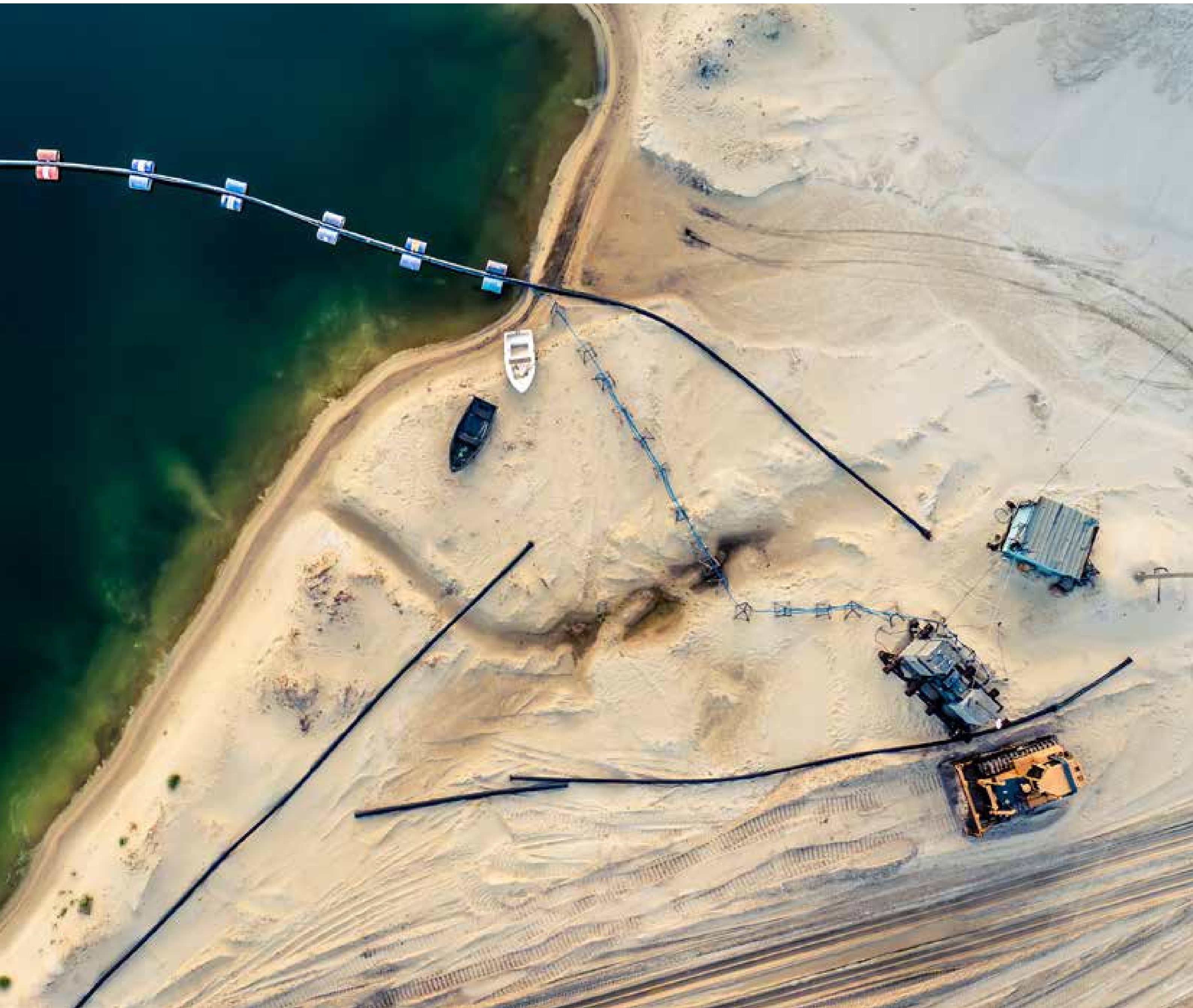
Global Expert Mission **Critical Materials - Canada and US**



Contents

Executive Summary

Innovate UK launched the Global Expert Missions programme in October 2017 to help businesses become truly global enterprises through strategic international innovation collaboration. Delivered by Innovate UK KTN, the missions provide an expert-led evidence base for the UK to be an international partner of choice for science and innovation. The missions strengthen Innovate UK's global investment strategy by creating opportunities for UK business through global partnerships with key economies.

In May 2022, as part of Innovate UK's Global Expert Missions Programme commissioned by the Department for Business, Energy and Industrial Strategy (BEIS) with funding from the Global Research & Innovation Programme (GRIP), a team of UK experts led by Innovate UK KTN visited Canada and the US to improve our understanding of the research and innovation landscape in the field of critical materials. The programme focused on four key areas:

1. Extraction industries and processing.
2. Manufacturing processes and supply chain.
3. Recycling and the circular economy.
4. Policy and innovation.

The UK team, consisting of representatives from Innovate UK, academia and industry, visited several organisations in Canada and the US working on critical material/mineral extraction and processing, new material development and advanced manufacturing.

Canada

Canada has a well-established primary mineral extraction industry alongside a long-term critical minerals strategy, and the government has invested in a number of key research programmes. The Critical Minerals Research, Development and Demonstration (CMRDD) programme aims to scale-up fundamental research to pilot-scale and demonstration projects. In the recent budget, the Canadian government announced an investment of CAD$2 billion into the production and processing of critical minerals. This is largely to support the growing battery electric vehicle market in which Canada is expected to rank third for global raw material supply due to its significant resource availability and proximity to the growing US market.[1]

During the visit to Canada, the UK team attended a full-day event at the British High Commissioner's Residence, with fifty stakeholders representing the Canadian mining and materials sector. A series of panel discussions across the four key areas of interest provided in-depth insights into Canada's position in the policy and innovation life cycle. These insights were endorsed during meetings with representatives from Natural Resources Canada (NRCan) and the Government of Canada's

Department for Innovation, Science and Economic Development (ISED). Evidence of research was gathered during visits to the National Research Council's facilities for Advanced Material Research, Lithium-Ion (LIB) Battery Recycling and Small Batteries, plus the NRCan-funded CanmetMATERIALS laboratories.

It is clear Canada is well endowed with critical raw material resources, and has a robust research and innovation landscape in material extraction and processing. This, however, can appear (and possibly is) fragmented due to the variety of funding delivery routes through both federal and provincial governments. The expansion of mining and allied research in Canada is centred on materials for batteries and rare earth elements which are critical in the design, manufacture and operation of high-performance electric motors. The mining expansion is at a very early stage and is being led by junior companies – this is a common approach for the mining industry where junior companies conduct most of the exploration and feasibility study followed by development by mid-tier and senior companies. There are also established Canadian producers of battery materials such as graphite and nickel with the country aiming to take advantage of the growth of the battery electric vehicle market. Discussions with the Saskatchewan Research Council highlighted opportunities for research and development (R&D) collaboration with the UK.

Our findings suggest that Canada is more advanced than the UK in domestic mineral extraction due to its endowment of georesources. It has allied experience in initial mineral processing of these resources, with a lot to offer upstream of the supply chain, but they are behind the UK in product

engineering, advanced manufacturing and through-life operation. In the battery sector, our findings suggest the UK to be ahead of Canada in new battery technology development and integration into vehicles. However, it was clear to the delegation that Canada could be a strategic partner for joint R&D in battery technology and critical raw material supply as the UK continues to invest in clean technology.

US

The team visited Argonne National Laboratory and the Critical Materials Institute (CMI) at the Ames National Laboratory in the US. This was followed by meetings in Washington DC with representatives from the National Science Foundation (NSF), National Institute for Standards and Technology (NIST) and Securing America's Future Energy (SAFE); a US think tank on (amongst other areas) critical minerals strategy.

Argonne National Laboratory provided an in-depth overview of its research related to critical materials. A range of topics were highlighted, including supply chain mapping, life-cycle assessment and circular economy processes, including handling of e-waste, AI-driven modelling and simulation. The research into national and international supply chain mapping of critical raw materials is considered by UK experts to be a vital topic and an opportunity to collaborate.

The CMI works closely with Lawrence Livermore, Idaho and Oak Ridge National Laboratories, which have unique capabilities and expertise in refining critical materials. While the CMI has a long-standing industrial partnership, most of the work is at the TRL 1-3 domain in a number of areas including:

- Supply chain mapping, manufacture and recycling of magnets.
- Acid-free recycling/reprocessing of waste streams including magnets and e-waste.
- Substitute materials for for LIB battery chemistry, permanent magnets and power electronics.

The discussions suggest opportunities for UK businesses and researchers to benefit from working closely with US counterparts to co-develop new permanent magnet materials for electric drives, new battery technologies, improved recyclability through processing of e-waste and global supply chain mapping.

In summary, the Global Expert Mission to Canada and the US provided an opportunity for the UK to connect and seek to forge new partnerships with overseas strategic partners. It was clear that Canada and the US have a lot to offer to the UK, and the team identified several initiatives that could be progressed to support the UK's critical materials strategy.

While the mission's main focus was on the UK's critical minerals list which includes rare earth elements and platinum group metals, it was unanimously agreed that all materials and minerals could be deemed critical based on supply and demand. Therefore, there needs to be policies in place to reduce our dependence on critical materials: key elements of which include responsible sourcing and supply chains, and designing products for increased durability to extend the lifetime of materials in circulation.

Acronyms and Definitions

ALM	Additive Layer Manufacturing
APS	Advanced Photon Source
BGS	British Geological Survey
C2M2A	Canadian Critical Minerals and Materials Alliance
CBET	Chemical, Bioengineering, Environmental and Transport Systems
CMIC	Critical Materials Intelligence Centre
CMMP	Canadian Minerals and Metals Plan
CMRDD	Critical Minerals Research, Development and Demonstration
DoD	US Department of Defence
DoE	US Department of Energy
ENG	Engineering Directorate at NSF
EoL	End of Life
ESG	Environment, Sustainability and Governance
GEM	Global Expert Mission
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technology
HVMC	High Value Manufacturing Catapult
IACMI	Institute for Advanced Composites Manufacturing Innovation
ISED	Innovation, Science and Economic Development
LCA	Life Cycle Assessment
LIB	Lithium-Ion Battery
MERF	Materials Engineering Research Facility
MSP	Minerals Security Partnership
NdFeB	A permanent magnet consisting of neodymium, iron and boron
NIST	National Institute of Standards and Technology
NRC	National Research Council
NRCan	National Resources Canada
NSF	National Science Foundation
NSTC	National Science and Technology Committee
REE	Rare Earth Elements
SAFE	Securing America's Future Energy
SmFeN	A permanent magnet consisting of samarium, iron and nitrogen
SRC	Saskatchewan Research Council
TRL	Technology Readiness Level
USGS	US Geological Survey
XRCC	Xerox Research Centre of Canada

1.0 Introduction

Innovate UK's Global Expert Missions (GEM) Programme is pivotal in building strategic partnerships with countries and overseas organisations. It is an important tool to support the UK's Industrial Strategy ambition and to be the international partner of choice for research and innovation.

