Midstream Processing and Refining

Unlocking Security of Supply

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About the Critical Minerals Association United Kingdom (CMA UK)

Critical Minerals Association United Kingdom

The Critical Minerals Association United Kingdom (CMA UK) is a key interlocutor between the UK Government and the critical minerals industry. Its mission is to support the development of socially and environmentally responsible critical mineral supply chains for the UK's strategic security of supply for the Energy Transition, Energy Security, and Green Economy.

The CMA UK unites industry, academia, and other stakeholders to address challenges in critical mineral supply chains. The CMA UK enables industry to generate a collective voice when outlining concerns and recommendations and provides a direct line of communication with government. The CMA UK aims to improve societal perceptions of the sector by showcasing the economic and social benefits of critical minerals. The CMA UK also provides the secretariat to the UK's All-Party Parliamentary Group (APPG) on Critical Minerals.

Critical Minerals

Critical minerals underpin the foundation of the modern world. Green technologies such as electric vehicles, wind turbines, solar panels, hydroelectric plants, or hydrogen-based technologies cannot be built without raw materials. Critical minerals are necessary for many key industries, including agriculture, energy, and defence.

Geoscience Australia defines a critical mineral as "a mineral or element (solid, liquid or gas) that is essential for modern technology and cannot be easily substituted with a different mineral AND there is a risk that the supply of that mineral could be disrupted".[1] However, criticality itself can evolve rapidly as geopolitical tensions disrupt monopolised supply chains. This means that minerals and metals can quickly become critical, and what is critical to one nation may not necessarily be critical to another.

Midstream Processing and Refining:
The Key to Security of Supply

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Abbreviations & Acronyms

BGS	British Geological Survey
BIL	Bipartisan Infrastructure Law
CAM	Cathode Active Material
CAPEX	Capital Expenditure
CMA UK	Critical Minerals Association United Kingdom
CMIC	Critical Minerals Intelligence Centre
COP26	2021 United Nations Climate Change Conference
DIT	Department for International Trade
DOD	Department of Defense
DOE	Department of Energy
DPA	Defense Production Act
EOL	End-of-life
ESG	Environmental, Social & Governance
EU	European Union
EV	Electric Vehicle
EVB	Electric Vehicle Battery
FCDO	Foriegn, Commenwealth & Development Office
FTA	Free Trade Agreement
GDP	Gross Domestic Product
ICA	Investment Canada Act
IEA	International Energy Agency
IRA	Inflation Reduction Act
JOGMEC	Japan Oil & Gas
LCM	Less Common Metals
LED	Light-emitting Diode
LIBS	Lithium Ion Batteries
LME	London Metal Exchange
LPAs	Local Planning Authorities
MSA	Mineral Security Act
MREDS	Mixed Rare Earths Durable Sulphate
MSP	Minerals Security Partnership
NIMBYISM	"Not in my back yard"
OEMs	Original Equipment Manufacturers
OPEX	Operating Expenditure
REE(s)	Rare Earth Elements
TVL	Tees Valley Lithium
UK	United Kingdom
UKRI	UK Research and Innovation
US	United States
USA	United States of America
USGS	United States Geographical Survey
WA	Western Australia
WEEE	Waste Electrical and Development Office

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Executive Summary

Critical minerals, defined as those that have high economic impact, high supply risk or strategic importance, are essential for technology needed to achieve net zero and many nations' industrial goals. Many critical minerals have no practical substitutes and some critical minerals are only produced as by-products of other metals.

Global demand for critical minerals is forecast to **increase by several hundred percent**. This will require an equivalent increase in mining and metal refining capacity – many Western nations have outsourced this to developing nations over the past century. This short-sighted strategy is most prominent in the midstream processing and refining space. Concerns over critical minerals shortages are already creating global competition. Especially as a handful of nations, for example China, Russia, Indonesia, South Africa, dominate specific critical minerals supply chains. **China's hegemony is dominant across midstream and downstream processing and refining** of many critical minerals – capturing value and control.

