended consequences of regulations, such as placing a higher cost burden upon UK companies or forcing the adoption of technologies that are not yet commercially ready or scalable. A high degree of thought and careful implementation would be required for this type of regulation to be successful, and care should be taken to undergo a full supply chain consultation before attempting this.

5. Build up a UK alternative to the REPM knowledge hub for the sector.

To drive and enable innovation, a deeper knowledge and skills base is required in the UK. This should be addressed before physical capabilities are expanded so that capital investment into facilities can be fully utilized. A knowledge hub could be the centre of this educational push. However, it is unlikely that companies would be willing to share commercial data, therefore leaving a knowledge hub at risk of either relying on outdated information or becoming too academically focussed.

6. Increase understanding of the environmental impact of the current REPM supply chain and how that would change by using less REE content in REPMs, or fewer REPMs.

This would allow for an objective benchmark against which to measure alternatives, providing a metric that would allow identification of technologies to pursue. However, it is hard to generate a reliable and robust data set for magnets. A material passport initiative would be beneficial for this purpose. There are concerns that accurate quantification of this data would not drive much behaviour change, as many end-users are currently aware of the supply chain issues and environmental damage is a secondary driver to price volatility.

7. Develop small scale and agile magnet sintering prototyping facility to produce bespoke magnets for REE-free/reduced motor designs.

This would accelerate the innovation of new motor topologies. Concern should be taken to assess the capabilities of other facilities to avoid unnecessary replication of capabilities. The scale of the facility should aim to bridge the gap between university labs and high volume production.

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