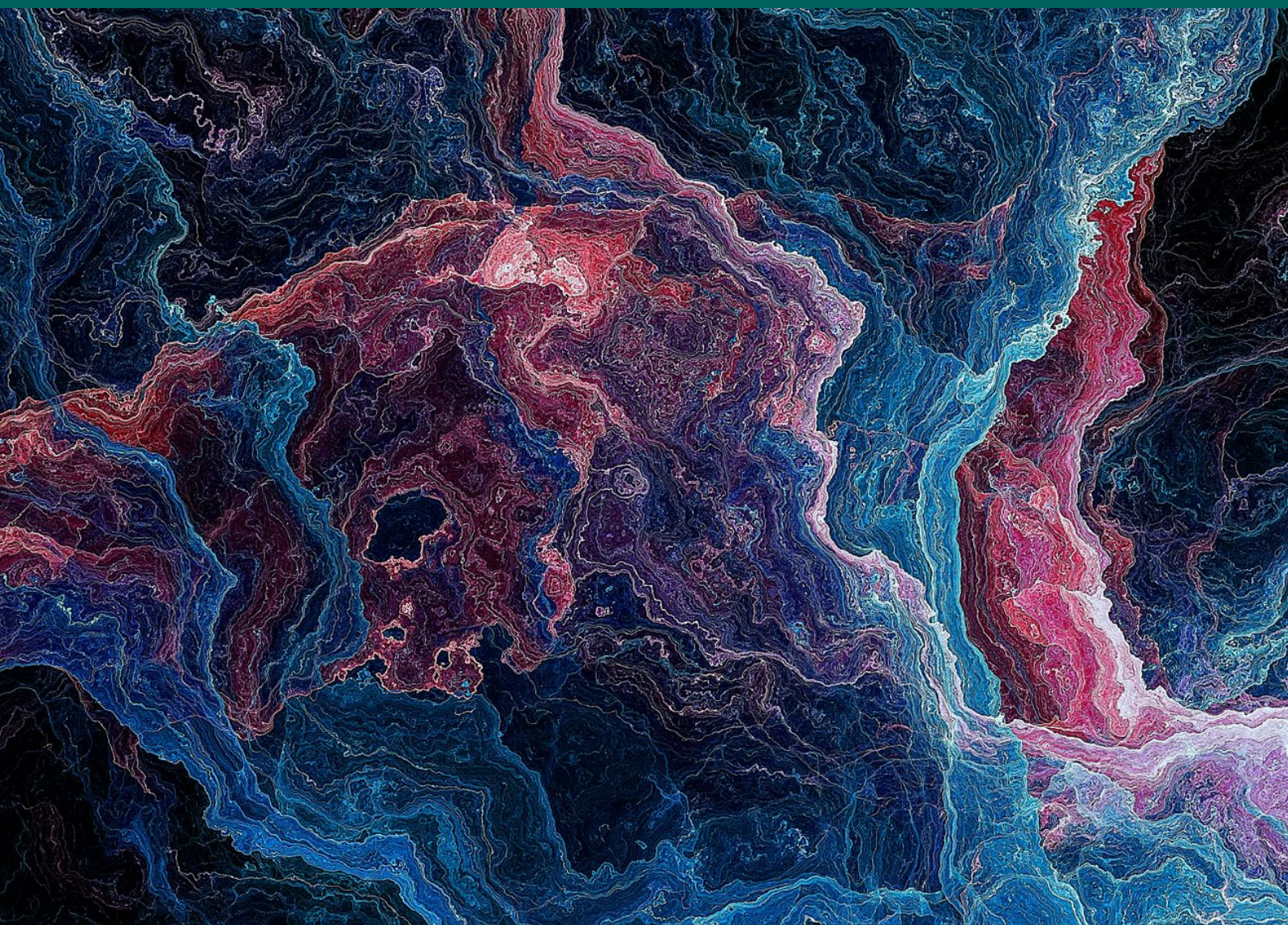
UK Critical Minerals Intelligence Centre

CRITICAL MINERALS

Research Landscape Review



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Author: Dr Matthew Reeves, Innovate UK KTN

1.0 Introduction

Critical minerals are a group of natural resources that are essential to modern society and are increasingly in demand for their use in a wide range of industries, including electronics, renewable energy, and transportation. These minerals are considered critical because they are difficult to obtain, have limited availability, or are geographically concentrated in a few countries, which can lead to supply chain vulnerabilities and geopolitical tensions.

The importance of critical minerals has gained increased attention in recent years, as countries and companies alike seek to secure reliable, responsible and sustainable sources of these essential resources. Examples of critical minerals include rare earth elements (used to make permanent magnets for electric vehicle motors and wind turbines), battery minerals (lithium, cobalt, nickel) and others used in the manufacture of advanced materials (graphite, palladium, tantalum etc.).

In July 2022, the department for Business, Energy and Industrial Strategy (BEIS) – now Department for Business and Trade (DBT) - published the UK's Critical Minerals Strategy, which set out how the UK will go about securing its supply of critical minerals. The strategy contains three main pillars:

To begin to deliver on the strategy, the Critical Minerals Intelligence Centre (CMIC) was established to work together with universities and private and public sector partners to gather and analyse intelligence on the supply and demand of critical minerals, their global value chains and use by UK industry.

Innovate UK KTN has been commissioned by DBT to produce this Critical Minerals Research Landscape Review. It documents large scale publicly funded research programmes and projects relevant to critical minerals, and other research performed by industry and community groups. It aims to inform the critical minerals stakeholder community about the research and innovation landscape in the UK and provide a basis for constructing a critical minerals research and innovation framework to guide future investments and interventions.

2.0 - Methodology

The 18 critical minerals and the additional 5 minerals placed on the "watchlist" in the CM Strategy are as follows:

Critical:

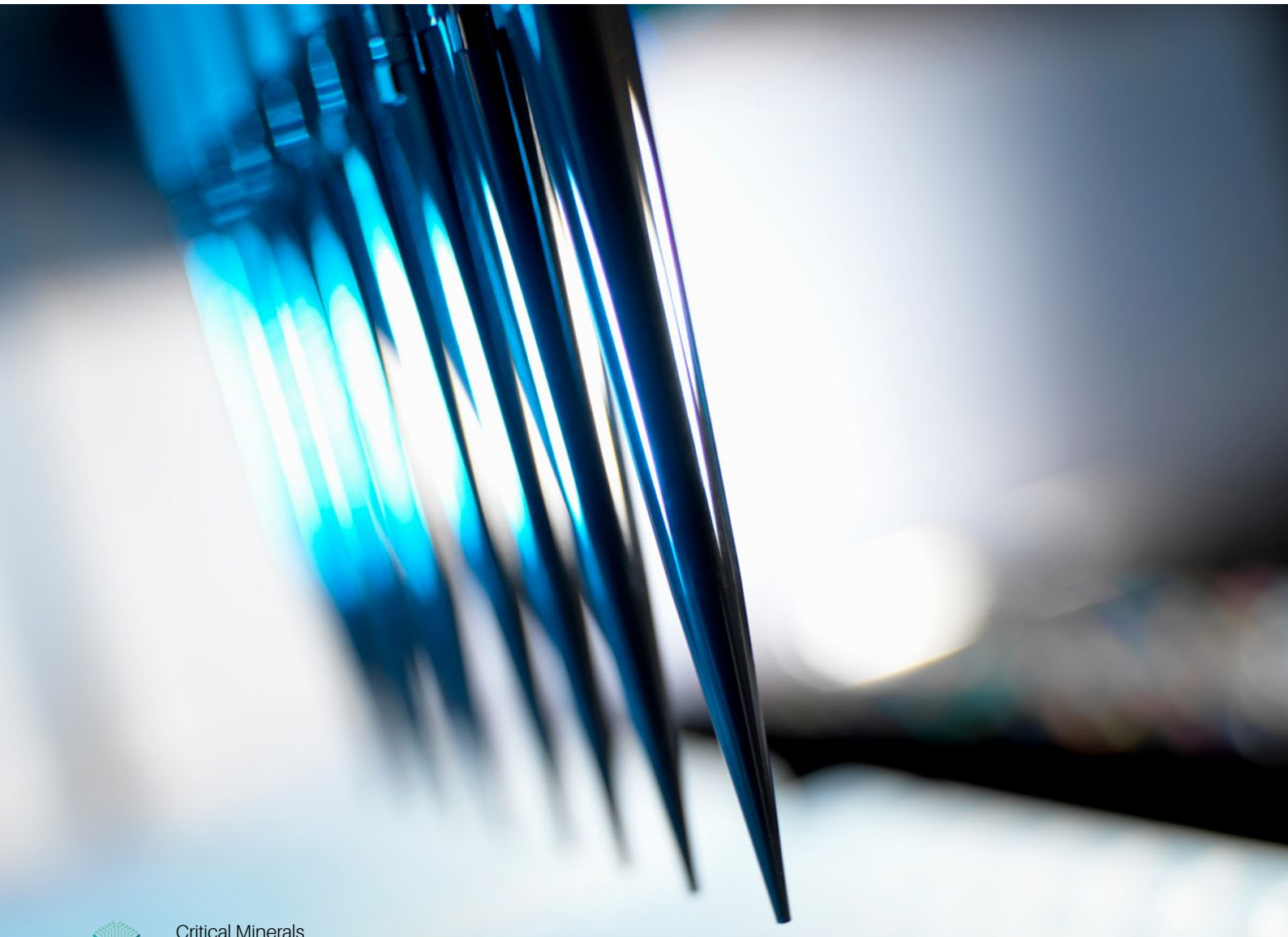
- 51 Sb Antimony — Antimony
- 83 Bi Bismuth — Bismuth
- 27 Co Cobalt — Cobalt
- 31 Ga Gallium — Gallium
- 6 C Graphite — Graphite
- 49 In Indium — Indium
- 3 Li Lithium — Lithium
- 25 Mn Manganese — Magnesium
- 41 Nb Niobium — Niobium
- 46 Pd Palladium — Palladium
- 78 Pt Platinum — Platinum
- REE — Rare Earth Elements (REEs)
- 14 Si Silicon — Silicon
- 73 Ta Tantalum — Tantalum
- 52 Te Tellurium — Tellurium
- 50 Sn Tin — Tin
- 74 W Tungsten — Tungsten
- 23 V Vanadium — Vanadium

Watchlist:

- 77 Ir Iridium — Iridium
- 25 Mn Manganese — Manganese
- 28 Ni Nickel — Nickel
- 15 P Phosphates — Phosphates
- 44 Ru Ruthenium — Ruthenium

Application Categories

- Agriculture
- Alloys
- Advanced materials
- Catalysis
- Coatings/adhesives
- Consumer
- Electronics
- Energy Storage
- Food
- Industrial
- Magnetics
- Med/ Pharma
- Nuclear



Primarily, these elements are defined as critical due to their use in important technologies, materials and applications. A simple analysis of the literature reveals the application areas for each element as follows:

	Catalysis	Alloys	Med/Pharma	Electronics	Magnetics	Coatings/additives	Energy storage	Adv materials	Industrial	Agriculture	Food	Nuclear	Consumer
Sb			●	●		●			●				
Bi	●	●	●			●							
Co	●	●		●	●		●		●				
Ga		●	●	●									
C		●					●	●	●			●	
In		●		●		●	●						
Li			●				●		●			●	
Mg		●		●									
Nb		●			●	●							
Pd	●		●	●				●					●
Pt	●			●					●				●
REEs	●				●	●		●	●				
Si		●		●				●	●				
Ta		●	●	●				●					
Te	●			●									
Sn			●			●	●		●				
W		●			●			●	●				
Va	●	●				●	●						
Ir	●		●	●					●				
Mn		●		●		●	●						
Ni		●		●			●		●				
Ph									●	●	●		●
Ru	●	●		●				●					

Table 1: The 18 critical (and 5 watchlist) minerals and their use across application categories

This review aims to document large-scale research programmes and projects, relevant to both the critical minerals themselves, and the range of application areas they are associated with. The search for research programmes and projects has involved multiple approaches.