Increased demand, geopolitical tensions, and logistics failures have ended the reliable, smooth, on-demand supply of critical minerals. Consumers are changing from just-in-time to just-in-case supply. However, navigating complex, opaque, and heavily monopolised supply chains is difficult for many original equipment manufacturers. Likewise, Western upstream (exploration, mining), and midstream (processing, refining) companies are facing challenges operating in controlled markets.

A secure supply of critical minerals is essential for the security of the UK's automotive, advanced manufacturing and defence industries. The UK is however falling further and further behind the key Western players in the race to secure critical minerals – at a risk of failing to cement a bright, sustainable future for the UK.

Despite the release of its Critical Minerals Strategy in July 2022, and creation of the Critical Minerals Intelligence Centre under the guidance of the British Geological Survey (BGS), the UK Government has done very little to change the domestic landscape, and support the industry through a dedicated fund to support UK-owned critical minerals projects both at home and overseas.

The UK has limited domestic ore deposits, but has projects currently under development to produce tin, tungsten, and lithium. These have been progressing despite lack of UK Government's support. Mining projects have a long lead time and can take 10 to 20 years to bring into production after discovery of the ore body.

With UK Government support, these projects of national strategic importance would produce critical minerals at a much faster rate and encourage further growth. However, the UK will continue to rely on imports of critical minerals, regardless of domestic production, due to the scale of the volume required for industrial applications. Hence, it is imperative that the UK focuses on enabling the growth of the UK's processing and refining sector.

Several UK midstream metal refineries closed in the late 20th century. A few large plants remain and there are smaller recycling plants with unknown capacity. To regain some security of supply, the UK Government will need to invest in strengthening the UK midstream industry. The UK already has several refining plants under development including for lithium hydroxide, and rare earths, but a future midstream industry will not operate without a secure and consistent supply of feedstock.

The UK Government will need to create a favourable business environment. Industrial energy prices in the UK are amongst the highest in the European Union and other G7 countries[2], but there are government support schemes for critical minerals producers. Nevertheless, the UK will face competition as a midstream producer from countries that have low-cost renewable energy from hydroelectric sources and existing midstream industries. Planning approval and permitting of critical mineral mines and midstream plants devolves to local authorities and Government agencies, such as the Environmental Agency, in the UK. They often lack adequate expertise in the technologies, leading to delays and increased costs.

Midstream processes are often complex and are feed specific. Specifications for midstream products are demanding and it can take time to develop a working solution. Yet, midstream plants can be brought into production far more quickly than mines, but this requires skills and expertise.

Lamentably, all mining and minerals processing degree courses in the UK have closed or are in temporary suspension. **Approximately 80% of registered mining and minerals processing engineers are aged over 50.** New graduates from these disciplines will be needed to design and operate future midstream plants. The UK's proposed circular economy will require these skills. Without significant investment and re-education process of the importance of critical minerals, the UK will have to import talent from Southern Africa, Eastern Europe, and Asia. Many Western nations are also facing a skills shortage.

The UK has significant scope to expand its circular economy for critical minerals. **It is essential to recycle end-of-life EV batteries domestically to protect the automotive industry, as well as end-of-life wind turbine magnets.** The scale of this recycling should make it economically attractive as well as necessary for domestic security. Many EVs will be reaching end-of-life by 2030, plants and processes should be set-up and refined now.

The UK may also have critical minerals resources in historic wastes from coal mining and steel mill flue dusts. This needs mapping and evaluation to determine the potential.

Facilities for recycling waste electrical and electronic equipment (WEEE) are limited. **WEEE and lithium-ion batteries are not currently included in UK recyclable waste classifications.** WEEE recycling is neither encouraged nor enforced, and collection methods are a disincentive. Historically, WEEE has (and continues to be) exported or discarded to landfill. The latter provides a potential resource for "urban mining".