The GEM programme delivers this by providing a deep dive into the research and innovation ecosystem in selected countries to help identify opportunities for UK innovation and shape future programmes. The objectives of a GEM are to:

1. Inform UK businesses and government.
2. Identify opportunities and build international collaborations.
3. Promote and share UK capabilities.

A team of UK experts representing businesses and academia supported by Innovate UK and Innovate UK KTN travelled to Canada and the US in May 2022 to improve our understanding of the research and innovation landscape in the field of critical materials. The GEM explored potential collaboration opportunities in four thematic areas:

1. Extraction industries and processing.
2. Manufacturing processes and supply chain.
3. Recycling and the circular economy.
4. Policy and innovation.

Mission Objectives and Scope

Critical materials are vital to the UK manufacturing sector and the economy. The GEM was designed to identify international collaboration opportunities to support UK-based businesses. The objectives of the visit were:

1. To help determine how Innovate UK can best support UK businesses more effectively and efficiently when considering innovation partnerships with the US and Canada.
2. Review technology and infrastructure gaps in both countries with a focus on critical material processing infrastructure, supply chain and manufacturing processes, business models and the circular economy.
3. To provide insights into synergies between the countries and determine whether there is an appetite for collaboration.
4. To capture key UK R&I and emerging market opportunities/challenges for developing innovative products and services when considering collaboration with the US and Canada.

The GEM focused on 4 key topics:

Extraction industries and processing: The majority of critical materials under consideration are extracted through mining operations and require processing to be turned into usable feedstock for manufacturing. For example, demand for rare earth elements (REEs) is set to grow substantially due to their use in permanent magnets for motors, wind turbines and in consumer electronics. Currently, 80-90% of this demand is being met by China.[2] There is an emerging consensus that REE supply chains should be developed outside of China to ensure supply chain stability. This will be achieved through the opening of new mines and new processing facilities, as well as adopting recycling techniques (less than 1% of permanent magnet material is recycled).[3] Therefore, extractive and processing industries in critical materials play a vital role to keep up with demand. This trend is repeated across the range of critical materials, with the diversification of supply a key theme. Hence, this GEM established links with organisations involved in mining and processing operations, as well as organisations involved in policy development, finance, and innovation around the primary and secondary processing of critical materials.

Manufacturing processes and supply chain: The development of a secure and stable supply chain of critical materials is vital to the economies of the UK, US and Canada. Critical materials are used in multiple manufacturing processes for products like permanent magnets, paints, coatings, electrical components, detectors and batteries. With the diversification of critical materials supply chains the raw material properties may require manufacturing processes to be adapted. Also, the characterisation and tracing of materials through the supply chain is of interest to original equipment manufacturers (OEMs) who want to evidence their environmental footprint or "green" credentials, as well as for end-of-life (EoL) approaches to recover and recycle these materials. It may also be necessary to integrate supply chains, e.g. in the case of rare earth elements (REE), where the technical challenges and risks undertaken in their extraction and processing will require more coordination and collaboration than is currently in place for many products. The GEM explored key manufacturing and fabrication processes for semi-finished and finished products while also reviewing the challenges and opportunities in their supply chains.

Recycling and the circular economy: The introduction of circular economy practices is on the agenda of governments in the UK, US and Canada. In many cases the recovery and recycling of EoL products will not only be environmentally necessary but will be required to meet the increasing demand for the critical materials (REE are a good example). Tracking, EoL policies and innovation in recycling approaches must be explored to facilitate this demand. Approaches to the circular economy, use of secondary sources, and research and innovation activities include:

- Provenance of secondary materials - tracking and auditing approaches.
- Recovery processes, remanufacturing and adoption of design concepts.
- Substitute materials and alternative processes/technologies.

Industry support, policy and innovation: To facilitate the changes required in critical material supply chains and manufacturing processes, there must be an associated shift in the policy and funding landscape. Many aspects of critical materials supply require intervention, including funding for innovation in the primary and secondary material processing, the development of new processing infrastructure, and the establishment of better collaboration between supply chain actors. The GEM engaged with key stakeholders to review policy and long-term investment strategy in critical materials and explore national programmes supporting this.

2. Critical Materials Sector Overview

Critical materials and minerals are fundamental to many of today's electronic components. The global energy transition towards a low-carbon future is accelerating the development of technologies such as solar panels, wind turbines and batteries for electric vehicles that incorporate critical materials. With only a few countries dominating the market, critical materials have adversely affected the global minerals market through price volatility, geopolitical influence and disruptions to supply chains.

The scale of infrastructure upgrades required for a low-carbon economy and the timeline of deployment means many materials seen as non-critical can become critical within a short period. This means investment plans and resources for critical materials are insufficient to keep pace with new development and rapid deployment of clean technologies. It is estimated that the zero-emission vehicle market in North America will be $174 billion by 2030. While it is projected to create 220,000 jobs in mining, processing and manufacturing[4], it would require a stable supply chain which is only possible through international collaboration. The recently announced Minerals Security Partnership (MSP) aims to circumvent supply chain vulnerabilities between the UK, Canada, US and other key international partners.[5] This will ensure critical minerals are extracted, processed and recycled to help support the economic development of the countries involved.

Canada Critical Minerals Strategy

Mining is vital to the economy of Canada with the value of mineral production reaching $43.8 billion in 2020.[6] Canada is a key global producer of copper, nickel and cobalt, in addition to REE, and is perfectly positioned to leverage its resources and innovation ecosystem to create a competitive supply chain for critical minerals. The government of Canada has published their list of 31 minerals considered to be critical for sustainability and for Canada's economy.[7] Through the Canadian Minerals and Metals Plan (CMMP) published in 2020,[8] federal, provincial and territorial governments are working together to strengthen domestic and international critical material value chains. The plan introduces six initiatives to improve the competitiveness of Canada's minerals and metals industry.

US Critical Minerals Strategy

The US is a net importer of most critical minerals and relies heavily on external supply chains and sources, including complete reliance on imports of 14 of the 35 critical minerals listed by the US government.[9] The US is dependent on a number of countries, including South Africa and China, for their critical mineral supply. In 2021 the US DoE published a comprehensive document detailing the short and long-term strategy to address this and support critical mineral supply chains in the US.[10] The strategy document covers supply chain uncertainty and the need for resilient and secure critical material supply, along with a number of calls to action that will mobilise federal agencies to advance R&D across the critical mineral supply chain.

Four strategic goals have been highlighted to achieve this:

1. Foster scientific innovation.
2. Support from the private sector.
3. Build long-term mineral and material innovation ecosystems.
4. Coordinate with international partners.

UK Critical Materials Strategy

The UK is a net importer of critical materials and therefore is susceptible to supply chain vulnerabilities. The GEM was carried out in parallel to the development of a UK national critical mineral strategy scheduled to be published in July 2022. However, a series of briefing papers have been published in recent years to highlight the challenges and opportunities for critical materials in the UK. While the UK does not yet produce any critical materials such as cobalt or rare earth elements (REE), a strong advanced manufacturing sector is utilising these critical minerals to produce materials with enhanced performance for developing applications. The UK has launched the Critical Materials Intelligence Centre (CMIC) in 2022 to support the UK in securing a sufficient and sustainable supply of minerals and metals.[11] The UK will require substantial quantities of several critical materials to enable the country's decarbonisation strategy. There are a number of programmes focusing on exploration to support this. For example, Cornwall has a huge reserve of lithium trapped in geothermal waters.[12]

There is a growing concern that the UK is projected to exceed its annual consumption of critical materials in the next decade. Therefore it is crucial to ensure an adequate and secure supply of raw materials to support UK manufacturing. The projected exponential increase in critical materials consumption is largely driven by the UK's policy of ending the sale of new petrol and diesel cars and vans by 2030; to be replaced by electric vehicles. Consequently, an enormous supply chain gap needs to be filled to support this transition. A recent report by the Faraday Institution estimates the UK will need to source 70,000 tonnes of lithium by 2035, a supply increase of 84% from 2025 levels.[13] Another independent report by Green Alliance[14] has found critical materials such as lithium and cobalt will far exceed the UK's fair share by 2035, which is predicted to hinder the UK's advanced manufacturing sector and 2050 net-zero targets.

3. Research and Innovation Landscape in Canada

Canada has a well-established near to long-term critical minerals strategy and has invested in a number of research programmes. In 2021, Natural Resources Canada (NRCan) received CAD$47.7 million to support the critical minerals value chain.[15]

The investment will support renewable energy and clean technology developments in applications such as:
- Batteries.
- Permanent magnets.
- Solar panels.
- Wind turbines.
- Consumer electronics.

The budget includes funding for demonstration projects supported by a CAD$10.95 million critical minerals research, development and demonstration (CMRDD) programme. The purpose of the CMRDD programme is to support Canada's 2050 net-zero targets by developing innovations at technology readiness levels (TRL) 6-8. In Canada's latest federal budget announcement in 2022, the government will invest CAD$2 billion in the production and processing of critical minerals. This is largely to support the battery electric vehicle supply chain market in which Canada is expected to rank third for global raw material supply.[16]

The UK delegation travelled to the Ontario province in Canada, home to a number of mining companies, many of which are headquartered in Toronto. The province has vast mineral wealth, with deposits such as nickel, lithium, platinum, cobalt and several other critically important raw materials. The province recently published a five-year roadmap on critical materials which sets out steps to position Ontario as a global supplier of ethically-sourced minerals.[17] The delegation visited a number of laboratories, research groups and companies during the trip to Toronto, Mississauga and Ottawa. The organisations were selected based on their research and innovation activity in the critical materials area, including the development and application of materials for various end-user markets.

Xerox Research Centre of Canada (XRCC)

The Xerox Research Centre of Canada (XRCC) is based in Mississauga. The company specialises in speciality materials research that underpins the Xerox product business. The research lab works on the application of chemistry and materials science to formulate new inks and 3-D printer feedstocks. The company has strengths and expertise in four technology areas:

1. Engineered particles.
2. Formulation and development.
3. Polymers and materials synthesis.
4. System design, process engineering and scale-up.

The company also provides lab space for new start-ups and has a vibrant community of highly innovative companies on site working on diverse areas, from pharmaceutical research to developing thin battery packs.

The delegation toured the facilities and had the opportunity to engage with researchers from XRCC to identify opportunities for collaboration:

- **Integration of sustainability** at the early stages of materials manufacturing scale-up using life cycle assessment (LCA) tools and implementing best practices.

- **Digitalisation of process scale-up.** Integrating advanced sensors to support digital twinning. XRCC have an in-house pilot plant.