Keyword searches of databases

Gateway to Research (https://gtr.ukri.org, GTR), and online database of publicly funded research projects, was searched using a series of keywords, including individual mineral names (e.g. "cobalt" or "rare earth elements") to identify database entries containing reference to the critical minerals as listed on Page 4. The following additional filters were applied:

- £1m funding and above
- Start date 2017 and after

This produced manageable lists of programmes and projects that were sifted manually, to identify relevant ones to include in this review.

Using our network and in-house expertise

By starting with the applications areas, Innovate UK KTN experts and key external contacts were canvassed to provide intelligence of major research programmes and projects in the application areas identified in table (1). A list of relevant programmes/projects was provided by contacts at NERC/UKRI, which was built upon (see acknowledgements). Projects less than £1m documented in this review have derived from previous work by NERC, and have been included as they have already been identified.

Labelling system

Each entry contains the following headline information:

- Project name and URL to GTR webpage
- Funding amount, rounded to nearest £0.1m
- Start year and end year
- Funder
- Relevant minerals/elements (if appropriate)
- Relevant application area (if appropriate)
- Relevant value chain segment (if appropriate)
- Text summary

Individual minerals/elements are tagged where directly relevant (e.g., a project looks to establish the location of new lithium deposits). Application areas are tagged when a project is directly relevant to an application area, and the relevant minerals are inferred by table (1) (e.g., a project developing alloy engineering practices). Value chain segment is tagged where a project has not already been organised under a value-chain segment section heading. Value chain categories are:


Circular economy and resilient supply chains


Exploration/ extraction


Manufacturing


Materials science (including biological), engineering and process (bio)chemistry


Social Science

3.0 Results

3.1 Academic-led natural science research programmes (£319.7m)

3.1.1 Exploration/extraction (£25.8m)

Volatiles, geodynamics and solid Earth controls on the habitable planet

£8 million 2014-2020 Natural Environment Research Council

Three consortia funded by NERC, aimed at understanding the dynamic role of mantle volatiles in mediating fundamental Earth processes that affect the habitability of the surface and establish the controls on the volatile flows and budgets into and out of the mantle.

Seabed Mining and Resilience to Experimental Impact

£3.2 million 2021-2025 Natural Environment Research Council

NERC funded consortium led by the National Oceanographic Centre (NOC) with the aim to better understand the ecosystem in the Pacific abyss and how the different components interact and interconnect, and to provide the critical scientific understanding and evidence-base to reduce the risks of future mining activities.

78 Pt Platinum | 83 Bi Bismuth | 52 Te Tellurium

From arc magmas to ores (FAMOS): A mineral systems approach

£ 3 million 2017-2022 Natural Environment Research Council

NERC funded consortia with the aim to develop new exploration tools that will help locate metal resources in volcanic arcs by understanding the fundamental processes involved in cycling magmas, fluids and metals in these zones.

Sustainable Mineral Resources in the Philippines

£3 million | 2021 – 2025 | Natural Environment Research Council

This programme, co-funded by NERC and The Philippine Council for Industry, Energy, and Emerging Technology Research and Development (DOST-PCIEERD), aims to improve understanding of the impacts of past and future mining practices in the Philippines, and develop new innovative approaches to the production of minerals that minimise negative impacts on the environment and the health and wellbeing of communities. Two projects (PROMT and PAMANA) were each awarded £1.2 million from NERC (80% FEC) and 15 million pesos from DOST-PCIEERD to develop a whole-systems view of sustainable mineral production, and to generate innovative solutions that minimise impact on the environment and local communities - crucial to sustainably meeting the growing demand for mineral resources used in green/low carbon technologies. In addition, NERC has invested £170,000 to support a Knowledge Exchange Fellow to work across the funded research project teams in the programme, to: help stakeholders work together and share information; to be responsible for policy and industry engagement; and to ensure visibility and legacy of outputs from the programme to relevant audiences (August 2022 - May 2025).

Lithium for Future Technology (LiFT)

£2.5 million | 2020 – 2023 | Natural Environment Research Council

NERC funded consortium led by BGS with the aim to increase our understanding of the geological processes that concentrate lithium into a range of different types of mineral deposit, from which lithium can be mined in both an economically feasible and environmentally responsible manner.

Copper Basin Exploration Science (CuBES)

£2.5 million | 2020-2025 | Natural Environment Research Council

NERC funded consortium led by University of Southampton with the objectives to identify the processes, operating over a range of scales, that lead to the formation of large Cu-Co-(V) deposits and derive new and practical exploration tools to support the development of lower risk mineral exploration strategies.

Ultramafic-hosted mineral Resource Assessment (ULTRA)

£2.2 million | 2020-2024 | Natural Environment Research Council

NERC funded consortium with the aim to improve understanding of the formation and preservation of ultramafic-hosted seafloor massive sulphide deposits, which host some of the largest deposits known of high metal concentrations of Au, Cu, Ni, E-tech elements (Co, Pt), and the potential impact on adjacent faunal habitats if they are mined.

REE

Towards a process-based understanding of rare-earth element deposits

£1.4m 2022-2026 Innovate UK

Developing a computational approach for understanding the formation of REE deposits, to aid in the exploration phase of REE mining using remote sensing techniques.

3.1.2 Circular economy and resilient supply chains (£59.8m)

Strategic Priorities Fund – National Interdisciplinary Circular Economy Research Programme (NICER)

£30 million 2021-2025

Investment into 5 interdisciplinary resource flow specific circular economy research centres and a coordinating CE-hub which aims to move the UK towards a circular economy. NICER is delivered in partnership with industrial organisations from across sectors and DEFRA to ensure research outcomes contribute to the delivery of industrial implementation and government policy. The Interdisciplinary Circular Economy Centre for Technology Metals (Met4Tech; Universities of Exeter, Birmingham, Leicester, Manchester and the BGS) specifically addresses circularity of technology metals through research on how to: improve and assure the supply of raw materials; manufacture good to be re-used and recycled; and recycle complex goods such as batteries. The first collaborative research and development (CR&D) competitions run by Innovate-UK for small and medium sized enterprise funding took place in late 2021 with a second CR&D competition opened in October 2022. Successful projects related to Critical Minerals from the first CR&D competition include:

REE 27 Co Cobalt 52 Te Tellurium 49 In Indium 31 Ga Gallium

Security of Supply of Mineral Resources

£15 million 2015 – 2019 Natural Environment Research Council Engineering and Physical Sciences Research Council This joint NERC and EPSRC programme funded four research grant projects (SoS RARE; CoG3: the geology, geometallurgy and geomicrobiology of cobalt resources leading to new product streams; MarineE-tech; TeASe: tellurium and selenium cycling and supply) covering research into e-tech elements: cobalt (Co), tellurium (Te), selenium (Se), neodymium (Nd), indium (In), gallium (Ga) and heavy rare earth elements (HREE). MarineE-tech, which focussed on improved understanding of E-tech element concentration in seafloor mineral deposits, also received funding from FAPESP.

Resource Recovery From Waste

£7.2 million 2014-2019 defra Natural Environment Research Council Economic and Social Research Council

A programme of research funded by NERC, ESRC and Defra aimed at delivering the science needed to accomplish a paradigm shift in the recovery of resources from waste, driven by environmental benefits and for human health, and not be economics alone. A total of six projects funded, several of which directly relate to the recovery of e-tech metals and/or Rare Earth Elements: B3 – Beyond biorecovery: environmental win-win by biorefining of metallic wastes into new functional materials, INSPIRE – In-situ processed in resource extraction from waste repositories, MeteoRR – Microbial Electrochemical Technology for Resource Recovery and R3AW – Resource Recovery and Remediation of Alkaline Wastes. Additional funding allowed the programme to conduct a policy impact project which focussed on 'Making the most of industrial wastes: strengthening resource security of valuable metals for clean growth in the UK'.

Towards a circular bioeconomy – technology-relevant metals and textiles

£5 million 2022-2025 Biotechnology and Biological Sciences Research Council

A BBSRC Strategic Research Fund opportunity for small grants (c. £350,000) of up to 2 years, inviting applications that apply biotechnological solutions to offer circularity and environmental impact reduction in one of two key areas:

- technology-relevant metal recovery
- textile manufacturing and recycling

Metals in Biology

£0.7 million 2014-2018 Biotechnology and Biological Sciences Research Council and subsequent E3B Network (£1.3 million 2019-2024 Biotechnology and Biological Sciences Research Council)

These networks funded by Phase I and II of the BBSRC Network in Biotechnology (BBSRC NIBB) initiative focus in part on the valorisation of metal-contaminated wastes, bio-remediating and bio-recovering metals in valuable forms. They provide networking between academia, industry, policy makers and others and have funding to distribute for small proof of concept grants and business interaction. They have funded proof of concept projects relevant to critical minerals and held a scoping workshop in December 2019 on this topic.

Technology critical metal recycling using ultrasonics and catalytic etchants

£970,000 2022-2025 Engineering and Physical Sciences Research Council

An EPSRC Standard Research grant that focusses on the use of targeted, catalytic etchants which can control the redox state of technology critical metals from complex architectures (such as photovoltaic and thermoelectric devices).

Critical Elements and Materials (CREAM) network

£0.3m 2018–2022 Engineering and Physical Sciences Research Council

EPSRC investment aiming to safeguard UK industry against shortages of strategic/critical elements and materials by bringing together leading UK academics from a wide range of disciplines alongside the key industrial users, to develop strategies to protect the UK supply of these materials and, where possible, develop alternatives. A roadmap has been produced as part of this work: Download the Securing Technology-Critical Metals for Britain Policy Commission Report - April 2021 (pdf -20mb)

3.1.3 Materials science, engineering and process (bio) chemistry (£235.1m)

The Henry Royce Institute

£200m ongoing Engineering and Physical Sciences Research Council

An EPSRC funded partnership of 9 institutions, coordinating over £200 million of facilities, to support world-recognised excellence in UK materials research, accelerating commercial exploitation of innovations and delivering positive economic and societal impact for the UK. Research areas include Advanced Metals Processing, Chemical Materials Design, and Atoms to Devices. They also run a series of National Materials Challenges and Associated ROYCE Roadmaps.