Recycling of WEEE is complicated by the small quantity of metal contained in devices, and the need for disassembly. Countries with which the UK has strong ties, for example Canada, have developed effective collection and recycling methods that could potentially be shared. Even with increased recycling, the UK's demand for critical minerals will not be met. It will still be necessary to import critical minerals derived from primary mining. Recycling would nevertheless increase the UK's security of supply.

Domestic mining, processing, and refining can ensure that any critical minerals made in the UK are not produced at detriment to the environment or communities. There is public and institutional objection to the import of goods that are not environment, social, and governance (ESG) compliant, and to the export of waste for reprocessing in countries that do not have high ESG standards.

The UK is already a leading centre for mining finance, legal services, insurance, metal trading, and consultancy – advantages that can be leveraged to secure the UK's critical minerals needs. However, the nation cannot afford any further government inaction. Favourable policies and significant funding are needed to secure the UK's future and lessen the nation's reliance on existing monopolies.

Recommendations

The success of the UK's midstream and downstream processing industry relies on the actions that the UK Government takes and the ability for like-minded nations to collaborate on creating alternative supply chains outside of the existing monopoly.

CMA UK recommends that the UK Government implements the following strategic solutions to secure the UK's stable and resilient green economy:

1. Incentivise and Accelerate Investment into UK Midstream and Downstream Processing

- Critical Minerals Intelligence Centre (CMIC) to create an investment portfolio and / or prospectus of key UK projects to stimulate private investment, prioritising metals, and minerals the UK most needs
- Underwrite critical mineral projects of national strategic importance that will help the UK regain control of security of supply
- Create tax incentives akin to those of the Inflation Reduction Act to ensure the UK becomes an attractive market for critical minerals supply chains
    - This could be targeted at specific critical minerals, most vulnerable supply chains, or the UK's dominant industries reliant on critical minerals
    - Practical conditions of eligibility could incentivise best-in-class environmental, social and governance, upskilling, training, and education for young people including in levelling-up areas, and acceleration towards decarbonisation of critical minerals supply chains
- Re-introduce the red diesel rebate for all critical mineral activities, from exploration through to downstream processing to ensure that the UK midstream is regionally competitive and has some local sources of feedstock available
- Introduce an energy cap and / or subsidies for projects that qualify as of national importance (i.e., those that add strategic, defence, or significant economic value) to ensure that any operating or wishing to operate in the UK, are not priced out by the energy crisis
- Accelerate access to low-cost renewable energy for production of critical minerals without Transmission Network Use of System Charges
- Create an innovation fund, out of UK Research and Innovation (UKRI), specifically for novel processing and refining technologies that pioneer environmental, social and governance (ESG) best practices
- Act as a bridge between companies wanting to implement innovative, responsible technologies at a commercial scale, and insurance to ensure timely progression towards better technologies and practices
- Ensure rules of origins in future Free Trade Agreements (FTAs) are favourable to export and import of processed and refined critical minerals

2. Align Government Departments on the Importance of Critical Minerals

- Create a Critical Minerals and / or Resource Agency that has overarching capability and remit to coordinate Government departments that involve critical minerals
- Ensure that the Agency has a dedicated minister who can make decisions that are in the best interest of the nation's security of supply
- Review current policies and legislation to ensure the current system is not prohibiting the timely delivery of critical mineral projects, specifically across planning and permitting, imports and exports
- Ensure departments are moving in the same direction (e.g., HM Treasury decisions reflect the net zero agenda and do not disadvantage industries reliant on fossil fuels, that currently do not have access to alternative energy sources at competitive prices)
- Ensure that the Critical Minerals and / or Resource Agency is a single point of contact for all companies in the critical minerals value chain to obtain information about planning and permitting, energy prices, laws and regulations, access to grants and funding
    - Assign a case worker for all projects of national importance who are responsible for removing barriers to timely operation of the project, subject to responsible business practices