- **Sharing best practice for testing membranes in batteries or other electrochemical processes.** Currently, there is no International Standards Organisation (ISO) for determining membrane performance.

NRC Advanced Materials Research Facility

The Advanced Materials Research Facility (AMRF) is a newly-built centre and the first National Research Council (NRC) laboratory in the Toronto area. At the time of the visit there were 15 NRC employees, with the aim of reaching 60 employees and a rolling cadre of 40 students when the site is fully operational. The facility serves as a national innovation platform supporting fundamental research in materials discovery through to production scale-up. The new facility is home to the Materials Acceleration Programme which aims to use AI, robotics and high-performance computing (HPC) to develop new materials and drive down processing costs. Other work areas include catalysts for carbon dioxide conversion and hydrogen production, smart materials for smart objects, meta-materials for volumetric 3D printing, and powder synthesis.

Accelerated Materials Discovery Platform

A typical timescale from the discovery of new materials through to commercial application can be around 20 years. There is an urgent need to accelerate this timeline, particularly when most nations are deploying clean energy technologies utilising often expensive critical materials. The Materials Acceleration Programme aims to overhaul traditional discovery routes in favour of utilising AI, robotics and HPC. The goal of the programme is to develop a fully automated laboratory that conducts material synthesis, characterisation, and testing. Machine learning algorithms are then used to predict and optimise synthesis reaction and processing conditions.

The team visited the NRC facility to learn about the funding priorities in material research and areas of importance for critical materials. A discussion between the NRC team and the UK delegation identified a number of areas that would be of interest to explore further for collaboration. These include:

- Working with the NRC to establish an international programme to introduce the Materials Acceleration Programme to UK academics and businesses.
- Development of the future workforce by understanding the needs of the sector.
- Working together to measure the impact on future research on critical materials.
- Working more closely with UK companies and institutions, such as the Materials Innovation Factory and the Sir Henry Royce Institute, on powder processing for recycling materials.

NRC Lithium-Ion (LIB) Battery Recycling and Small Batteries Facilities

The facility is based in Ottawa, in one of Canada's largest research parks. The centre is part of the NRC Energy, Mining and Environment Research Centre and works to support materials for clean fuels and advanced clean energy national challenges. The UK delegation's tour of the facilities covered the following:

- New battery chemistries and electrode membranes being developed and tested in small coin cell sizes.
- Development of organic "ligands" for targeting specific rare earth elements (in oxide form) to improve the efficiency of the process of element separation of mined deposits.
- Development of a variety of separation/fractionation columns, combined with the organic ligands to demonstrate lab scale, proof of concept, and high-efficiency separation of a given target rare earth element.
- End-of-life processing of batteries to recover the constituent materials (the "black mass").

The research capabilities reflect TRL 1-3 operations with moderate investments with two key areas highlighted for collaboration:

- Connect with the UK Faraday Industrial Strategy Challenge Fund (ISCF) programme. The UK has advanced capabilities in rapid scale-up and testing of new battery chemistries.
- Development and scale-up of efficient techniques for processing ores containing rare earths and for elemental separation.

NRC Advanced Clean Energy Programme

The programme is designed to translate fundamental projects in clean energy technologies and scale them to mid-to-high TRL clean to support the Canadian Government's 2050 energy target.

The programme has three research pillars:

1. Battery energy storage.
2. Low-carbon fuels.
3. Hydrogen.

The research aims to develop capabilities in battery material and development through the introduction of new technologies in mineral processing, material discovery, production and the modelling of performance. A key area of focus is battery energy storage, recycling and secondary use.

CanmetMATERIALS

CanmetMATERIALS is the largest research centre in Canada dedicated to fabricating, processing and evaluating metals and materials. The centre is in Hamilton, the major location of the Canadian steelmaking industry. Thus, the centre has strengths in steelmaking, casting, rolling and press forming of metallic parts. The centre concentrates on:

- The transportation sector: Primarily working with vehicle, engine and component manufacturers who require new advanced-materials solutions to improve fuel efficiency while maintaining safety and performance.

- The energy sector: Working on components in clean energy production and reliable pipelines to transport gas, oil, biofuels and carbon dioxide.

- The manufacturing sector: Working on components for various sectors that rely on high-performance materials, such as defence, aerospace, health and construction.

Critical materials projects include material recovery from the battery supply chain and its recycling. The centre has expertise and leads nationally in corrosion of metallic pipeline and pressure vessels, civil nuclear powerplant, non-destructive testing of structural components and Cray supercomputing for large-scale simulations. The centre recently announced a budget of CAD$20 million over the next five years for international collaborative research. Potential areas for collaboration with CanmetMATERIALS include:

- Use of facilities for specific projects such as laser optical sorting, graphite and LFP recycling, production of smaller magnets, hydrogen pipelines and steelmaking.

- Analysis of industry best practice for workforce and skills development.

Joint Innovate UK KTN and National Resources Canada Symposium at the British High Commission

The symposium at the British High Commission was organised by Innovate UK, Innovate UK KTN, and National Resources Canada (NRCan), supported by the Canadian Critical Minerals and Materials Alliance (C2M2A). The aim was to bring together key stakeholders from industry, academia and government agencies representing the Canadian mining industry.
The event focused on the GEM topic areas:

1. Extraction industries and processing.
2. Manufacturing processes and supply chain.
3. Recycling and the circular economy.
4. Policy and innovation.

A list of industry attendees can be found in Annex 1.

The meeting was arranged as a series of round-table discussions initiated by a panel of UK and Canadian experts. The panel rotated to include the different topics over the day with good representation for each sector. It was clear from the discussion that the funding landscape in Canada is complex, with a number of delivery routes through federal and provincial bodies. However, there was a sense of urgency and commitment by the Canadian government to invest in critical mineral mining and extraction, with much of the discussion focusing on the environment, sustainability and governance (ESG), future workforce and supply chain traceability.

Extraction Industries and Processing

Canada has been blessed with a rich supply of many specialist raw minerals vital to economic growth. However, many of these rich deposits are located in the northern territories. This is a major challenge and requires close work with the indigenous communities to construct roads and the infrastructure needed for mining operations. It is critical that mining companies and businesses working in the supply chain of raw minerals build an effective relationship with local communities. There are initiatives to be more inclusive and to bring on board local businesses to supply operations and mining services. However, these businesses may not have the required experience, and the challenge is how best to support them – knowledge sharing is vital. Training programmes for indigenous people and community liaison officers have been funded to support local communities to enter the workforce. In the context of sustainability and climate goals, mining operations often have a large carbon footprint. The challenge is how to make the extractive industries "greener", and it is difficult to get green materials if the energy itself is not from renewable sources. While these are key issues across the global mining industry, the Canadian government has provided support to develop early-stage processing requirements such as purification to make the final processes economically viable.[18]

Manufacturing Processes and Supply Chains

The global supply chain of critical materials is dominated by China, which was once a net exporter but has recently been importing many of the minerals and REE for processing in China. For example, cobalt mined in DRC is processed in China. China no longer sells REE or RE production equipment. For Canada to compete, there needs to be international partnership and cooperation to enable the security of the supply chain and support business.

The REE mining industry is dominated by regional mining initiatives led by smaller junior companies. While Canada has one of the largest REE reserves, they are not a commercial producer and are only engaged in exploration programmes.[19] Search Minerals, a company located in British Columbia, has exploration and development programmes in Southeastern Labrador, Canada, focusing on critical REE extraction. REEs are used in various industrial applications, including aerospace, electronics and clean energy, with the major application of REE in permanent magnet production.

Timing and synchronicity are also issues – building a battery megafactory takes about two years. However, as noted earlier, to develop a material from discovery to commercial adoption can typically take up to 20 years.

Mining companies
There are two types of companies in Canada; senior companies that drive operating revenue through mines and junior companies that do not own a mine and rely primarily on equity markets for investment to conduct exploration programmes. It is common for junior companies to work on exploration and feasibility studies, followed by development and scale-up by senior companies.

Recycling and the Circular Economy

Mining has one of the largest waste footprints of any industry. In the context of the circular economy, there is a growing need for mining operators and supporting businesses to implement sustainable waste management programmes and explore avenues to extract waste minerals from mine tailings. For example, lanthanum and cerium are common minerals found in waste streams; these can be recovered and used in high-value products and not just retained as costly waste. The discussion on recycling and the circular economy largely focused on extending the time to EoL of materials and designing products with increased durability. There is also the issue of traceability of recycled material – it is challenging to measure recycled content and, therefore, difficult to impose regulations and mandates. From a consumer's perspective, too much recycled material in a product may not be desired, particularly in high-value products such as permanent magnets.[20] Geomega, a company specialising in REE extraction from waste magnets, is working on processing 1.5 tonnes of waste magnet per day. The gap between supply and demand for critical materials will widen as the world transitions towards a clean energy future. The raw materials required will not be able to keep pace with the technology rollout. This is where design for recycling comes into play to ensure products have extended shelf-life and durability. This will alleviate many of the long-term issues facing critical material supply.

Mine tailings
These are the by-product of mining. After the commodity mineral is mined from the ore in a processing plant, the resultant waste stream is termed tailings. Tailings can be deposited in large piles or as ponds. Mine tailings have a huge environmental impact, and initiatives are underway to minimise waste and extract the lesser valuable mineral from mine tailings.

Policy and Innovation

Policy drivers to mitigate mining waste are vital to ensure sustainable mining operations. Innovation in waste management has stagnated and has been the same for the last 35 years, with waste going to tailing ponds. This can cause a significant delay in opening new mines due to deferral of social license, which enables mines to be operated and the requirement to convince the local community.[21] While there are no single policy drivers to change this, there is a growing need to innovate the mining operation and take steps to drastically reduce waste. Companies like Cheetah Resources use sensor-based sorting technology to concentrate on raw materials. Here, X-ray transmission sensors separate the host rock from the target ore, significantly reducing the footprint of the mine.[22] To date, innovation in critical materials research has not kept pace with materials and technology development. There needs to be a system-wide approach to material strategy development that takes into account the electrical revolution, battery technology and clean technology growth to ensure a resilient supply chain in the future. Equally, concerns were raised around the future workforce, policies and the educational programmes that need to be put in place to attract students to the mining sector. There has been a significant decline in recruiting students to geoscience in recent years. While it is estimated that 20-35% of activities will likely be conducted by AI and automation in the future,[23] the consensus of the discussion was to invest in the future workforce.

The symposium highlighted a number of priority areas where the UK and Canada can collaborate through international programmes and activities:

- Re-processing of mine tailings to obtain raw minerals. This could reduce the number of new deposits and ensure the profitable use of waste materials. The challenge is installing new infrastructure that requires significant investment, particularly for legacy operations and equipment.