Digital navigation of chemical space for function

£8.7m 2021-2026 Engineering and Physical Sciences Research Council

Working across the computer science and natural science domains to transform the ability to access functional materials with unprecedented chemical and structural diversity, by building a digital discovery platform for materials.

14 Si Silicon

Nanoscale Advanced Materials Engineering

£7.7m 2021-2026 Engineering and Physical Sciences Research Council

Developing a new approach to delivering material functionalisation based on Nanoscale Advanced Materials Engineering. The approach will enable the modification of materials through the addition (doping) of single atoms through to many trillions with extreme accuracy (~20 nanometres), alloying material fabrication for use in e.g., quantum computing.

LightForm: Embedding Materials Engineering in Manufacturing with Light Alloys

£4.8m 2017-2023 Engineering and Physical Sciences Research Council

Developing the science and modelling capability needed for a more holistic approach to designing light alloys for performance and manufacturability.

The UK Catalysis hub

£3.7 million 2013 – 2018 Engineering and Physical Sciences Research Council

An EPSRC investment to coordinate the expertise of collaborative groups in novel areas of catalytic science, with a focus on developing catalytic processes for more effective use of water and energy, waste minimisation, and material reuse and reduction in gaseous emissions.

Centre for Doctoral Training (CDT) in Sustainable Materials and Manufacturing (EngD)

£3.3 million 2013-2022 Engineering and Physical Sciences Research Council

EPSRC CDT led in collaboration between the University of Warwick, Exeter and Cranfield. The recruitment period for this CDT has ended with existing students due to end in October 2022. Their key capabilities are sustainable materials and processes, materials engineering, chemistry, life cycle analysis (LCA), industrial biotechnology, economics and multi criteria decision aiding with a key goal to create a cleaner future.

High Reliability Interconnects: New Methodologies for Lead-free Solders

£1.3m 2018-2022 Engineering and Physical Sciences Research Council

Work to understand and control solidification kinetics in solder alloys, to provide a step-change improvement in the understanding, prediction and manufacturing of solder joints that are optimised for high reliability in high value UK industry and in consumer electronics.

Earth-abundant catalysts and novel layered 2D perovskites for solar water splitting (H2CAT)

£1.2m 2021-2024 Engineering and Physical Sciences Research Council

Project to overcome the current limitations of photo-electrodes (cathodes and anodes) for use in water splitting, by using layered 2D halide perovskites as extremely efficient light absorbers and voltage sources. Aim to understand key processes that underpin their stability so that devices with unprecedented energy efficiency and performance can be realised.

74 W Tungsten

Bcc-superalloys: Engineering Resilience to Extreme Environments

£1.2m 2020-2024 Innovate UK

Investigation of body-centred cubic intermetallic compounds for a step-change in temperature capability of a new class of superalloys based on tungsten, titanium and steel, for use in extreme environments e.g., nuclear fusion, generation 5 fission reactors and aerospace gas turbine engines.

46 Pd Palladium | 45 Rh Rhodium | 78 Pt Platinum

Metal-free couplings for molecules, materials and bioactive targets

£1.1m 2015-2020 Engineering and Physical Sciences Research Council

Developing metal-free catalytic processes that complement existing metal-catalysed cross-coupling technologies that could eventually lead to their replacement.

78 Pt Platinum | 45 Rh Rhodium | 46 Pd Palladium | 12 Mg Magnesium

Molecular s-block Assemblies for Redox-active Bond Activation and Catalysis: Repurposing the s-block as 3d-elements

£1.1m 2023-2026 Engineering and Physical Sciences Research Council

Using synthetic chemistry and computational modelling to exploit a new design principle for heterobimetallics for use in catalysis, taking advantage of the cooperative interaction between magnesium-magnesium bonds and sodium cations.

Deep Eutectic Solvents and the Future of the Critical Metals Circular Economy

£1 million 2022-2026 Innovate UK

A Future Leaders Fellowship aiming to provide low-impact alterative solutions for recovering and recycling critical minerals using Deep Eutectic Solvents to extract metals from Waste Electrical and Electronic Equipment (WEEE).

3.2 Academic led application specific (£146.7m)

The Faraday Institution

2017-2023 UK Research and Innovation

The Faraday Institution (£108 million) was established in 2017 to overcome key industrial challenges in energy storage technology. Their research programme spans nine major research areas in lithium-ion and beyond lithium-ion technologies as well as battery recycling. The Faraday Institution is part of the Faraday Battery Challenge (see Challenge led programmes from UKRI).

The ReLiB project (£14.1 million, 2018-2023) is a Faraday Institute funded project which aims to devise and develop alternative recycling routes that could provide UK businesses with a competitive advantage, using a range of physical, chemical and biological techniques to separate and recover the materials contained in the full range of current battery compositions.

Success will be demonstrated by the patenting and construction of demonstrator plants that can:

- Strip down the whole battery more safely and much faster than present techniques allow
- Reduce environmental impact by minimising the use of chemicals
- Minimise human intervention by using advanced robotics to automate most processes.
- Recover a high proportion of the original materials in a reusable form
- Maintain high value materials streams to improve the economics of recycling

Driving the Electric Revolution Industrialisation Centres

£33m ongoing Innovate UK

The Driving the Electric Revolution Industrialisation Centres project is part of the £80 million Driving Electric Revolution Challenge from UK Research and Innovation (UKRI).

The Driving the Electric Revolution Industrialisation Centres (DER-IC) is a UK-wide project to accelerate delivery of Power Electronics, Machines and Drives (PEMD) solutions for global market.

Across the UK, the DER-IC partner network has world class capability in PEMD including design, manufacturing and testing facilities. The DER-IC's encourage cross sector collaboration and drive industries to invest and collaborate with our network of excellence in academia and Research Technology Organisations, growing this capability, and promoting this both in the UK and overseas to transform the UK into a PEMD exporter.

The aim is to grow PEMD supply chains and deliver long term industrial growth. We want to make the UK globally recognised as the centre of excellence in PEMD manufacturing processes.

Future Electrical Machines Manufacturing Hub

£10.7m 2019 – 2026 Engineering and Physical Sciences Research Council

The Hub will address key manufacturing challenges in the production of high integrity and high value electrical machines for the aerospace, energy, high value automotive and premium consumer sectors. Through delivering world-class manufacturing research and innovation, the Hub will assist UK manufacturing to capture significant value in the electrical machine supply chain, improve UK industrial productivity and deliver the environmental benefits and cleaner growth at the heart of the UK's industrial strategy.

14 Si Silicon

QUantum Dot On Silicon systems for communications, information processing and sensing

£6.1m 2020-2025 Engineering and Physical Sciences Research Council

Work to build on a demonstration of the first successful telecommunications wavelength lasers directly integrated on silicon substrates.

14 Si Silicon

Application Targeted and Integrated Photovoltaics - Enhancing UK Capability in Solar

£6.0m 2020-2025 Engineering and Physical Sciences Research Council

Research to address the next generation of printed PV technologies which could deliver solar energy with far greater functional and processing flexibility than c-Si or traditional compound semiconductors, enabling tuneable design to meet the requirements of market applications inaccessible to current PV technologies.

46 Pd Palladium 28 Ni Nickel

Accelerated Discovery and Development of New Medicines: Prosperity Partnership for a Healthier Nation

£5.5m 2019-2024 Engineering and Physical Sciences Research Council

A research partnership to develop and apply AI and ML techniques to the efficient identification of next generation medicines, next generation catalysis and synthesis, sustainable processes and to create a Digital Design toolset for equipment, enabling Digital Manufacturing of novel pharmaceutical processing equipment.

31 Ga Gallium

Integrated GaN-Diamond Microwave Electronics: From Materials, Transistors to MMICs

£4.3m 2017-2023 Engineering and Physical Sciences Research Council

Developing new diamond growth approaches that maximize diamond thermal conductivity close to the active gallium-nitride (Ga-N) device area, for realizing GaN-on-diamond high electron mobility transistors (HEMTs) and monolithic microwave integrated circuits (MMICs) for use in microwave electronic devices.

51 Sb Antimony 83 Bi Bismuth

Pnictogen-based semiconductors for Harvesting EneRgy from Ambient Light to power autonomous Devices (HERALD)

£1.3m 2022-2027 Innovate UK

HERALD aims to instigate a step-change in how smart devices are powered by developing new classes of pnictogen-based semiconductors to more efficiently collect the widely available energy from lighting inside buildings, using indoor photovoltaics (IPV). Current IPV based on hydrogenated amorphous silicon have poor efficiency.

12 Mg Magnesium

Development of strong, formable, stainless and low-cost magnesium alloys for next generation cars

£1.2m 2020-2022 Innovate UK

Developing new routes of alloy design, simultaneously developing innovative manufacturing processes, thereby producing strong, formable, stainless and low-cost Mg alloys.

31 Ga Gallium

EPSRC Manufacturing Fellowship in Gallium Nitride

£1.1m 2017-2022 Engineering and Physical Sciences Research Council

Research into the manufacturing process for gallium nitride device layers onto silicon wafers, for use in e.g., LEDs, power electronics.

51 Sb Antimony 49 In Indium

EPSRC Engineering Fellowships for Growth: Narrow Band-gap Semiconductors for Integrated Sensing and Communications

£1.0m 2014-2018 Engineering and Physical Sciences Research Council

Research to create the core technology for fabricating narrow-band gap semiconductors to perform without cooling, for use in sensor applications and others e.g., mobile communications and renewable energy.

52 Te Tellurium

Electrodeposited 2D Transition Metal Dichalcogenides on graphene: a novel route towards scalable flexible electronics

£1.0m 2022-2024 Engineering and Physical Sciences Research Council

Work to take advantage of recent breakthroughs in electrodeposition of few layer 2D chalcogenides (ME2, where M is a transition metal and E is sulphur selenium or tellurium), which could be used in flexible electronic devices.

3.3 Academic led social science programmes (£37m)

GCRF Trade, Development and the Environment Hub

£18.2 million 2019-2024 Innovate UK

The Hub aims to help make sustainable trade a positive force in the world. It focuses on the impact of the trade of specific goods, and on seeking solutions to these impacts, and trades where there is potential to have a major impact on biodiversity, as well as those that are important for local livelihoods.

Centre for Climate Change and Social Transformations

£7.7m 2019-2024 Economic and Social Research Council

Collaboration between the Universities of Cardiff, East Anglia, Manchester, York and Bath and the charity Climate Outreach. Conducting research into material consumption, diet mobility and thermal comfort across society.

Centre for Understanding Sustainable Prosperity

£6.1m 2016-2025 Economic and Social Research Council

The Centre for the Understanding of Sustainable Prosperity (CUSP) is a cutting-edge research organisation core-funded by the UK's Economic and Social Research Council and the Laudes Foundation. Directed by Prof Tim Jackson at the University of Surrey, it takes the form of a rich international network, drawing together expert partners from academic and non-academic institutions as co-producers of the work programme.

The overall research question is: What can prosperity possibly mean in a world of environmental, social and economic limits? The CUSP works with people, policy and business to address this question, developing pragmatic steps towards a shared and lasting prosperity.