3. Leverage UK Freeports to Promote International Business

- Ensure that companies with the potential to contribute to the UK's security of supply are granted priority access to valuable real estate
- Actively engage with energy providers to ensure freeports are powered 100% by 'green' energy at regionally competitive prices
- Introduce energy caps and / or subsidies for industry to ensure growth and to retain jobs especially during economic downturns

4. Extend the UK's Soft Power by Supporting UK Critical Mineral Companies Operating Overseas

- Create a joint multibillion-dollar investment fund to support the set-up of midstream facilities in allied nations
- Create a task force dedicated to supporting Western companies, and those of allied nations) operating or attempting to operate outside of monopolised markets across multiple nations
- Extend the Minerals Securities Partnership (MSP) to include like-minded African and South American nations
- Align the Department for International Trade (DIT), Foreign, Development & Commenwealth Office (FCDO) and HM Treasury with UK export finance to provide funding for UK companies operating overseas that intend to partially supply UK-based OEMs
- Provide resource to Department for International Trade (DIT) and Foreign, Development & Commonwealth Office (FCDO) to act as point of contact between industry and foreign governments and to facilitate growth of British businesses overseas
- Collaborate with Western governments to plug into their planned midstream and downstream processing facilities
    - This can involve providing funding in exchange for a certain amount of processed material, providing UK feedstock, or providing access to UK-based original equipment manufacturers (OEMs)

5. Invest in the Next Generation of Critical Mineral Leaders

- Ensure that the disconnect between end products and where raw materials come from is addressed via early years curriculum and secondary education
- Actively engage with UK university leaders to emphasise the underpinning role of geosciences in mitigating climate change
- Create discounted university programmes for most at-risk occupations, for example mining engineers, metallurgists, and mineral processors, to encourage uptake by individuals from lower socio-economic backgrounds, particularly those from mining heritage areas that would otherwise be unable to finance undergraduate and postgraduate studies required to enter the industry
- The Prime Minister to issue a public statement of commitment to support critical mineral projects and highlight the necessity of critical minerals to tackling the energy crisis, ensuring the UK's economic prosperity, and building the UK's green economy

Supply Chain Crunch

> **Rules of Origin**
>
> Rules of origin are the criteria needed to determine the national source of a product. Rules of origin allow businesses to claim tariff preference on imports, and prove the origin of exports.

The importance of critical minerals is now widely recognised by Western governments and allied nations after decades of China's monopolisation of the midstream and downstream processing. Supply chain disruption during the COVID-19 pandemic, increasing public pressure to decarbonise, and more recently, the European energy crisis, have put critical minerals in the spotlight, as the building blocks of "net zero" and emerging technologies.

The impacts of rules of origin, specifically between the UK and European Union, following Brexit, are increasingly causing original equipment manufacturers (OEMs) to scrutinise their supply chains. Likewise, the European Battery Passport[3] will require OEMs to have thorough understanding of the value chain involved from mine to electric vehicle battery (EVB) to satisfy the Green House Gas Rulebook[4] and capture ESG performance indicators. It is currently unclear how European OEMs will navigate opaque supply chains to meet both rules of origin and Battery Passport criteria.

The **demand for critical minerals** required for net zero technologies alone is f**orecast to increase sixfold from 7.1Mt in 2020 to 42.3Mt by 2050**.[5] However, extraction alone will not help the Western world regain security of supply without an alternative midstream located outside of existing monopolies for different critical minerals including China, Russia, and Indonesia