- The development of the future workforce was a high priority. Specifically using a local workforce that mining developments may otherwise displace. The number of people studying geoscience has steadily declined, and there needs to be a combined effort to attract students to ensure a future workforce.

- There needs to be supply chain traceability through digital tracking of materials including LCA assessments to meet UN SDG standards for climate impact and social equity (non-conflict minerals).

The UK delegation attended a closed-room discussion with NRCan, NRC, Saskatchewan Research Council (SRC), NGen, CanmetMINING and Innovation, Science and Economic Development (ISED). The discussion focused on innovation and policy in the mining and critical mineral application area and the scope for international collaboration. CanmetMINING has a portfolio of work they conduct in the mining and minerals area and have invested in battery materials, mining value from waste and projects in REE and have allocated CAD$50 million for international collaboration. They have engaged with the Horizon Europe Programme and have a joint action plan with the US.[24] NGen operates a vast network of manufacturing companies in Canada and typically funds collaborative projects at a 50% rate. They have working groups in additive layer manufacturing (ALM), digital twins and automation, the three core competencies at the High-Value Manufacturing Catapult. The conversation concentrated on bilateral collaboration, and several opportunities arose at the business and government levels:

- Joint projects on aluminium/magnesium additive manufacture for light weighting of materials.

- There are opportunities for co-developing digital twinning and automation infrastructure.

- UK to join Canada, US and Australia on joint critical materials mapping programme.

- Collaboration with SRC on novel processes for battery recycling.

- Collaborative projects on extraction capabilities. Develop biological methods and membrane technology for separation.

REE Processing at Saskatchewan Research Council

Saskatchewan Research Council (SRC) is the second largest organisation in Canada working with industry and government. As a research council, it is overseen by an independent board of directors and is accountable to the minister responsible for SRC. The government partly funds the organisation with the remaining income generated from contract research. With 1,500 clients across 27 countries, SRC generates CAD$137 million in annual revenue.[25] The organisation is uniquely positioned to bridge fundamental concepts to commercial development by actively working with partners on feasibility studies and scaling up to demonstration projects. SRC has four divisions i) mining and minerals, ii) energy, iii) environment and biotech, and iv) REE.

REE Supply Chain

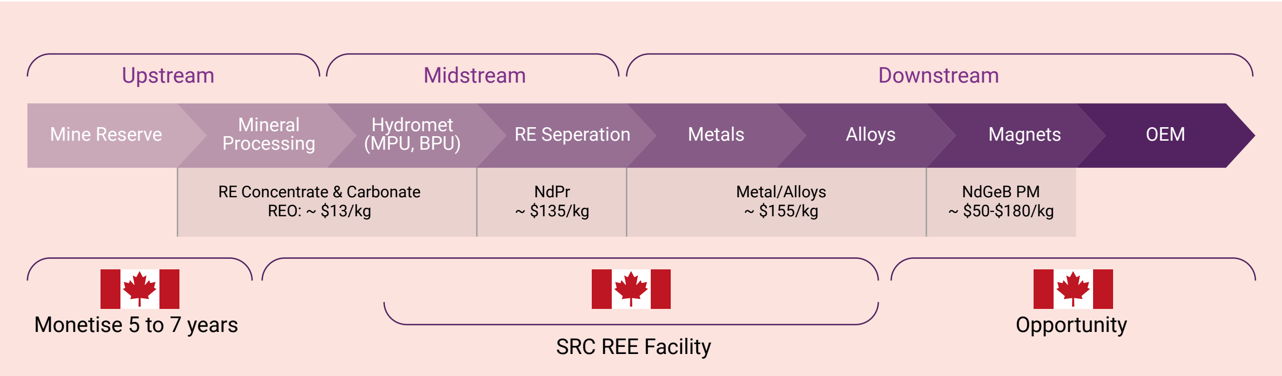


Figure 1. Rare Earth Element (REE) supply chain in Canada and opportunities for collaboration in downstream processing. Source: Adapted from SRC presentation

The REE division at SRC has processing and separation capabilities for heavy and light REEs to support commercialisation and has opened a rare earth processing facility with funding from the Government of Saskatchewan. SRC intends to develop a suite of REE products by 2024, including lanthanum, cerium, dysprosium and neodymium.

Natural Resources Canada (NRCan)

NRCan is the government department responsible for developing Canada's policy and programmes in the natural resources sector of the economy. They are established leaders in energy, earth science, forestry, energy efficiency, minerals and mining and science and data.

The Canadian Critical Minerals and Materials Alliance (C2M2A)

The C2M2A is a non-profit, independent organisation which endeavours to grow the Canadian economy through critical mineral supply chains. The organisation's vision is to help Canada diversify its economy, foster job creation and provide a healthy environment for future generations.

Innovation, Science and Economic Development (ISED)

ISED is a department of the Government of Canada. They are responsible for a number of the federal government's functions in regulating industry and commerce, promoting science and innovation, and supporting economic development. Together they support the government's goal of building a knowledge-based economy. ISED works in all areas of the economy to enhance Canada's innovation performance and share of global trade and to help build a fair and efficient competitive market.

CanmetMINING

CanmetMINING is part of the minerals and metals sector of NRCan, based in Ottawa. CanmetMINING aligns its research activities across three business areas: extraction, processing and environment. Research and development include a wide range of processes involving extracting and transforming ore into concentrate and mineral products. Much of this is in partnership with industry, provincial and federal governments.

NGen

NGen is an industry-led non-profit organisation leading Canada's advanced manufacturing supercluster. NGen is dedicated to building world-leading advanced manufacturing capabilities to strengthen Canada's economy and create high-value jobs. NGen leverages its research, technology and industrial strengths to achieve these goals.

4. Summary and Conclusion for Canada

The UK delegation visited both NRC and NRCan labs. The engagement from Canadian stakeholders was positive, and they were keen to engage and continue the dialogue with the UK. Canada clearly has vast mineral resources, and they have published a number of roadmaps to ensure investment is directed towards extraction and processing. While several global mining companies operate in Canada, the majority of mineral exploration is conducted by junior companies.

Canada aims to be a global leader in critical minerals through responsible, inclusive and sustainable production. There is a clear drive by the Canadian government to invest in research, innovation and exploration and building sustainable infrastructure. The government recently announced CAD$2 billion to support Canada's mineral strategy. Building a diverse workforce and working closely with the indigenous community is a high priority and came across strongly across all organisations. Environment, sustainability and governance (ESG) was a key topic across all sectors with a focus on sustainable waste management, extracting waste minerals from mine tailings, designing products for recycling and the requirement for policy to drive innovation in automation.

Identified opportunities for collaboration:

- Work closely with Xerox and NRC on compostable batteries project. Link with the UK's Faraday Institution.

- Several R&D areas would benefit from closer alignment between UKRI and the NRC. Innovate UK leads on an existing MoU between NRC and UKRI and there are opportunities to be involved in NRC's major challenge programmes, including Materials for Clean Growth and Advanced Clean Energy.

- Co-funding with NGen. Set up bilateral R&D competitions in advanced manufacturing and automation. There are opportunities for sharing capabilities in Digital Test Bed.

- Work closely with NRCan (CanmetMATERIALS and CanmentMINING) and SRC to develop a scale-up of efficient techniques for processing ores containing REE for elemental separation. Canada is a member of the Mission Innovation programme alongside the UK. There are opportunities for joint R&D and investment in critical materials.

5. US Research and Innovation Landscape

The US, like the UK, is in the early stages of developing a long-term critical materials strategy. With China dominating the REE market, the US is looking to build a resilient supply chain for REE that will reduce its dependence on China. With the drive towards clean energy, there is a renewed effort under the Biden Administration to invest and develop new technologies to mine and process REE. The Department of Defence (DoE) recently announced a $140 million programme to design and construct a new demonstration facility to process REE and critical minerals.

In addition, The White House has announced a number of investments and projects to extract and process REE, these include:[26]

- MP Materials awarded $35 million to separate and process REE and a further $700 million to create a magnet supply chain in America.
- Investment of $3 billion from the Bipartisan Infrastructure Law to refine battery materials, including lithium, cobalt, nickel and graphite.
- Redwood Materials to work with Ford and Volvo to recycle EoL lithium-ion batteries.

As part of the US visit, the UK delegation visited key research labs working on critical materials and their applications, the use of substitute materials and recycling and the circular economy. The team visited Argonne National Laboratory (ANL) in Chicago, followed by a visit to the Critical Materials Institute (CMI) at the Ames National Laboratory. These facilities are two of the 17 US National Labs funded by the US DoE. The UK delegates also travelled to Washington DC to meet with the National Science Foundation (NSF), National Institute of Standards and Technology (NIST) and Securing America's Future Energy (SAFE), an organisation working in Washington to lobby the US government in critical materials and energy strategy.

Argonne National Laboratory (ANL)

The visit included a tour of the facilities and presentations by group leaders on the different strands of research. Research activities are largely at the TRL 1-3 stage, and while there are industrial collaborations, much of it is focused on academic research. Parts of ANL, for example, the Advanced Photon Source, can be described as analogous to the UK's STFC but with more focused research activity and a turnover of $1.1 billion. ANL is committed to i) enabling the scale-up of fundamental research and closing the gap between R&D and commercialisation and ii) building a diverse STEM pipeline and workforce. Clearly ANL has received substantial investments to modernise some of its facilities. The experimental labs and instrumentation are world-leading, and the tour evidenced this.

Materials Engineering Research Facility (MERF)

The MERF is a state-of-the-art, 28,000-square-foot R&D facility focused on processes for accelerated materials synthesis, scale-up of new chemistries, and the development and validation of emerging materials manufacturing technologies. The MERF houses many capabilities relevant to DoE strategic energy and climate priorities, including energy storage, where work is underway to scale-up materials for higher-density, longer-lived, faster-charging, and safer batteries both for long-duration grid storage and the transportation sector. The MERF is home to DoE's advanced battery recycling centre, which develops recycling techniques for lithium-ion and future batteries. Collaboration with the High Value Manufacturing Catapult and Warwick Manufacturing Group was evident by their logos in the MERF.

The ReCell Centre at Argonne

The ReCell Centre focuses on the recycling of spent lithium-ion batteries. ReCell aims to improve methodologies and reduce the cost of deploying recycling technologies on the range of battery specifications and configurations at scale. To achieve this, they break down the recycling problem into four parts – direct cathode recycling, other material recovery, design for sustainability, and modelling and analysis. Direct recycling of cathode materials provides cost-effectiveness versus traditional hydro- and pyro-processing routes. Their modelling work breaks down the various components and stages of manufacture to identify the best opportunities for reducing cost and environmental impacts. The long-term vision is to drive the cost of battery packs down to the DoE's $80/kWh usable energy goal, provide stability to the battery supply chain and minimise environmental impacts.