Relevant projects and themes to critical minerals are:

- Informed mining: risk reduction through enhanced public and institutional risk awareness
- Sustainability Transformations in Artisanal and small-scale gold mining: a multi-actor and trans-regional perspective
- Reconfiguring livelihoods, re-imagining spaces of transboundary resource management: a study of mining and agency along the Zimbabwe-Mozambique border
- The legal cultures of the subsoil: the judicialization of environmental politics in central America
- Theme: Investing in the future

Advancing Capacity for Climate and Environmental Science (ACCESS)

£5m 2022- 2027 Economic and Social Research Council

An ESRC investment building capacity in environmental social science to improve interdisciplinary working and effectiveness in engaging in policy, business and civil society.

3.4 Business led programmes and projects (£0.95bn)

The following programmes and projects are relevant to application categories that require the use of critical minerals. Most of the funding deployed through these programmes has not been targeted at mitigating mineral criticality, however they have built up and coordinated a significant amount of expertise and capability that could be directed towards criticality mitigation in the future.

3.4.1 Challenge led programmes from UKRI (£0.90bn)

Faraday Battery Challenge

£541m 2017-2025

The FBC has and is investing in research and innovation projects, and facilities, to drive the growth of a strong battery business in the UK. It aims to develop battery technologies that are cost-effective, high performing, longer range, faster charging, long-lasting, safe and sustainable. The FBC funded the Faraday Institute, as outlined in section 3.2. The FBC also invested in the UK Battery Industrialisation Centre.

Medicines Manufacturing

£360m 2017-2022

The Medicines Manufacturing Challenge Fund was established in 2017 to support and grow the UK's capabilities in manufacturing medicines. £360 million has been invested in developing first-of-a-kind technologies to manufacture medicines and accelerate patient access to new drugs and treatments, firmly establishing the UK as a leading global hub for the development, production and delivery of cutting-edge therapies.

Driving the Electric Revolution

£80m 2018-2022

This challenge is investing £80 million in electrification technologies including power electronics, electric machines and drives (PEMD). The investment will support the UK's push towards a net-zero carbon economy and contribute to the development of clean technology supply chains, worth £80 billion in gross domestic product by 2050. The challenge will focus on growing the UK's PEMD supply chains and manufacturing capability through three areas of activity:

Industrialisation centres (see Academic-led application specific section)

It has invested £33 million to create a network of regional centres, based at existing areas of expertise in Strathclyde, Sunderland, Nottingham and Newport. The centres will be used by industry and researchers to develop and scale up PEMD technologies and manufacturing processes.

Collaborative innovation funding

A further £33 million has been invested in collaborative, industry-led innovation projects that will help businesses grow strategically important UK PEMD supply chains and develop manufacturing capability. These projects will enable UK to deliver the next generation of PEMD technologies across nine key sectors undergoing accelerated electrification.

Talent and skill development

There is an investment of up to £6 million to support skills and provide training at all levels. This will up-skill and grow the workforce into a high-tech industry at the heart of a green UK economy. There will also be opportunities for people of all ages and backgrounds.

Transforming Foundation Industries

£66m 2020-2024

Innovate UK Engineering and Physical Sciences Research Council

The UK's foundation industries are vital for its manufacturing and construction sectors. The foundation industries are: cement, metals, glass, paper, ceramics, chemicals.

The challenge aims to transform the UK's foundation industries by: making them internationally competitive, securing more jobs throughout the UK, growing the sector by 2024 in an environmentally sustainable way.

3.4.2 IUK funded programmes and projects (£69m)

Some of the following projects have been funded under the large-scale programmes documented in previous sections (e.g., TFI, FBC and DER).

REE

CLIMATES (Circular Critical Material Supply Chains) programme

£15m 2023-2025

The Circular Critical Materials Supply Chains programme will support collaborative research and development projects, feasibility studies and Innovation Exchange challenges with the aim of building cross sector partnerships and establishing resilient supply chains. The programme has 4 focus areas:

- Extraction & processing: Novel and sustainable mining processes, mid-stream processes and routes to rare earth alloys.
- Magnet manufacture: Sustainable manufacturing routes to high-performance magnets, increased specification of high-performance magnets.
- Circular economy: Collection and sorting of REE-containing products, sustainable routes for processing recovered rare earth materials.
- Alternatives: Novel materials for high-performance magnets, rare earth substitution in high-performance magnets.

3 Li Lithium

High Power Lithium Storage Device (HP-LiSD)

£12.1m 2017-2021

Project to develop a High-Power Lithium Storage Device (HP-LiSD), with a modular design and at least 5kW/kg, compared to 1-2 kW/kg for the best hybrid lithium-ion batteries today.

14 Si Silicon

ESCAPE - End-to-end Supply Chain development for Automotive Power Electronics

£9.7m 2019-2024

Project to bring together industrial leaders and pioneers from across the supply chain to work as a single coherent team to kickstart the manufacture of high value electric vehicle components and capture value in the UK.

14 Si Silicon
6 C Graphite

SUNRISE (Synthomer UCL Nexeon Rapid Improvement in the Storage of Energy)

£7.0m 2018-2021 Innovate UK

Project to deliver a novel silicon anode material for advanced lithium-ion batteries, utilising new infrastructure in the National Battery Manufacturing Development Facility to have built batches of automotive Li-ion cells for testing in conjunction with direct material sampling to automotive OEMs and leading cell manufacturers.

3 Li Lithium

Lithium Sulfur: Future Automotive Battery (LiS:FAB)

£4.4m 2018-2021 Innovate UK

Project to develop a next generation lithium sulfide (LiS) cell and module that is suitable for large electric vehicles such as trucks and buses.

14 Si Silicon

Silicon Product Improvement via Coating Enhancement (SPICE)

£2.6m 2019-2021 Innovate UK

Project to establish an effective, repeatable and scalable carbon-coating process for next-gen silicon anodes materials that will improve the current performance of lithium-Ion batteries, and hence accelerate the adoption of Nexeon anode materials by cell manufacturers and at major OEMs, via an 18 month 3.3m project utilizing PSI's scaled process know-how, AGM's cell fabrication expertise and Oxford University's analytical capabilities.

31 Ga Gallium

P3EP UK Supply Chain Project

£2.5m 2022-2024 Innovate UK

Project to develop a UK supply chain for printed circuit board (PCB)-embedded power systems with Gallium Nitride (GaN) devices.

REE

SCREAM – Secure Critical Rare Earth Magnets for the UK

£2.4m 2022-2025 Innovate UK

The aim of SCREAM is to provide a UK based supply of REEs by recycling magnets from end-of-life scrap (EoL). HyProMag, Mkango Rare Earths UK, GKN Hybrid Power, European Metal Recycling (EMR), Jaguar Land Rover (JLR), Bowers and Wilkins and the University of Birmingham (UoB) will work together in the SCREAM project to secure critical permanent magnets for the UK.

27 Co Cobalt | 3 Li Lithium | 28 Ni Nickel

CALIBRE - Custom Automotive Lithium-Ion Battery Recycling

£2.2m | 2018-2021 | Innovate UK

Project to demonstrate a scalable battery recycling process that will lead to the UK being the primary batter recycling hub in Europe, involving assessment of end-of-life packs, disassembly, recycling methodologies, and reuse of recovered material.

3 Li Lithium

Trelavour Hard Rock Lithium Demonstration Plant

£2.0m | 2022-2024 | Innovate UK

Project to develop a demonstration scale lithium extraction plant at Cornish Lithium's Trelavour Project in Cornwall using patented technology licensed from Australian company Lepidico. The process uses water-based chemistry to remove lithium and other metals from rock to produce battery grade lithium hydroxide and other critical metals.

3 Li Lithium

BritLit: British Lithium Production

£2.0m | 2022-2024 | Innovate UK

Project to accelerate through validation of processes the scale-up of lithium production from pilot-scale, to a planned £446M quarry/refinery producing 20,800tpa LCE, meeting one-third of projected UK lithium requirements.

3 Li Lithium

VALUABLE: VALUe chain And Battery Lifecycle Exploitation

£2.0m | 2018-2021 | Innovate UK

Project to develop commercially viable metrology and test processes as well as new supply chain concepts for recycling, reuse and remanufacturing of automotive lithium-ion batteries to create a complete End-of-Life (EoL) supply chain network within the UK.

REE

RaRE – Rare-Earth Recycling for E-Machines

£1.9m 2020-2023

RaRE will establish an end-to-end supply chain for recycled rare-earth ancillary motors. Building on work completed at the University of Birmingham to devise a method to extract magnets from waste electronics the process will be scaled, and the material re-processed back into new magnetic materials at pilot scale by Hypromag to demonstrate the quality of material which can be produced in terms of its magnetic behaviour, mechanical performance and corrosion resistance which are key to the end user application. The recycled magnets will be built into an ancillary electric motor designed by Advanced Electric Machines Research to a Bentley Motors specification and focused on reducing the overall complexity of electrical systems in electric vehicles and designed with recycling in mind. This will be the first time that such a recycled motor will have been demonstrated. Unipart will take this motor design and use it as the core focus for the design of a flexible volume motor assembly line suitable for production volumes of 100,000 units p.a.

REE

A demonstration scale magnet recycling plant towards securing the UK supply of critical rare earth metals for EV manufacture

£1.6m 2022-2024

Seren (now Ionic Technologies) has developed a rare earth separation and purification technology – based on the use of ionic liquids - for the recovery of rare earths from magnets. The company has developed the technology and progressed through research and development, and techno-economic qualification. The next step for the company is to embark on construction and operation of a demonstration plant to (a) provide large-scale samples for customer qualification and (b) to de-risk the technology to secure investment for construction of a full-scale plant.

28 Ni Nickel

Development of 1 kWh sodium nickel chloride battery system and associated manufacturing processes

£1.2m 2021-2022

Project to demonstrate an innovative sodium-nickel-chloride (NaNiCl2) prototype system to TRL6 in representative automotive-sector conditions.

3 Li Lithium | 27 Co Cobalt | 28 Ni Nickel

Pilot demonstration of a novel extraction process to recover critical metals from end-of-life Li-ion batteries for immediate entry into electric vehicle battery supply chain

£1.0m | 2022-2024 | Innovate UK

Project to address challenges with a novel, highly efficient process to extract nickel, cobalt and lithium from end-of-life vehicle lithium-ion batteries in a quality and format that can be directly reused in battery manufacture.

6 C Graphite

UK-Anode: creating a graphite anode supply chain for the UK automotive Li-ion battery industry

£1.0m | 2020-2021 | Innovate UK

Project to assess the feasibility of establishing commercial-scale production of a (r)-C anode material in the UK using the graphite concentrate from Sweden and serving upcoming local demand.

31 Ga Gallium

Recovery of Gallium from Ionic Liquids (ReGaIL)

£0.27m | 2020-2021 | Innovate UK

An Innovate UK investment to develop a recovery process of Gallium from bulk sourced end-of-life (EoL) LEDs, to supply the uptake of Gallium Nitride (GaN) semiconductors in power electronics, machines, and drives.