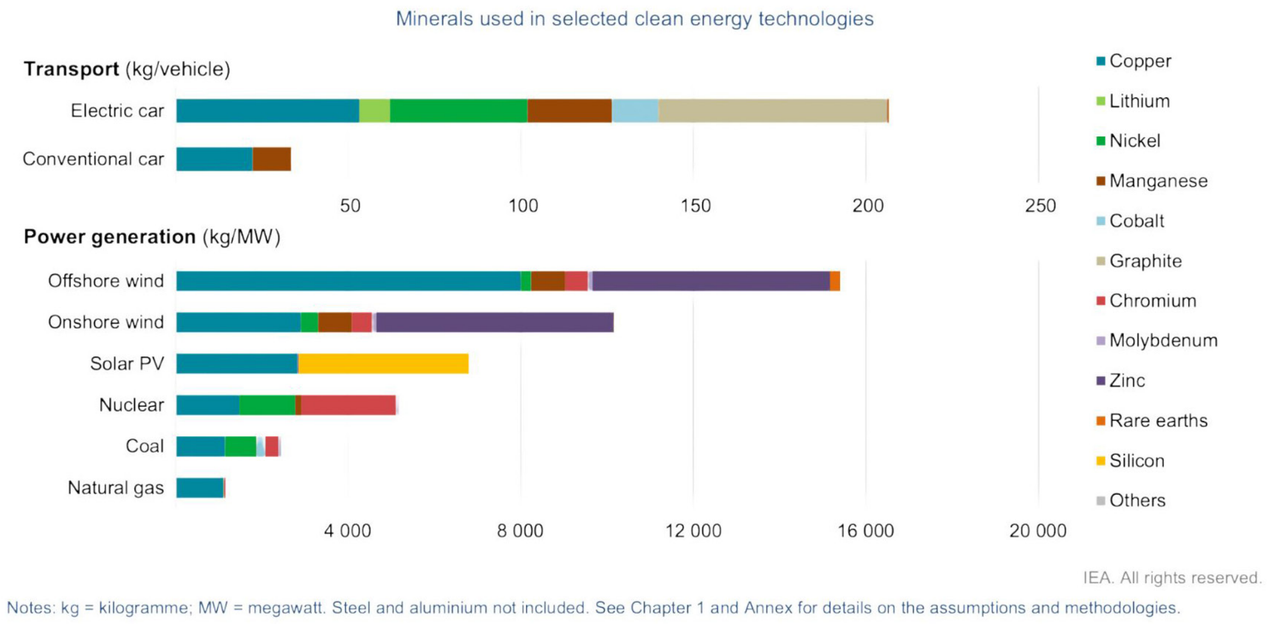


Figure 1: Projected demand for key critical minerals needed in the production of selected net zero technologies. This projection does not include the amount of critical minerals needed for the associated infrastructure (e.g. cables, generators etc), or other sectors including defence, medical, high-spec tech, aviation, space and more.

The West discarded much of its mining, processing, and refining capability as it became cheaper to mine, process, and refine critical minerals in Asia, particularly in China and Indonesia. Access to cheaper labour, abundant coal for energy generation, strong government backing, and relaxed regulations around health and safety and environmental practices created a much cheaper supply of minerals and metals required by Western OEMs. The resultant drop in international metal prices, as the market was flooded by cheaper alternatives, undermined feasibility of Western extraction and refining. In the meantime, Chinese policy leveraged increased globalisation to gain strategi control of some critical minerals supply chains through midstream and downstream processing. Whether this occurred by design, through evolving markets, or both, the Chinese Government had the foresight to support an emerging sector that presently underpins infrastructure, the economy, and the transition towards fossil fuel alternative energy sources.

Currently, the majority of critical minerals, with several exceptions (e.g. niobium, nickel), are processed and refined in China, this leaves the rest of the world over-reliant on a single nation without access to alternative markets. This leaves many OEMs exposed to sudden supply chain crunches and resultant price fluctuations.