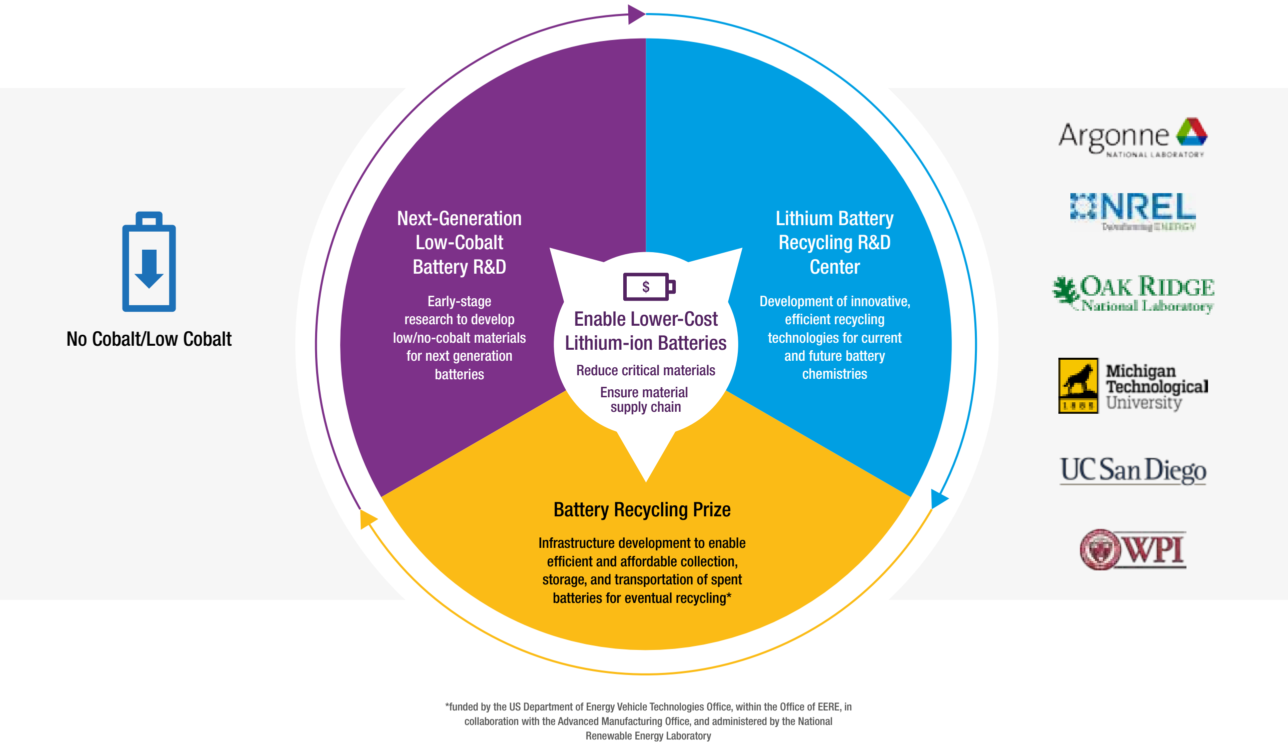


Figure 2. Programme overview of developing low-cost LIB for EVs.
Source: Courtesy of the Vehicle Technologies Office

Materials and Microelectronic Research in Argonne

Materials and chemistry research at Argonne focuses on the reduced use and recovery of critical materials as a design parameter for multiple physical systems. The Materials Science Division embraces heterogeneity in materials discovery to advance understanding and application in quantum, hard and soft matter. The Applied Materials Division develops the process R&D and scale-up of complex materials to accelerate at-scale deployment. The Centre for Nanoscale Materials focuses on quantum materials production and characterisation using X-ray scanning tunnelling microscopy and ultrafast electron microscopy, amongst others. The cross-cutting themes are AI and ML approaches, computer modelling, and the use of advanced characterisation techniques using, for example, the Advanced Photon Source (APS) also located at Argonne.

Transformative Manufacturing for the Circular Economy

This programme focuses on the transformation of linear manufacturing processes into circular ones, by designing materials and chemical processes for circularity, substituting for critical minerals, and reducing environmental impacts. Specific areas of interest are finding ways to deconstruct waste into new value-added feedstocks, and to recover critical materials from e-waste and wastewater and reduce their use in manufacturing. Recent progress has been made in the plastics sector, with new methods for upcycling waste polymers into feedstocks for a range of applications including transportation lubricants and surfactants.

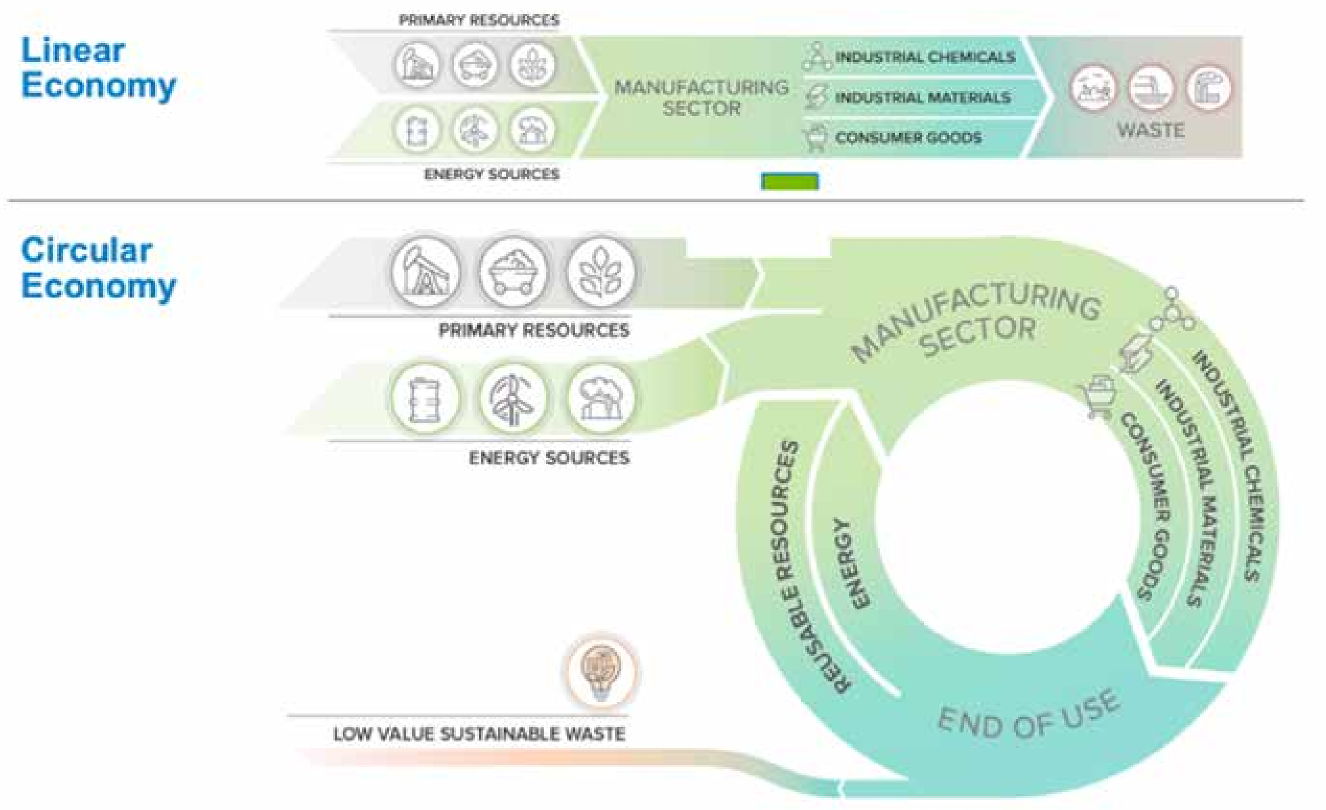


Figure 3. Linear and circular economy model for the manufacturing sector

Advanced Photon Source (APS)

The Advanced Photon Source (APS), a DoE Office of Science user facility, provides access to ultrabright X-rays to obtain images of structures and dynamics inside many types of materials, chemical systems, and biological systems. More than 5,500 scientists each year use the APS to spur pivotal discoveries across almost the entire spectrum of science and technology, from clean energy and biology to geology and engineering. The tour highlighted the transformative research using the APS and provided an overview of the ten-year APS Upgrade project, scheduled for completion in 2024. The upgrade will increase the brightness of the X-ray beams by up to 500 times, keeping the facility at the forefront of global light sources. The APS Upgrade will allow users to probe materials faster and at higher resolutions, opening up new frontiers for science and industry.

Global Supply Chain Mapping at Argonne

During the visit to Argonne, the UK team were exposed to a number of research topics delivered by group leaders. The Argonne team talked authoritatively on a wide range of topics, including supply chain mapping, LCA, the circular economy (including e-waste), energy storage, battery recycling and quantum computing. An area which drew considerable attention was the work supported by the Department of Defence (DoD) on global critical materials supply chain mapping. The project uses agent-based modelling as an analytical tool to assess supply disruption, dependencies, substitutions and trade policies to strengthen critical material supply chains.

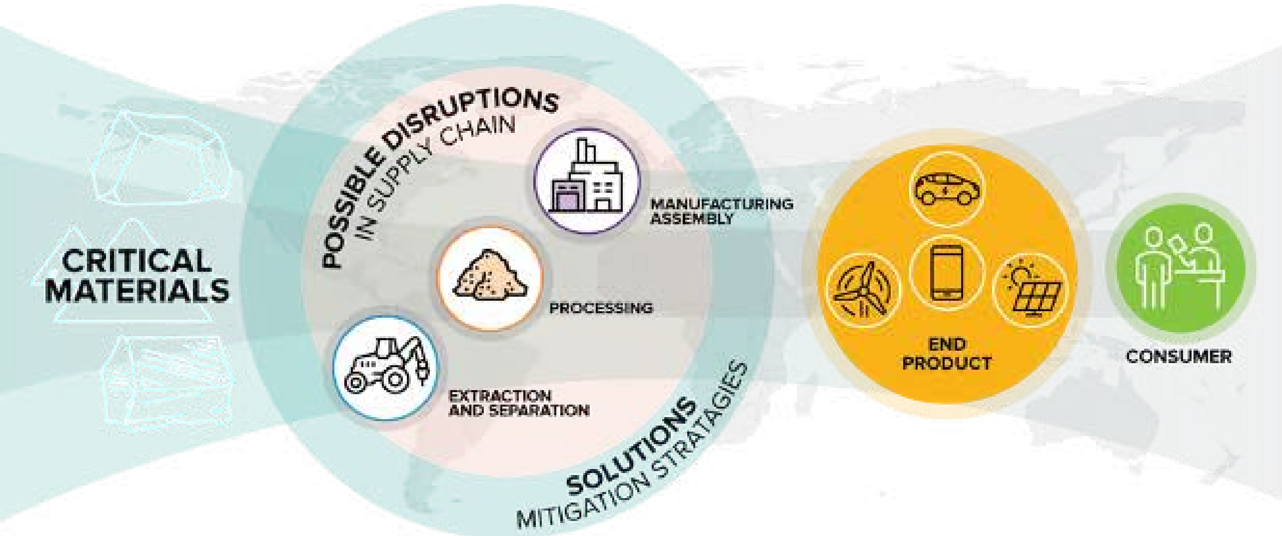


Figure 4. Global Critical Materials (GCMat) model
Source: Argonne National Laboratory

Several areas were identified for collaboration:

- Development of global supply chain mapping. The Argonne team has developed an LCA model for energy usage and emissions called greenhouse gasses, regulated emissions, and energy use in technologies (GREET). It is working towards the Global Critical Materials model to predict supply chain disruptions. GREET has 50,000 users globally.