MineLoop

£0.07m | 2022-2023 | Innovate UK

Integrating high-resolution circular economy metrics within life cycle assessment software to drive resource circulation and reduce criticality of key technology metal.

41 Nb Niobium

Circular Niobium

£0.07m | 2022-2023 | Innovate UK

A feasibility study to assess the economic, technical and environmental opportunity to develop a value chain for the recycling of niobium products.

3 Li Lithium | 25 Mn Manganese | 27 Co Cobalt | 28 Ni Nickel

ULTRAsound-assisted recycling of Lithium and Critical metals from spent lithium-ion batteries (ULTRALiC)

£0.07m | 2022-2023 | Innovate UK

Project to develop recycling technology to recover valuable metals from spent lithium-ion batteries without shredding.

3.5 Catapults & Innovation Centres

The catapult centres are physical entities that support SMEs through innovation, scale up and commercialisation projects. Most were created in the period post-2010. The catapults contain a significant amount of in-house expertise and physical capabilities including research, testing, pilot and scale up facilities across a broad range of science domains and industry sectors. There are also a number of innovation centres that perform a similar role.

The Catapults and Innovation Centres included here will have performed some research relevant to critical minerals and/or criticality mitigation, and contain significant expertise and capability (across multiple application categories) that can be called upon for future criticality mitigation research.

3.5.1 High Value Manufacturing Catapult (HVMC)

The HVMC is composed of multiple centres, located across the UK:

CPI

CPI acts as a catalyst bringing together academia, businesses, government and investors to translate bright ideas and research into the marketplace. They do this by giving our customers access to the right experts, equipment, networks, funding and more – connecting the dots for effective innovation.

CPI operates in sectors such as AgriFoodTech, Energy, HealthTech, Materials and Pharma, with capabilities spanning process chemistry, formulation, industrial biotechnology, photonics, electronics and digital.

Warwick Manufacturing Group (WMG)

WMG is based at the University of Warwick. They conduct research programmes with industrial partners in areas such as intelligent vehicles, digital technologies, energy and materials and manufacturing.

National Composites Centre (NCC)

The National Composites Centre was created as the UK's Centre of Excellence for Composites Research and Development following the inclusion of this disruptive technology into government industrial strategy. Their mission is to be recognised as a world leader in composite technology, accelerating the development and uptake of digital technologies for sustainable composites and growing the market for composites by driving innovation through collaboration and partnerships.

Advanced Manufacturing Research Centre (AMRC)

The University of Sheffield Advanced Manufacturing Research Centre (AMRC) is a network of world-leading research and innovation centres working with manufacturing companies of any size from around the globe.

The AMRC now employs over 500 highly qualified researchers and engineers from around the globe, on the Advanced Manufacturing Park and Sheffield Business Park in South Yorkshire, as well as in Broughton and Preston. They have 11 core capabilities.

Nuclear AMRC

The Nuclear Advanced Manufacturing Research Centre helps UK companies win work across the nuclear sector – in new build, operations and decommissioning – and in other high-value manufacturing industries. They provide a range of supply chain development support to help manufacturers enter the nuclear market and compete worldwide.

Manufacturing Technology Centre (MTC)

The MTC was established in 2010 as an independent Research & Technology Organisation (RTO) with the objective of bridging the gap between academia and industry – often referred to as 'the valley of death'. It represents one of the largest public sector investments in UK manufacturing and, after four years of planning and a 16-month build, the facility opened at Ansty Park in Coventry at the end of 2011. In December 2011, there were 16 industrial members, 44 staff and just a few key pieces of equipment in the 'workshop'. Over the following seven years the MTC's rapid growth has seen the expansion of the campus with the construction of three more facilities, including the opening of the Advanced Manufacturing Training Centre and the National Centre for Additive Manufacturing. Their role has also increased to cover not only R&D but also Training, Advanced Manufacturing Management and Factory Design.

National Manufacturing Institute Scotland (NMIS)

The National Manufacturing Institute Scotland (NMIS) is a group of industry-led manufacturing research and development facilities with a network of Partners across Scotland brought together to boost the manufacturing community, based at the University of Strathclyde. NMIS is composed of the Advanced Forming Research Centre (AFRC), the Digital Process Manufacturing Facility, the Lightweight Manufacturing Centre, and the Manufacturing Skills Academy.

3.5.2 Offshore Renewable Energy Catapult (OREC)

OREC is the UK's leading technology innovation and research centre for offshore renewable energy. OREC plays a key role in delivering the UK's net zero targets by accelerating the creation and growth of UK companies in the offshore renewable energy sector. OREC uses their unique facilities and research and engineering capabilities to bring together industry and academia and drive innovation in renewable energy.

3.5.3 Compound Semiconductor Applications Catapult

The CSA Catapult was established to help the UK become a global leader in compound semiconductors through collaboration with both large companies, and start-ups to develop and commercialise new applications utilising this technology. They have expertise in areas such as Power Electronics, RF & Microwave, Photonics and Advanced Packaging.

In addition to the catapult centres, there are several innovation centres across the UK that also support SMEs and industry with innovation, scale-up and commercialisation projects.

3.6 Innovation Centres

3.6.1 Materials Innovation Factory (MIF)

The MIF is a purpose-build facility hosted by the University of Liverpool which focusses on the application of computational, automation and robotic technologies to chemical synthesis, material fabrication and formulation development. The MIF works with companies to design and scale new automated experimentation platforms and apply them to new chemical product development across multiple sectors including agritech, FMCG, and pharma.

3.6.2 STFC Hartree

The Hartree Centre helps UK businesses and organisations of any size to explore and adopt supercomputing, data science and artificial intelligence (AI) technologies for enhanced productivity, smarter innovation and economic growth. Backed by significant UK government funding and strategic partnerships with industry leaders such as IBM, Atos and the University of Liverpool, the Hartree Centre is home to some of the most advanced digital technologies and experts in the UK.

Their experts collaborate with industry and the research community to explore the latest technologies, upskill teams, and apply practical digital solutions to individual and industry-wide challenges for societal and economic benefit.

The Hartree Centre is part of the Science and Technology Facilities Council (STFC) – one of Europe's largest multidisciplinary scientific research organisations – within UK Research and Innovation, building on a wealth of established scientific heritage and a network of international expertise.

3.6.3 DSTL

Dstl is an executive agency of the Ministry of Defence (MOD) providing world class expertise and delivering cutting-edge science and technology for the benefit of the nation and allies. DSTL's responsibilities include:

- supplying sensitive and specialist science and technology services for MOD and wider government
- providing and facilitating expert advice, analysis and assurance on defence procurement
- leading on the MOD's science and technology programme
- understanding risks and opportunities through horizon-scanning
- acting as a trusted interface between MOD, wider government, the private sector and academia to provide science and technology support to military operations by the UK and her allies
- championing and developing science and technology skills across MOD
- international work such as coordinating the UK's involvement in NATO science and technology activity

3.6.4 Industrial Biotechnology Innovation Centre (IBioIC)

IBioIC was established in 2014 to fulfil the aims of the National Plan for Industrial Biotechnology to grow the industrial biotechnology sector in Scotland to over £900 million in turnover, with over 200 companies operating in the sector by 2025. IBioIC is a networking and support organisation that connects industry, academia and government to bring biotechnology processes and products to the global market. They do this by offering scale-up facilities, talent development, funding provision, and promotion of Scotland's unique assets.

3.6.5 Map of centres across applications

	Catalysis	Alloys	Med/Pharma	Electronics	Magnetics	Coatings/additives	Energy storage	Adv materials	Industrial	Agriculture	Food	Nuclear	Consumer
CPI	●		●	●	●	●	●	●	●	●	●		●
WMG		●		●	●		●	●	●				
NCC								●					
AMRC		●							●				
NAMRC		●						●	●			●	
MTC		●	●				●		●		●		
NMIS		●							●				
OREC					●			●					
CSA				●					●				
MIF	●		●			●		●			●		●
STFC Hartree	●		●	●		●	●	●					
DSTL								●				●	
IBioIC			●					●		●	●		●

3.7 Public sector organisations

3.7.1 Critical Minerals Intelligence Centre (CMIC)

CMIC is run by the British Geological Survey (BGS) and was established in 2022 following the launch of the UK Critical Minerals Strategy. Its purpose is to commission and provide research and intelligence on critical minerals to the scientific and industrial community in the UK. Reports produced to date include:

- Activities Related to Raw Materials Standards and Resource Management
- Battery Minerals Report
- Good Practice and Recommendations for Securing Supply of Critical Raw Materials
- UK Critical Minerals List 2021
- The Geological Potential of the UK for Battery Minerals (Lithium, Nickel, Cobalt, and Graphite)

3.7.2 Innovate UK KTN

Innovate UK KTN is the knowledge transfer arm of Innovate UK. Innovate UK KTN has been involved in several projects related to critical minerals in the recent past:

SCREEN and SCREEN2

SCREEN and the continuation SCREEN2 are pan-European projects creating and managing an expert network in critical raw materials (CRMs) to produce and update factsheets pertinent to the EUs CRM list. The project also advocates for improved policy making to ensure the supply of CRMs to the EU over the long term.

Global Expert Missions (GEMs)

GEMs are operated as part of Innovate UK's international activities. GEMs involve a UK delegation making a trip overseas to potential partner countries on topics of importance. A recent GEM was conducted with Canada and the USA on critical materials in May 2022 (report and outcomes here).

3.7.3 Parliamentary Office for Science and Technology (POST)

POST produces analysis and reports on key issues to inform lawmakers, called POSTNotes. Relevant POSTNotes for critical minerals include the following:

- POSTNote: Mining and the sustainability of metals
- POSTNote: Access to critical materials
- POSTNote: Meaningful environmental and social governance reporting for Net Zero
- POSTNote: Regulating product sustainability
- POSTNote: Supply of medical radioisotopes
- POSTNote: Biological solutions for environmental challenges

3.7.4 Zero Waste Scotland

ZWS conducts research and innovation projects to deliver the circular economy in Scotland, from focussing on food waste, energy use and material resource efficiency and recycling approaches. Recent work on areas relevant to critical minerals includes:

- ZWS Battery Report
- ZWS Offshore Wind Decommissioning report (in conjunction with OREC)

3.8 Community organisations and trade bodies

3.8.1 Royal Society of Chemistry (RSC)

The RSC is the UK's professional body for chemistry, that draws on the expertise of its members to produce analysis and reports on key issues facing the country where chemistry can play an important role. The RSC also publishes peer-reviewed research in its many journals, as well as providing support for its members through networking (between academia and industry), funding and advocacy. Relevant work for critical minerals includes:

- Recovering the critical raw materials in batteries
- CRMS in WEEE
- Review of Net Zero
- Decarbonisation: materials and circularity challenges for clean technologies. The role of CRMs in reaching net-zero emission

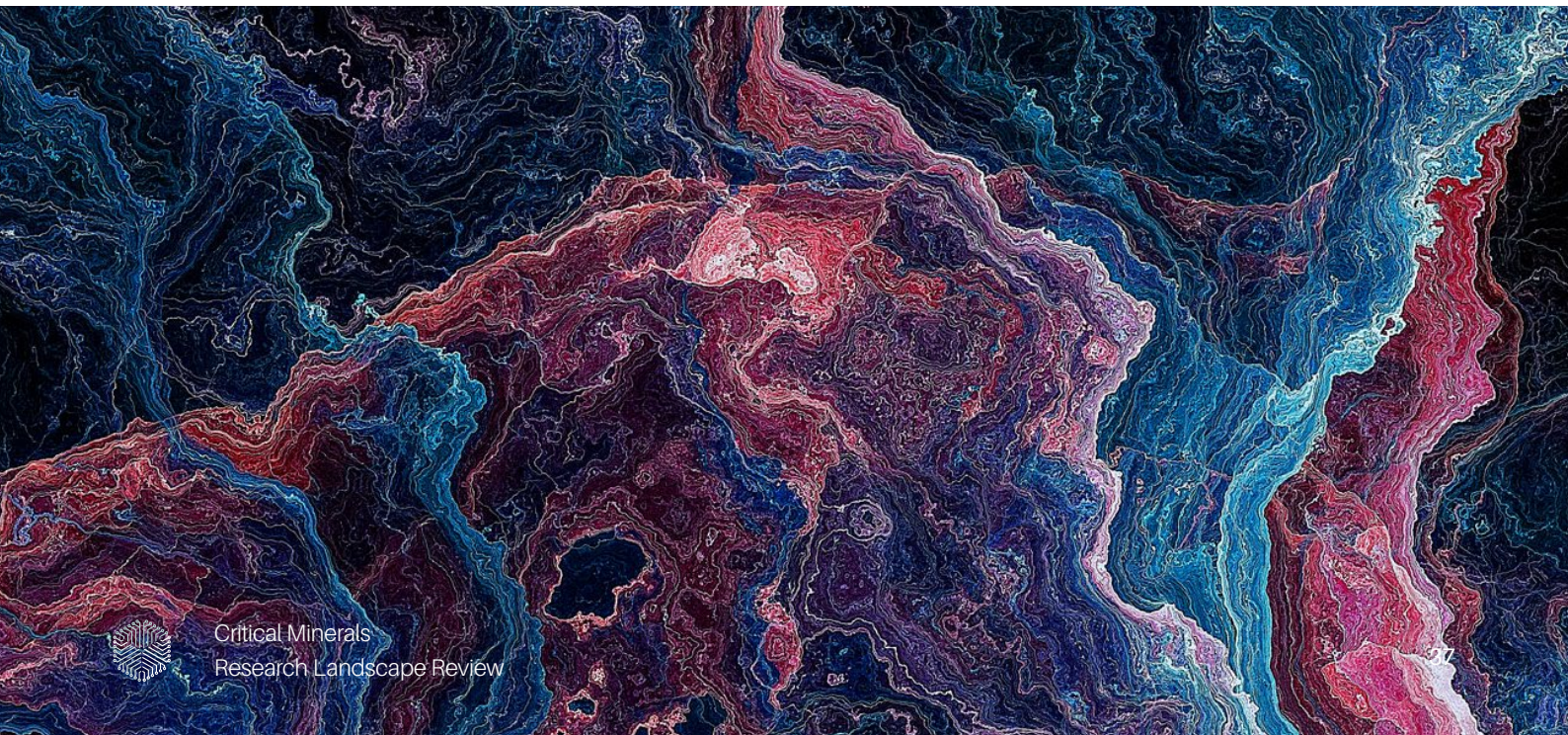
3.8.2 Critical Minerals Association (CMA)

The CMA is the UK's industry association for companies involved in critical mineral supply chains. They have written several reports into key aspects of critical minerals supply chains:

- A Talent Pipeline for Critical Minerals
- UK Planning & Permitting for Critical Minerals
- Mineral Rights – England, Scotland, Wales. Unlocking Great Britain's Potential
- Midstream processing and refining: Unlocking security of supply

3.8.3 IOM3

The Institute of Materials, Minerals and Mining (IOM3) is a professional engineering, environmental and scientific institution, a registered charity and governed by a Royal Charter. IOM3 supports professionals in materials, minerals, mining and associated technical disciplines to be champions of the transition to a low-carbon, resilient & resource efficient society. It seeks to be the best professional membership body it can be by providing modern, flexible services; quality technical content; and value for money.

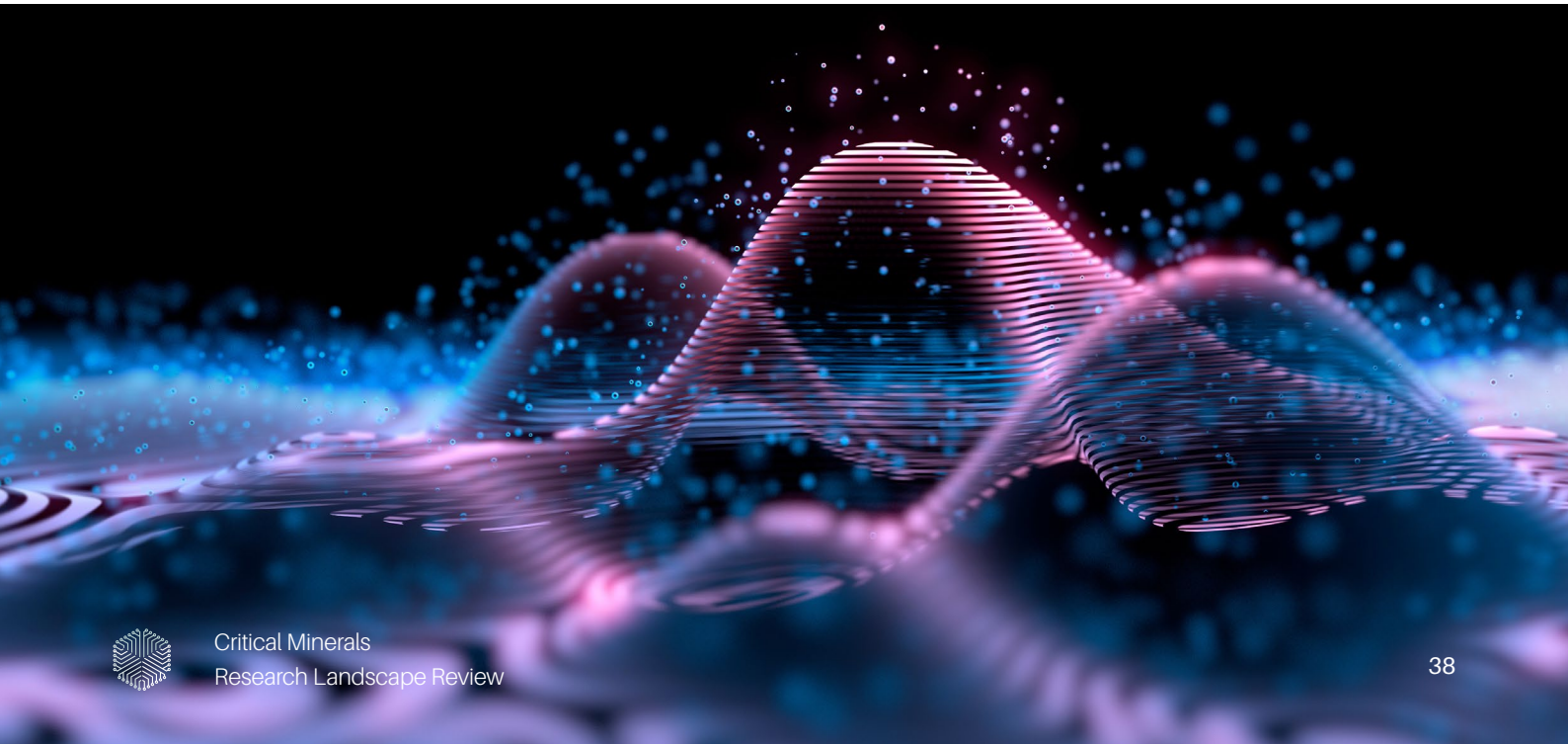


4.0 Analysis

4.1 Projects directly relevant to critical minerals

Caveat: The analysis and discussion given in the following section is based on the data set outlined in the results section, which is not necessarily the complete picture as projects funded by an amount less than £1m have largely been excluded. The discussion points and conclusions should be read with this in mind, however they can be built upon and refined through future work by including more data.

Where projects are tagged with multiple elements or supply chain segments, these amounts have been split equally between them.



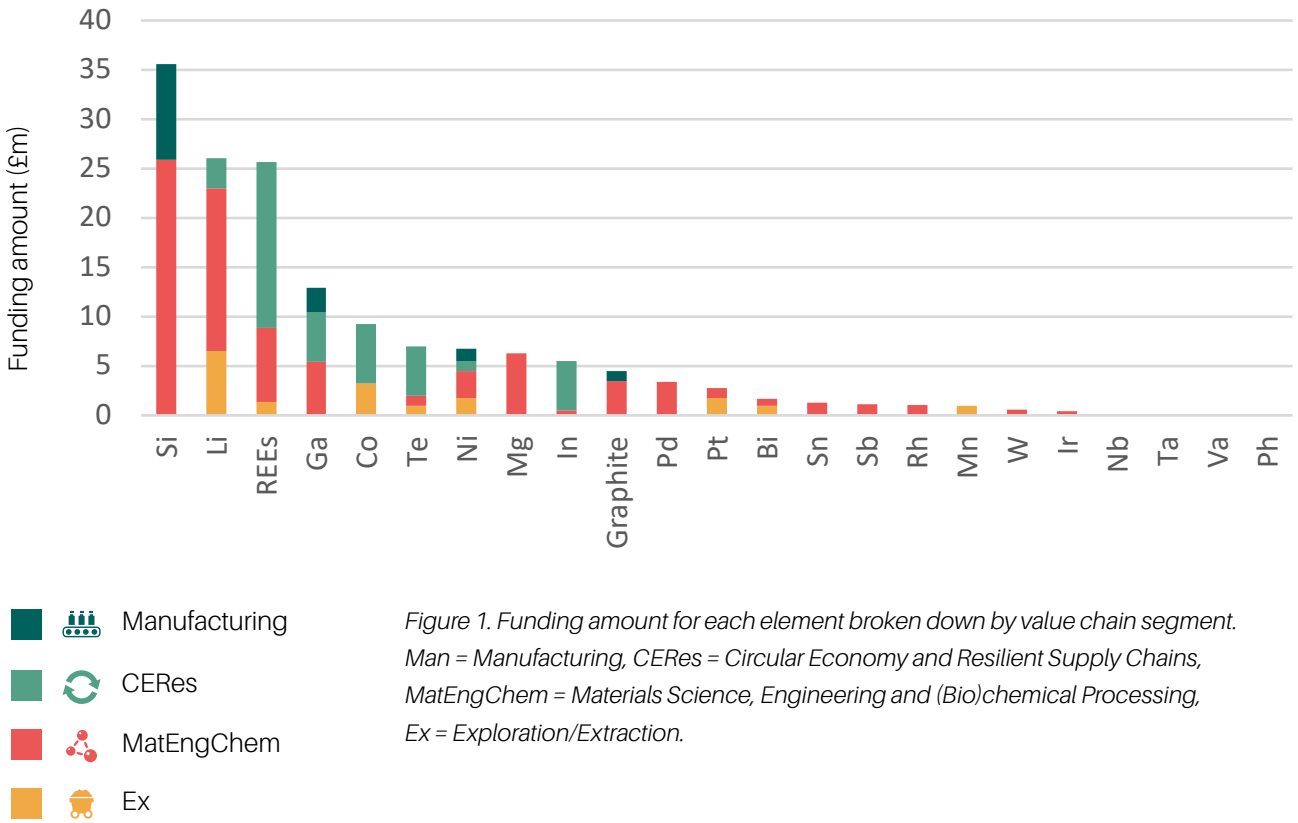


Figure 1. Funding amount for each element broken down by value chain segment. Man = Manufacturing, CERes = Circular Economy and Resilient Supply Chains, MatEngChem = Materials Science, Engineering and (Bio)chemical Processing, Ex = Exploration/Extraction.