- There is an existing collaboration between the UK's Faraday Institute and Argonne's ReCell programme. Recycling and circularity are key to the UK's critical material strategy and energy transition.

- Academic exchange programmes will help train and support UK researchers and strengthen collaboration between the UK and US.

- Opportunities to collaborate with UK companies on digital twinning.

Ames National Laboratory

The delegation visited the Critical Materials Institute (CMI), situated in and led by Ames National Laboratory, with representatives from Lawrence Livermore and Idaho and Oak Ridge National Laboratories. The facility has a rich history and is well known for its work on the Manhattan Project, where scientists at Ames developed the process to purify uranium by what is now known as the Ames process. While the facility is the smallest of all 17 DoE labs (annual budget of $60 million), the work conducted at Ames is highly specialised with a focus on structure, properties and processing of metallic materials with an emphasis on niche elements such as REE. The CMI has a balanced portfolio of research activities, from fundamental research to scale-up and industrialisation. These include developing permanent magnets for EV motors and wind generators, Li-ion batteries for energy storage and electronics for solar energy. It was clear from the facility tour that Ames researchers are world-leading in processing and refining metallic elements and alloys. While the CMI has strong partnerships with industry, our findings suggest most of the work is conducted at TRL 1-3. Several key areas were covered during the visit i) transformative material supply, manufacture and recycling of magnets, this includes supply chain mapping, ii) acid-free recycling/reprocessing of waste streams, iii) disruptive technologies for diversifying the supply chain through substitute materials, and iv) international collaboration.

Circular Economy at CMI

Driving reuse and recycling is one of four strategic areas at the CMI. The circular economy is vital to the critical materials and manufacturing sector to minimise waste and ensure components and products have extended end of life. At the CMI, the research portfolio in the circular economy includes i) recovery of LIB materials for remanufacturing, ii) permanent magnet recycling, and iii) metal and alloy production. There are a number of challenges to recycling electronic components for REEs. Product designs constantly evolve to match consumer demand with no content labelling, making recycling difficult. In addition, due to the variable and dispersed feedstock, collecting and sorting electronic waste is challenging. This is further compounded by insufficient incentives to design products that mitigate many recycling issues. The CMI has developed methods to extract and purify high-value minerals from LIB and magnet waste. For batteries, the CMI has demonstrated they can recover nickel, manganese and cobalt from the black mass with very high purity using a three-step process of leaching, separation and concentration. REE recovery from permanent magnet shreds, swarf, or e-waste shreds can be achieved via a bioleaching route, using bacteria-produced acid from organic waste, coupled with membrane solvent extraction. They are also exploring using bioligands with high selectivity for individual REEs to provide a more facile method of separation without the need for acids.

Black mass
Black mass is an industry term used to describe e-waste containing shredded LIB battery cells. The powder contains lithium, cobalt, nickel and manganese which can be recovered through chemical processes.

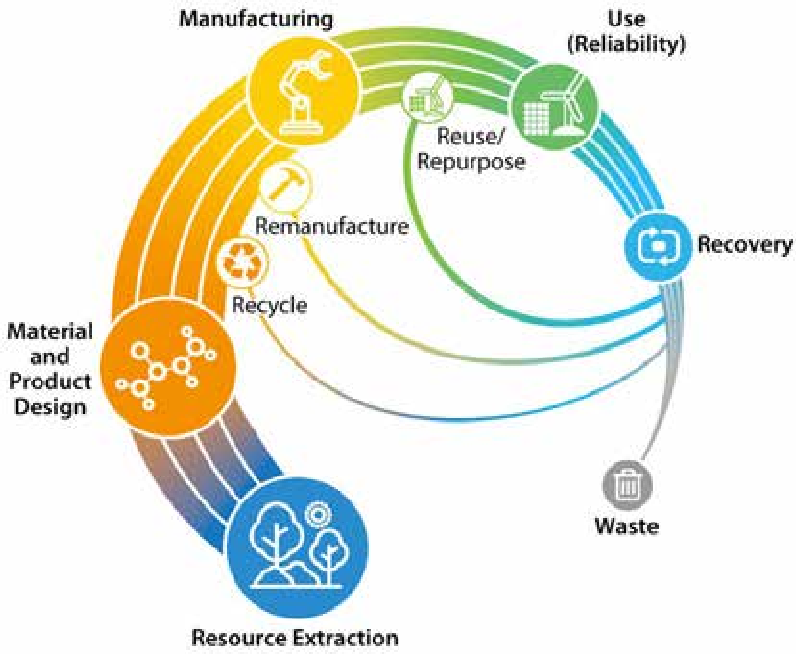


Figure 5. Product life cycle highlighting aspects of recycling, remanufacturing and reuse.
Source: NREL, Circular Economy for Energy Materials https://www.nrel.gov/about/circular-economy.html

Developing Substitute Materials at Ames

The US is undergoing a massive energy transition with the clean energy revolution. This is supported by the country's growing diverse renewable energy sector – including solar, wind, water, geothermal, bioenergy and nuclear.[27] General Motors recently announced that they will phase out gas-powered cars and only manufacture zero-emissions vehicles by 2035.[28] While this initiative is welcome, it will have an unintended consequence of creating a supply chain gap of critical minerals used in permanent magnets for use in electric vehicles (EV). Nearly all magnets are neodymium ($Nd_2Fe_{14}B$) based, which creates a supply risk, especially as neodymium is presently imported from overseas markets. It is projected that 100,000 tons of $Nd_2Fe_{14}B$ is required, which is 50% of the market size, to match the EV market demand by 2030. The overarching aim of the substitute materials programme at CMI is to reduce or eliminate material criticality as a threat to the economic and climate security of the US. The programme aims to develop appropriate substitutes for critical minerals that are used in components and technologies that are vital to the US clean energy transition.

Enabling science	Technology achievement	Impact
Low-Nd version of $Nd_2Fe_{14}B$ theorized, proven	33 MG-Oe BH_{max} in La-substituted Neo; coercivity increased; patent filed	U.S. competitor to $Nd_2Fe_{14}B$ at reduced cost, critically
Development of $NdCl_3$ handling method	Process developed to convert Nd_2O_3 to $NdCl_3$	Continuous, High-volume processing of RE oxide metal
Hard magnet properties in $Sm_2Fe_{17}N_3$ and $TbCu_7$- structure materials proposed	Significant coercivity and energy products achieved	High-performance $Sm_2Fe_{17}N_3$ and $SmFe_7$- based magnets
AlCe Alloys Discovered	Temperature resistance better than standard Al alloys achieved	Large volume AlCe applications; resolve RE balance problem

Figure 6. Summary of technology achievements in substitute materials at the CMI

The CMI is engaged in two strands of development i) magnets with reduced REE content and ii) developing novel functional alloys. Significant strides have been taken in substituting lanthanum and cobalt into the $Nd_2Fe_{14}B$ alloy to reduce the concentration of Nd and Dy whilst maintaining the magnet performance. Alternative magnet materials, based on samarium, iron and nitrogen (SmFeN), are being developed to match the $Nd_2Fe_{14}B$ performance. On the functional alloys side, cerium has been found to improve the properties of aluminium, which could provide a major use as one of the by-products of REE mining, thereby positively impacting REE production economics.

Permanent magnets for EVs

Current high-performance permanent magnet technology is based on an alloy of neodymium, iron and boron ($Nd_2Fe_{14}B$), with additives such as dysprosium (Dy). This material, coupled with state-of-the-art manufacturing processes, provides magnets with very high magnetic energy density, high resistance to demagnetisation, and maintenance of performance at high temperatures. $Nd_2Fe_{14}B$ magnets are, therefore, the technology of choice for electric vehicle traction motors. Current alternatives (e.g. induction motors) offer poorer performance on at least one of these fronts, which have knock-on impacts on the requirements for other vehicle components, e.g. battery capacities.

CMI Partners

The CMI, a DoE energy hub led by Ames National Laboratory, is partnered with universities, companies and other national laboratories including Lawrence Livermore, Oak Ridge and Idaho.

Lawrence Livermore National Laboratory:[29] Lead on crosscutting research which involves developing new research tools to forecast material usage and criticality. The team focuses on enabling science, supply chain and economic analysis and environmental sustainability.

Oak Ridge National Laboratory:[30] The team leads on diversifying the supply chain and developing substitute materials. Here the team are working on new uses for co-products, developing new processes and synthesising materials with reduced REE content.

Idaho National Laboratory:[31] The team leads on the reuse and recycling of materials by developing tools and processes to reduce waste in manufacturing processes. The team focuses on energy storage systems, electric machines and enabling and optimising co-production.

The round-table discussions at CMI included representation from all three national laboratories who work virtually across all four Ames priority areas, carrying out crosscutting research in areas such as:

- Machine learning of thermodynamics.
- Digital twin studies to predict mechanical properties.
- Environmental sustainability, including wastewater.
- Economic assessment of emerging battery technologies.
- Processes to accelerate technology transfer and steer toward industry needs, including:
  - Technical reviews and roadmapping.
  - Invention disclosure.
  - Criticality assessment of elements.
  - Scenario planning, risk assessment and mitigation.

The GEM team identified multiple areas for collaboration with the CMI, including working with other DoE national laboratories.

- Joint programme in developing transformative materials supply, manufacture, recycling of power electronics, machines and drives (PEMD).

- Global and national critical materials supply chain mapping. The CMI seems to have a distinctive supply chain mapping programme.

- Work closely with the CMI at the low to mid-TRL level to develop substitute materials.

- Joint CR&D on plastic upcycling and recycling of electronic waste.

Securing America's Future Energy (SAFE)

SAFE is an energy think tank providing fact-based analysis and policy recommendations for lawmakers, regulatory agencies and the public. The team relies on the expertise of retired military officers, Fortune 500 CEOs and in-house knowledge to lead the discussion on America's future energy uses. The UK team met with the SAFE representatives leading on critical materials strategy. The discussion provided a broad overview of geopolitical issues surrounding the critical materials supply chain and policies needed to curtail any vulnerabilities. Critical minerals sourced in the US are often shipped abroad for processing. For example, China processes the majority of the world's critical materials. There has been a shift in mindset for many companies now looking into material sourcing to ensure components used in consumer products are ethically sourced.[32] There was an appetite for further discussion and building international cooperation between allies in this area. SAFE expressed their interest in learning about the scenario planning model for critical materials, particularly in the work by the HVMC on CO_2 emissions mapping in the supply chain. There is a public perception issue which can only be addressed through engagement and public/private partnerships. SAFE estimate that the US is ten years behind Europe and 30 years behind China, and this is the time to change. They were interested in working with the UK to understand the wider supply chain on emissions and material usage.

Net zero design and make: End to End CO_2 Mapping Thoughts

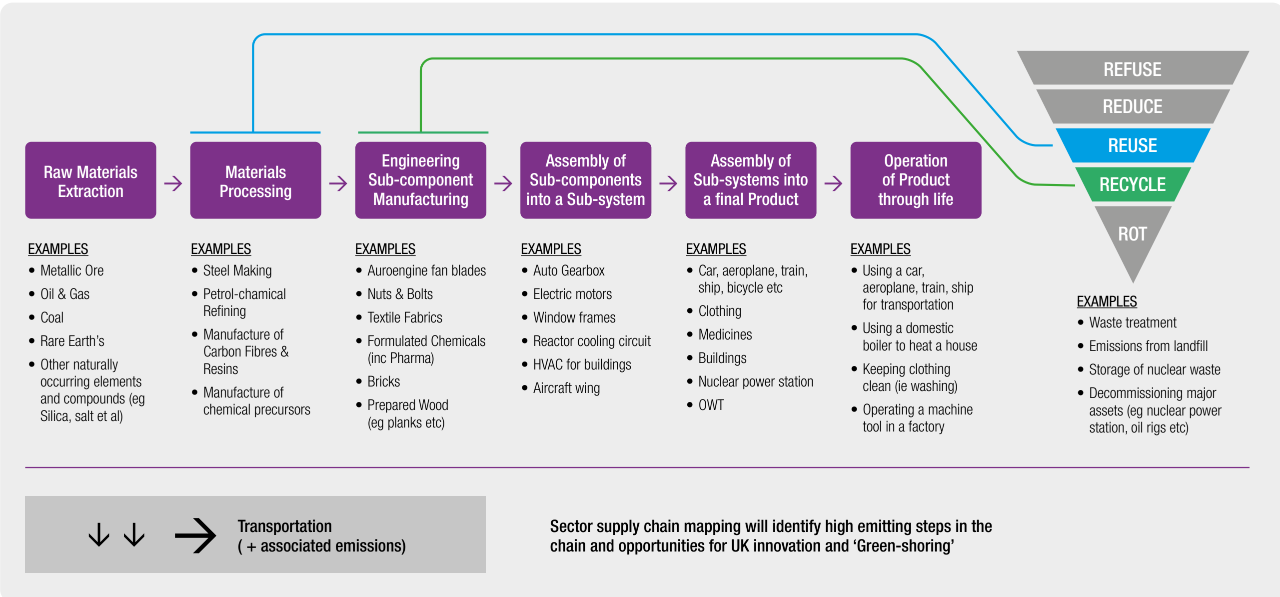


Figure 7. Sector supply chain mapping to highlight high-emitting steps.
Source: High Value Manufacturing Catapult (HVMC)

National Institute of Standards and Technology (NIST)

NIST is part of the Department of Commerce and is one of the oldest physical laboratories in the US. NIST was established by congress to promote US industrial competitiveness in science and innovation by advancing measurement science, standards and technology. With an annual budget of $1 billion, 3,500 employees and 3,500 visiting scientists and contractors, it is one of the largest organisations in the US. This enables NIST to work across several sectors and operate on a broader TRL and MRL level. There is a very strong engagement with industry through several work programmes including Manufacturing USA. NIST has a long-standing programme on materials by design, looking to design new products with increased durability and recyclability. They are also involved in the critical minerals and materials area and work closely with the National Science and Technology Committee (NSTC), United States Geological Survey (USGS) and DoE, focusing on the circular economy and recycling. The Materials Science/Engineered Systems laboratory at NIST looks at polymers, concrete and steel to develop new test protocols on measurement and standards. This ensures manufacturers produce durable and stable products to mitigate the high breakdown rates for materials reaching EoL. The NIST Intelligence Laboratory includes 3D printed components, robotics and circular economy areas.

UKRI and NIST have an MOU signed in November 2020 to facilitate collaboration through:

- Exchange of information.
- Exchange of staff.
- Support for joint research.
- Support for training.
- Joint conferences and workshops.

Manufacturing USA Programme

As part of NIST's manufacturing programme, Manufacturing USA, established in 2014, provides a platform consisting of manufacturing innovation institutes with common goals. Industry, academia and government partners leverage existing resources to facilitate collaboration and investment. The most recent institutes cover industrial decarbonisation and semiconductors. The programme nurtures manufacturing innovation and supports businesses to scale-up and commercialise new products and services. The programme was inspired by the Catapult network in the UK and the Fraunhofer Institute in Germany to help bridge the gap between basic research and commercial application. The US is behind the UK and Europe in industry collaboration which has impeded technology transfer and innovation.[33] The US Government Accountability Office (GAO) conducted a review of the Manufacturing USA institutes and found the majority of projects started at TRL 1-4 and transitioned towards TRL 6-9.[34] This demonstrates the high level of basic research translating to prototype projects ready for commercialisation.

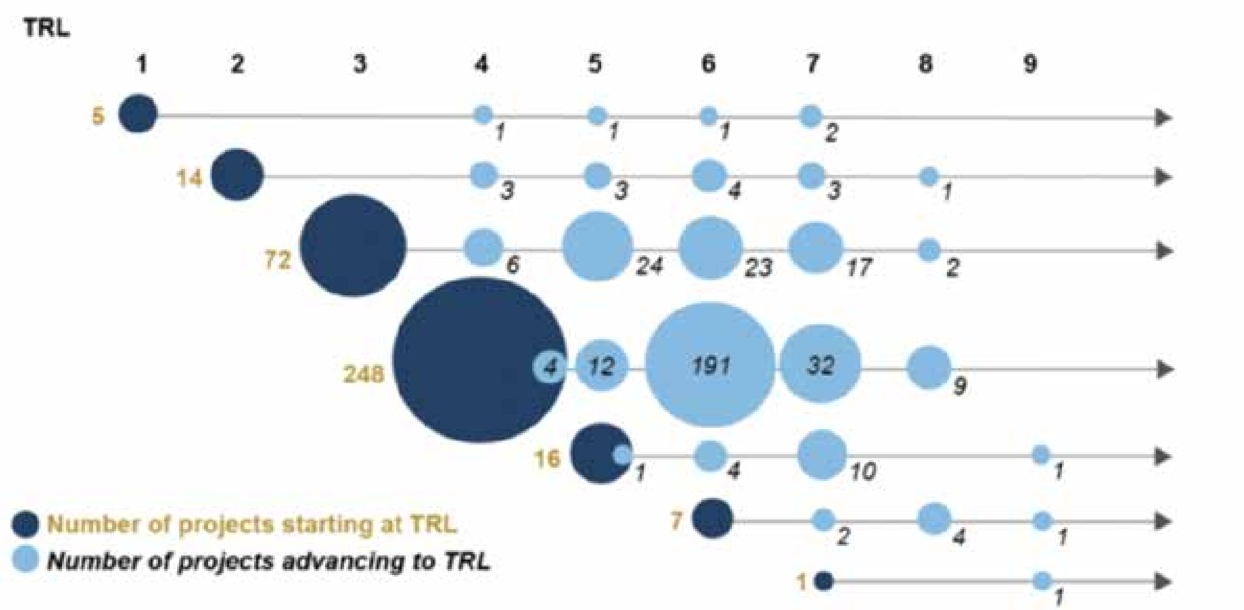


Figure 8. Advancement of TRL for completed Manufacturing USA institute projects. Source: GAO analysis of data provided by Manufacturing USA

Innovate UK has an MOU with the Manufacturing USA's Institute for Advanced Composites Manufacturing Innovation (IACMI), with whom they successfully carried out a bilateral CR&D programme 2019-21. In the area of critical materials and recycling, there is potential to build on this relationship with the Manufacturing USA's ReMade Institute in Rochester, New York.

National Science Foundation

The National Science Foundation (NSF) is an independent federal agency analogous to UKRI operating in the TRL 1-3 domain. With an annual budget of $8.8 billion, NSF provides approximately 25% of all federally-supported basic research. The meeting with NSF was facilitated by the UKRI North America office which has a close working relationship with NSF. The UK delegation met with a senior NSF team consisting of division and programme directors. The purpose of the meeting was to gain an understanding of the country's advanced materials and critical minerals research at the fundamental level. The majority of NSF's critical minerals work sits in the engineering directorate (ENG) under the Chemical, Bioengineering, Environmental and Transport Systems (CBET) and Civil, Mechanical and Manufacturing Innovation (CMMI). There is a growing interest from CBET in biomining, ocean acid mine drainage and recovery of critical minerals from secondary sources such as e-waste, magnets and batteries. In the broader context of recycling materials, digitalisation and product passports were discussed, with a specific concern over tracking and retaining data for products with longer lifetimes than the companies that made them. Education and workforce development in critical materials and mining was highlighted several times and has been a recurrent theme during the mission. While initiatives are underway to review strategies for fostering talent, NSF also organised workshops on converging social and behavioural efforts with engineering and the circular economy to promote recycling.

Convergence Accelerator Scheme

The NSF's convergence accelerator programme aims to address national-level challenges. This is a two-phase programme, with phase 1 providing funding for 12 months to develop the project, followed by phase 2, which is funded for 24 months with significant resources available to develop solutions and prototypes. The scheme allows industry to apply for funding alongside research institutions. The convergence accelerator has a number of research tracks to address societal challenges, with Track 1 focusing on sustainable materials for global challenges. The objectives are to converge advances in fundamental materials science, new processes for materials design and manufacturing and to consider full life-cycle analysis when designing new products to ensure they are environmentally and economically sustainable.

There are a number of overlaps between NIST and NSF, and both organisations seem to have similar R&D priorities. The meeting with NIST and NSF highlighted a number of key areas for collaboration that are highly compatible with UK objectives.

- The Materials Genome project is a federal multi-agency initiative for the discovery and manufacturing of advanced materials. In Canada, there is the Accelerated Materials Discovery programme. There is an opportunity to launch a similar initiative in the UK with a on developing next-generation advanced materials with reduced dependence on critical materials.