Figure 1 shows the funding amount for each of the 23 elements, ranked by the total amount of funding received through projects that have been identified as directly relevant to them (i.e., that have received individual element tags in the results section). This provides an insight into the level of targeted funding across the elements in the timescale of this review. Silicon, Lithium and REEs feature in the top 3, with other battery minerals Cobalt, Nickel and Graphite also featuring within the top 10. Most of the watchlist minerals are located towards the bottom of this ranking, which is to be expected.

The data in Figure 1 is also broken down by value chain segment. Materials Science features strongly across the elements that have received targeted funding, with exploration/extraction also featuring for just less than half of the elements. Circular economy projects are a large part of the funding for the elements that have received the most (e.g., REEs, Li, Ga, Co). Projects pertaining to manufacturing processes are less prominent, but this is probably because funding towards manufacturing activities tend not to be critical mineral specific, but instead technology specific.

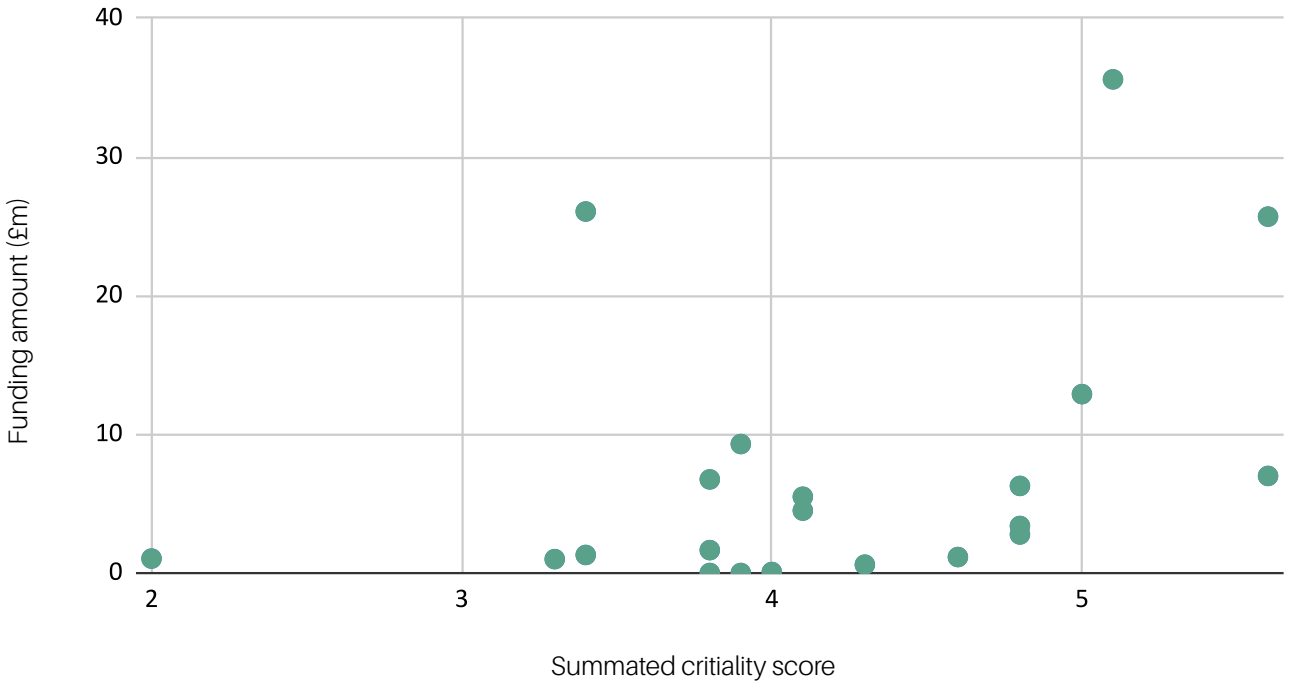


Figure 2. Funding amount plotted against the elements' summated criticality score.

Figure 2 shows the total funding amounts plotted against the elements' summated criticality scores, as given in the UK criticality assessment of 2022. This analysis gives an insight as to whether the targeted projects have been, or are being, targeted towards the most critical elements. The biggest funding amounts do appear to be targeted at the elements with the highest criticality scores, with the exception of Nickel, which seems to be overfunded relative to its score, however this is explainable due to Nickel's use as a battery material, and the level of focus given to battery technology across the UK research and innovation landscape. A simple correlation calculation (Pearson's correlation coefficient) gives a value of 0.39, indicating much room for improvement in terms of targeting the funding at the most critical elements.

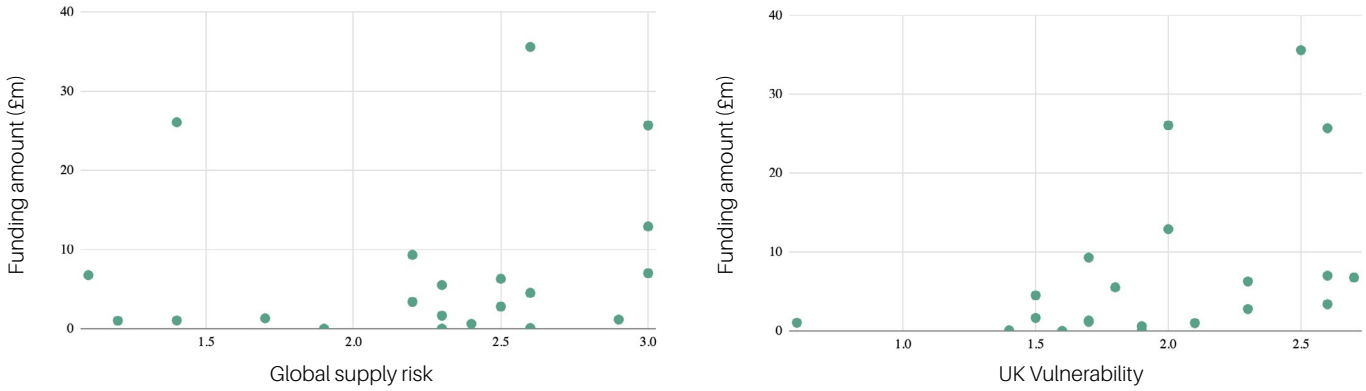


Figure 3: Total funding amounts plotted against the disaggregated criticality scores, Global Supply Risk (left) and UK Vulnerability (right).

Figure 3 shows the total funding amounts plotted against the disaggregated criticality scores (Global Supply Risk, and UK Vulnerability) as given in the UK criticality assessment of 2022.

This gives an insight as to which of these factors has played a bigger (implicit) role in the targeting of the funding. The correlation coefficient of the data plotted against Global Supply Risk is 0.17, and UK Vulnerability is 0.44. This suggests that, up to this point, the UK vulnerability to particular elements played a bigger role in decision making than global factors. Now that a quantitative analysis using both factors is now available, this provides an opportunity to use both sets of information to make innovation funding decisions in the future.

4.2 Funding across categories

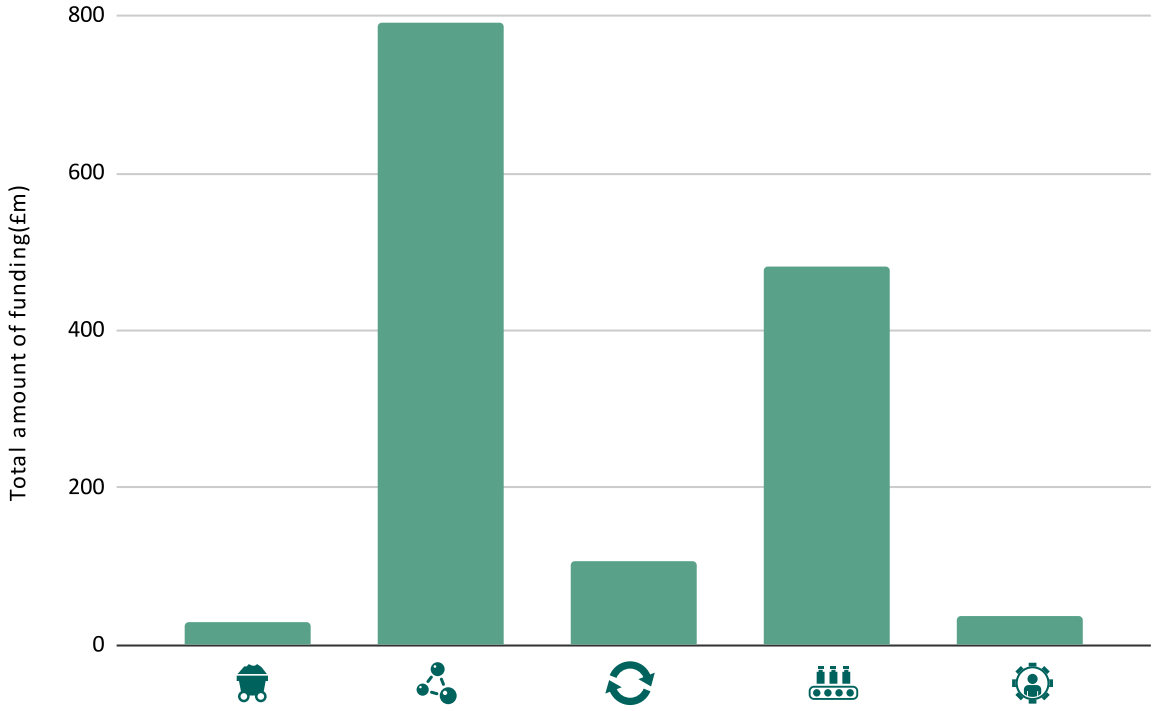


Figure 4. Total funding amounts plotted for each value chain category.

Figure 4 shows the total funding amounts across each value chain category. For the programmes and projects relevant to critical minerals, most of the funding targets Materials Science and Manufacturing, with much smaller amounts for circular economy, extraction research projects and social science. However, some of the funding categorised as Materials Science could play a role in other areas such as Circular Economy and vice versa. Also, Circular Economy has only emerged as a strong theme in the past 5 years, so we would expect the funding in this particular category to rise in the coming years as a matter of course. Extraction research can only be applied to the small amounts of minerals the UK has any potential for domestically.

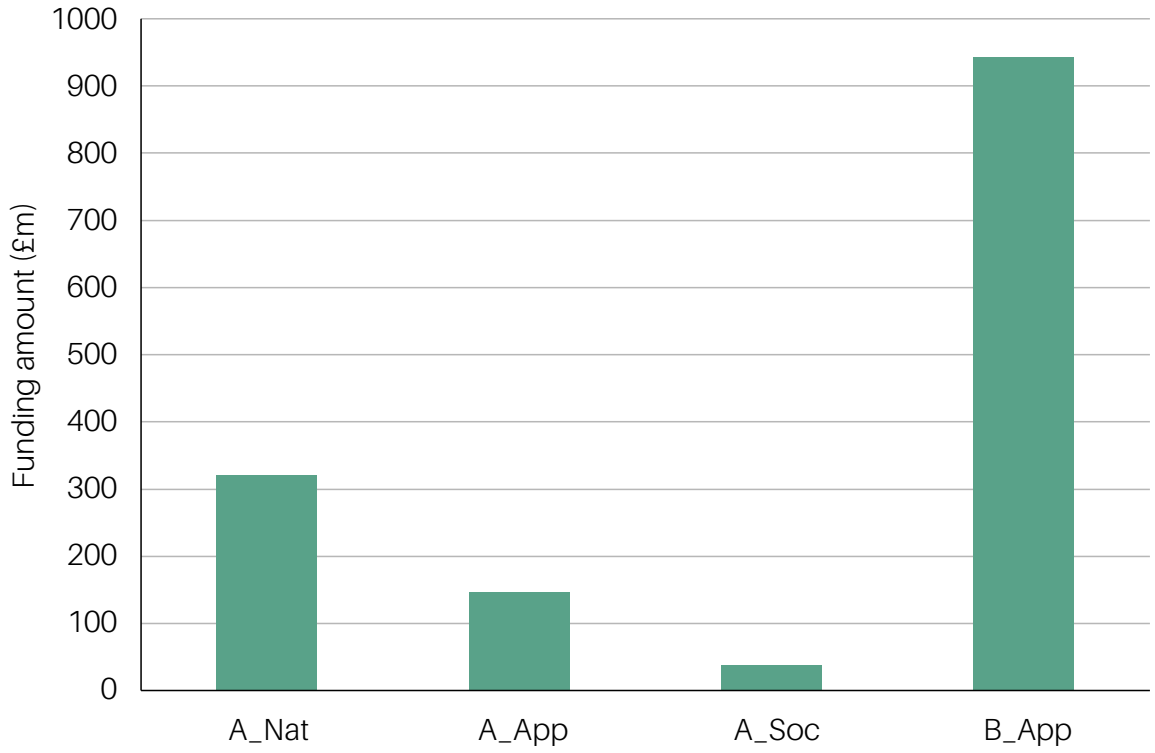


Figure 5. Total funding amounts plotted for each domain area. A = Academic-led, B = business-led. Nat = natural science, App = application-specific, Soc = social science.

Figure 5 shows the total funding amounts across the domain categories. The biggest proportion of funding identified in this review is deployed in business-led application-specific programmes, made up mostly of the ISCF challenge areas. Academic led natural science is funded 2nd most, and application-specific 3rd most, as we would usually expect (academic work tends to focus on low TRL projects). Social science appears to be a relatively underfunded area.

5.0 Discussion

5.1 Size and concentration of funding

- Overall, we have identified £1.45Bn investment in R&D and innovation projects from 2017 onwards
- The biggest investments documented in this report have derived from the UKRI challenge programmes (Faraday, DER, TFI and Medicines, £0.9bn), which are largely business-led investments and are in the natural science domains. However, it should be noted that only a few projects funded under these programmes seek to address underlying issues of criticality or are directly relevant to particular elements or minerals (£153m out of the grand total of £1.45bn documented in this review).
- The big investments through the UKRI challenge programmes have largely focussed on scaling up commercially relevant innovations in specific application areas such as electric vehicle batteries, power electronics machines and drives (PEMD), semiconductors, renewable energy systems, catalysts and consumer products, where larger investments are usually needed to e.g. invest in physical capability (equipment, manufacturing or pilot facilities, etc.) as well as the work needed to scale mid-TRL materials and components manufacturing processes.
- The academic-led investments (approx £0.4bn) have both complemented the UKRI challenge programme priorities (Faraday, DER industrialisation centres) and targeted adjacent priority areas set by other research councils (EPSRC, BBSRC, NERC etc.) such as catalysis, exploration and extraction research, fundamental advanced materials R&D, green chemistry, sustainability and circular economy (e.g. NICER, BGS research, CUSP, Catalysis Hub, Resource Recovery From Waste, Digital Navigation of Chemical Space for Function).

- Overall, strong investment is made into Materials Science, Engineering and (Bio)Chemical processing part of the value chain (£0.79bn), with some investment in Manufacturing (£0.48bn) and Circular Economy (£0.11bn), and little in exploration/extraction (£0.03bn) (Figure 4). This is perhaps illustrative of the relatively small role domestic extraction is predicted to play in supply chain resilience. Investment is also focussed on application areas that the UK has previously prioritised (e.g., via UKRI challenge programmes), and where the market opportunity is well-defined (batteries for EVs, semiconductors for communication and power electronics).

- Elements with a summated criticality score of less than 4.5 (Table 2), which definitely cannot be regarded as low criticality, have received very little targeted funding (Nickel being an exception due its role in batteries). Some of the critical minerals do not feature at all specifically in the data – Ta, Va and Ph. This could be because of the £1m project size limit on the data acquisition, or it could indicate a lack of focus on these particular elements. Ta and Va are both used in alloys, Va in catalysts, coatings and energy storage, Ta in med/pharma, electronics and advanced materials. Phosphates are used in agriculture, industrial, food and consumer goods. Although there are programmes that cover these areas, perhaps the criticality of these elements is underappreciated.

- There is potentially an underfunding of integrated natural science and social science programmes for critical minerals. This is concerning given the important social issues to address in this area, such as increasing public awareness and acceptance of mining activities at home and abroad to address our sustainability and net zero goals, public engagement on the impact of mining on local communities and inspiring young people to see mining, natural science and engineering and manufacturing as attractive careers paths.

- Circular economy and supply chain resilience also appears relatively underfunded, as standalone programmes. The level of funding may be underestimated due to CE-relevant projects or considerations being buried within the other major programmes. This raises a question of the best approach for realising the circular economy and building resilience of supply chains – targeted funding programmes aimed at these objectives, or a reorganisation of e.g., application-specific programmes to include large CE components? Whole system approaches are needed to examine in detail the complex supply chains of critical minerals to determine appropriate interventions to achieve a circular economy and secure responsible and resilient critical mineral supply chains for the benefit of multiple stakeholders, the environment, and the economy.

- Few projects are directly relevant to particular critical minerals. Of the ones which are, most funding is given to those with higher criticality scores, however the degree of criticality is a weak correlating factor between funding and target mineral. Breaking criticality down into its component parts, Global Supply Risk and UK Vulnerability, we see that UK vulnerability has played a bigger role so far in the correlation between funding amount and degree of criticality. There is also a strong correlation between funding for particular minerals and their use in applications that are deemed critical to the UK economy by other prioritisation methods (e.g., UKRI challenge programmes).

- Recently, investment has started to migrate towards critical minerals and supply chains research as a specific focus area, through e.g., IUK CLIMATES, IUK KTN GEMs, work at the NICER centre, HVMC activity and work commissioned and run by CMIC. These programmes are centrally driven by the assessments of criticality and the impact on UK manufacturing and supply chain resilience, with the emergence of rare earth elements and battery minerals, due to their previous determination as strategic priority areas for the UK, across these and other programmes. Programmes and projects that are relevant to the other critical minerals only contain indirect aspects of criticality mitigation, through work to replace expensive or problematic elements in e.g., alloys, semiconductors, catalysts and energy storage systems.

5.2 UK Strengths

Looking at the range of funded programmes and projects (both academic and business-led, and the map of physical centres, RTOs, and catapults, some key strengths emerge.

- Application area strengths: Batteries, semiconductors, metals/alloys, catalysis, PEMD, coatings/additives, medicines manufacturing and advanced materials. Strengths in materials science and manufacturing innovation across these application areas.
- These strengths are expressed through investments in enabling technology infrastructure, e.g. Royce, MIF, HVMC, Catalysis hub, CSA, STFC Hartree. Prioritisation has largely been driven by UKRI challenge programmes. No formal coordination of research infrastructure to tackle criticality challenges until very recently.
- Extraction research for critical minerals appears weak compared to the other categories, however there is a host of capability in the UK that could be deployed, found in the BGS and geoscience departments at UK universities. There is also strong expertise in oil & gas extraction, which could be translated into the mining space.

6.0 Recommendations

- Significant investment into research and innovation is required, on a multidisciplinary basis, to address major challenges around security of supply of critical minerals for the UK economy. Building on previous investments, these new investments should aim to develop appropriate criticality mitigation strategies to increase UK resilience across critical mineral value chains relevant to multiple applications. To provide interdisciplinary solutions that can be easily translated into impact for decision-makers in government and industry, integrated research and innovation is needed across three key areas: (1) responsible raw material acquisition and processing; (2) building resilient, secure and productive supply chains; (3) identifying alternative materials, manufacturing technologies and business models to achieve a circular economy.

- Opportunities for domestic mineral extraction should be maximised through research and innovation in extraction and processing practices.

- Increased global interest in the exploitation of new mining environments for critical minerals (such as ultra-deep subsurface, polar, and submarine), requires the UK to resolve our position on the exploitation of these resources as an alternative or complement to terrestrial sources but investment is needed to improve our scientific and technological understanding of the feasibility, environmental and wider implications of doing so.

- The UK should utilise existing strengths in materials science to redesign materials and components to reduce critical mineral demand by embedding efficiency and long-term sustainability.

- Accelerate investment in circular economy approaches, including mineral recovery processes, to take advantage of mineral stocks already in the UK in waste streams.

- Look at increasing funding of integrated social and natural science to address critical minerals issues that can unlock investment in critical minerals supply chains, such as public perception of mining and the role of critical minerals in meeting net zero and sustainability targets, the need to invest in high-tech skills, and the need to r educe demand of critical mineral-containing products as a mitigation strategy.

- Assessments of criticality should be used directly to inform policy making and funding priorities, but forecasting of future changes in criticality will be necessary to support decision making.

- This review could be built upon to include projects less than £1m to provide more precise information, and be made available in an interactive and "live" format to inform the critical minerals stakeholder community into the future.

This report was commissioned by the Department for Business and Trade and authored by Dr Matthew Reeves, Innovate UK KTN, with support from Dr Sarah Newport and colleagues at NERC and across UKRI and Dr Peter Clark and Dr Sheena Hindocha at Innovate UK KTN.

UK Critical Minerals Intelligence Centre

Contact us

E enquiries@bgs.ac.uk
T +44 (0)115 936 3100

bgs.ac.uk