- Developing standards and tools to track GHG emissions for accounting and to support the drive towards a circular economy. Tracking emissions in the product life cycle (manufacturing to EoL) is key to achieving net-zero targets. The UK is already working on Scope 1, 2 and 3 emissions tracking and management across the product life cycle. NIST is extremely active in LCA modelling and tracking, and there are opportunities to work collaboratively in this area.

- NIST is working on the digitalisation of engineering and Industry 4.0, and there is a drive to transform the way new materials are designed and manufactured. A US/UK collaboration would facilitate knowledge transfer and co-developing of international tools and standards. These new tools will form the foundation for developing a "materials passport" for critical materials – from mine-to-EoL.

- There is considerable interest in jointly working on the future workforce with NSF and NIST. This could be through joint workshops on topics including foresighting the future workforce capability and needs, addressing EDI in STEM-based industries, education on critical materials and the mining industry and creating industry-ready researchers.

Scope 1, 2 and 3 emissions and their impact on mining operations

Scope 1: This is the GHG emission the company emits directly.
Scope 2: These are emissions the company makes indirectly.
Scope 3: These are emissions the company does not produce but is indirectly responsible for. For example, buying products from suppliers. It considers the whole supply chain.

Mining is an energy-intensive industry and requires constant power and fuel to operate. However, a significant effort through government policies, new technology in automation and efficient processes has reduced GHG emissions in mining. Scope 1 and 2 account for 4-7% of global GHG emissions. However, the challenge is reducing Scope 3 emissions, which account for 28% of all GHG emissions.[35]

6. Summary and Conclusion for US

The UK delegation visited Argonne National Laboratory and the Critical Minerals Institute (CMI) at the Ames National Laboratory. This was followed by meetings in Washington DC with representatives from the National Science Foundation, the National Institute for Standards and Technology, and Securing America's Future Energy (SAFE), a US think tank on critical minerals strategy.

The visit provided insights into the national strategy and investment plan in critical materials and an opportunity to identify potential bilateral collaboration between the two countries. The visit to Argonne and the CMI in Ames offered key insights into strategic priorities and R&D in critical materials. The US does not have a strong mining industry compared to Canada, and most minerals are shipped overseas for processing. However, the US is very strong in advanced manufacturing and material design, which was apparent from the conversations with NIST and NSF. There is already a strong collaboration in battery technology and recycling between the ReCell centre in Argonne and the Faraday Institute in the UK. There are a number of research programmes that align with UK objectives and are areas where there should be an ongoing dialogue to develop long-term partnerships. These include:

- Engaging with DoE labs such as the CMI at Ames to help develop future bilateral programmes. There is an existing network between the CMI and Japan, and the UK will benefit greatly in setting up a similar international initiative or joining an existing network.

- Recycling and implementing circular economy principles to reduce dependency on critical materials. Argonne and the CMI at Ames have long-standing research programmes in critical materials recovery from waste batteries through the ReCell centre and the development of substitute materials. Collaborative R&D programmes will provide an opportunity for UK businesses and research and technology organisations to learn and share best practice.

- Supply chain mapping and forecasting is vital for the UK to mitigate any critical materials supply chain vulnerabilities. The UK and the US are working on similar programmes, and our findings suggest there is synergy in combining efforts. Both Argonne and Ames are working in this area.

7. Global Expert Mission in the Context of the UK's Critical Mineral Strategy

The Government recently published a strategy for the UK in response to the challenges in global supply and resourcing of critical minerals. The strategy document aims to improve supply chain resilience and to ensure critical minerals are made available in the quantities needed to support UK manufacturing now and into the future.

The strategy sets out three key areas of focus:

1. Accelerate the UK's domestic capabilities.
2. Collaborate with international partners.
3. Enhance international markets to ensure the UK is at the forefront on critical mineral stewardship and the green industrial revolution.

The UK strategy was published shortly after the delivery of the critical material GEM. The GEM was, therefore, incredibly timely and of strategic importance as the UK looks to engage and develop international partnerships in this topic area.

The GEM enabled UK experts to deep dive into the research and innovation ecosystems of both Canada and the US, allowing greater understanding of the R&D priorities, synergies between the three countries and opportunities for collaboration.

The table which follows highlights the key opportunities identified by the GEM and retrospectively maps these against the objectives set forth in the UK Critical Mineral Strategy document.

UK Critical Mineral Strategy[36]	UK Critical Mineral Objectives[36]	Critical Material Global Expert Mission Recommendations
Accelerate the UK's domestic capabilities	Rebuild our skills in mining and minerals.	Set up bilateral collaboration between UK and international organisations on skills and workforce development. Collaboration on workforce foresighting is needed to identify gaps in the critical minerals supply chain (mine-to-manufacture)
	Carry out cutting-edge research and development to solve the challenges in critical minerals supply chains.	Work closely with the CMI and other DoE national laboratories to set-up joint CR&D calls.
	Make better use of what we have by accelerating a circular economy of critical minerals in the UK – increasing recovery, reuse and recycling rates and resource efficiency, to alleviate pressure on primary supply.	Design materials for increased durability and develop methods for efficient recovering of critical minerals from e-waste.
Collaborate with International partners	Diversify supply across the world so it becomes more resilient as demand grows.	Develop global supply chain and demand modelling. Work closely with CMI and Argonne National Laboratory and include UK counterparts, BGS and CMIC.
	Support UK companies to participate overseas in diversified responsible and transparent supply chains.	
	Develop our diplomatic, trading and development relationships around the world to improve the resilience of supply to the UK.	
Enhance international markets	Boost global environmental, social and governance (ESG) performance, reducing vulnerability to disruption and levelling the playing field for responsible businesses.	Develop and lead international standards in GHG tracking and accounting across supply chains. Work with US and Canadian organisation to develop LCA modelling and methods to account for Scope 1, 2 and 3 emissions.
	Develop well-functioning and transparent markets, through improved data and traceability.	Develop global supply chain and demand modelling. Work closely with CMI and Argonne National Laboratory and include UK counterparts, BGS and CMIC.
	Champion London as the world's capital of responsible finance for critical minerals.	

Annex 1: Companies Attending the Global Expert Mission Event in Ottawa

The Canadian Critical Minerals and Materials Alliance (C2M2A)

The C2M2A is a non-profit, independent organisation which endeavours to grow the Canadian economy through critical mineral supply chains. C2M2A's vision and mission will help Canada diversify its economy, foster job creation and provide an economically-viable and healthy environment for future generations. The organisation enables stakeholders around the country to collaborate on shared priorities while respecting each jurisdiction's needs and abilities – including the need to ensure the continued competitiveness and viability of businesses.

Centre for Excellence in Mining Innovation (CEMI)

CEMI's objective is to help the mining sector achieve a step-change improvement in performance by accelerating the adoption of commercially-viable innovations in mines and increasing the innovation capacity of the mining services companies that deliver techniques and technologies to the industry. Their services are designed to bridge the gap between a challenge and a solution.

Cheetah Resources

Cheetah Resources, a vitals metals company, is Canada's first rare earths producer. Cheetah Resources aims to become the lowest cost producer of mixed rare earth oxide outside of China by developing one of the highest grade rare earth deposits in the world and the only rare earth project capable of beneficiation solely by ore sorting.

COREM

COREM is a not-for-profit centre of expertise and innovation that provides mining companies with a range of specialised services and R&D expertise to optimise and develop key mineral processing processes. COREM works closely with its members, customers and partners to improve competitiveness and reduce environmental impact through innovative solutions.

Defence Metals

Defense Metals is a mineral exploration company focused on the acquisition of mineral deposits containing metals and elements commonly used in the electric power market, military, national security and the production of green energy technologies, such as high-strength alloys and rare earth magnets.

Geomega

Geomega is building the world's first sustainable rare earths recycling facility to help meet surging global magnet demand as the transition to vehicle electrification and renewable energy sources accelerates. By using Geomega's innovative technology and Quebec's renewable hydropower, they are keeping permanent magnets from the landfills and putting these critical rare earths back into a more self-sustaining supply chain. They are then leveraging their technical expertise to help extract value from various feeds which contain rare earths and other critical metals.

SGS Canada

SGS is one of the world's leading testing, inspection and certification companies. SGS is recognised as the global benchmark for quality and integrity. The company's 96,000 employees operate a network of 2,700 offices and laboratories, working together to enable a better, safer, more interconnected world.

Saskatchewan Research Council (SRC)

SRC is Canada's second largest research and technology organisation with 1,500 clients in 27 countries. SRC focuses its efforts on the mining, minerals, agriculture and energy sectors, and the important environmental considerations across each sector.

Search Minerals

Search Minerals focuses on exploring and developing the Critical Rare Earth Element District in Southeastern Labrador, Canada. This district is road accessible, on tidewater, and contains significant quantities of those elements that are in short supply and considered strategic or critical due to their use in green economy technologies. Based on these attributes, the company hopes to become a competitive, low-cost, environmentally responsible supplier of critical rare earth elements (CREE) to the global market.

University of Toronto

Department of Materials Science and Engineering. A combined theoretical and experimental approach to address the world's major challenges regarding growing demand for natural resources (energy and materials) and anthropogenic environmental impacts through enhancement of overall process performance and utilisation of new materials in various industrial sectors (energy, water, and metals).

Wyloo Metals

Wyloo Metals, formerly Noront Resources, is a Canadian-based mining company headquartered in Toronto with ownership or a controlling interest in all the major discoveries in the Ring of Fire, an emerging multi-metals area located in the James Bay Lowlands of Northern Ontario. The company is developing resources essential to a decarbonised future, including nickel, copper, chrome and platinum. The company's first project is Eagle's Nest, a 100%-owned, high-grade nickel, copper and platinum group element (PGE) deposit.

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15 Critical minerals research, development and demonstration programme

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17 Ontario's Critical Minerals Strategy 2022-2027

18 Panel discussion feedback from Search Minerals a company conducting exploration of REE in Canada.

19 Natural Resources Canada Rare earth element facts

20 Discussion with Geomega, a company working on recycling magnet waste.

21 Presentation from Centre for Excellence in Mining Innovation.

22 Sorting it out: Ore sorting gains traction

23 Feedback from Saskatchewan Research Council, Canada's second largest R&T organisation.

24 Conversation with Bryan Tisch from NRCan on Friday 20th May at the British High Commissioners Residence meeting

25 Latest SRC performance highlights presented by SRC

26 Securing a Made in America Supply Chain for Critical Materials

27 DoE Clean Energy

28 GM to Phase Out Gas- and Diesel-Powered Vehicles by 2035

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36 Resilience for the Future: The United Kingdom's Critical Minerals Strategy

Connecting for
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