Figure 2

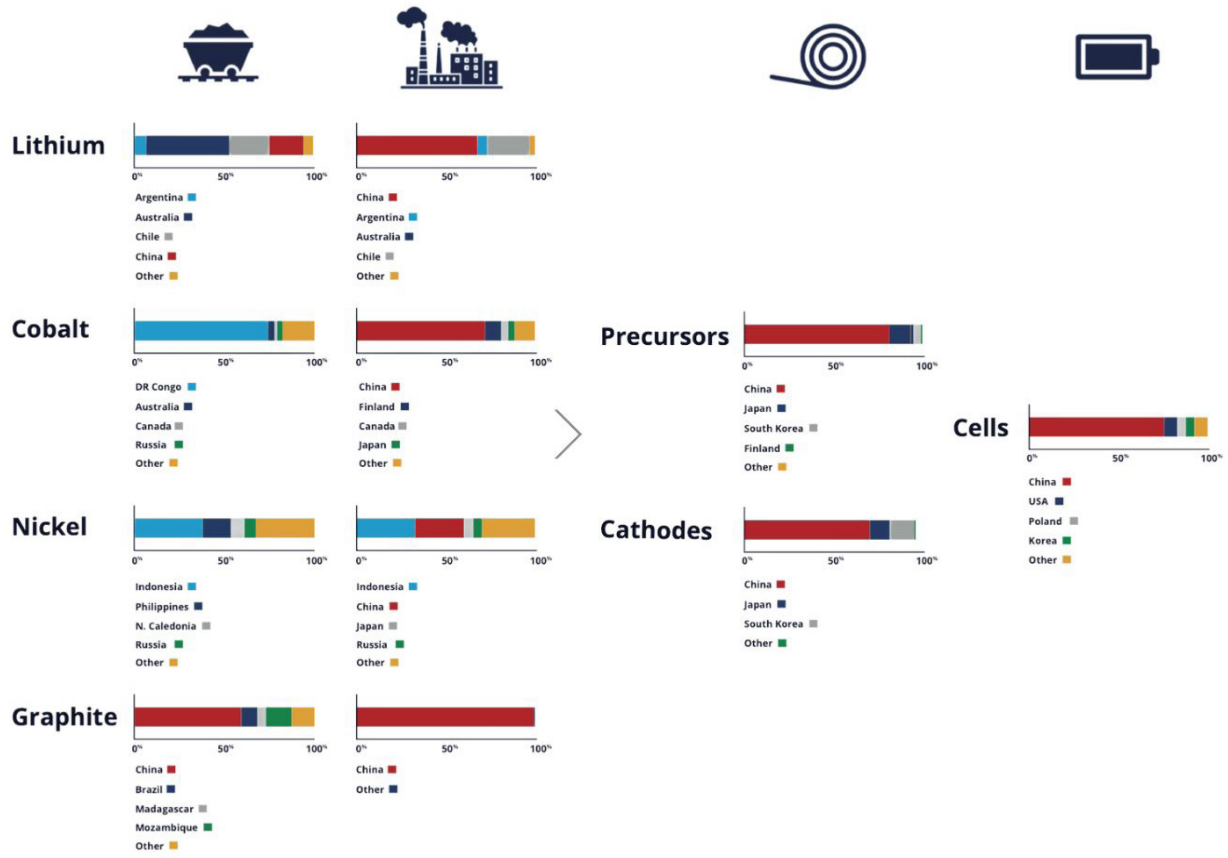


Figure 2: Supply chain monopolisation of key battery materials. Battery minerals, like the reminder of critical minerals, are geographically distributed across the globe and controlled by geology. Some nations are the dominant producers of certain critical minerals, e.g. the Democratic Republic of Congo (DRC) produces the majority of the world's cobalt, due to natural geological endowment and (more often) due to cheap labour costs and a lack of stringent environmental protections and legislation. The extracted critical mineral ore is sometimes processed on site, and in many instances, shipped to China for further processing and refining. Waste material is separated from valuable critical minerals - this is where the significant value-add happens. For the battery minerals supply chain, precursor materials to anode and cathode production are controlled between 60% to 80% by China, as is battery cell production. This leaves many aspiring and existing miners reliant on offtake agreements with Chinese companies, at a price dictated by them.

Source: Wood Mackenzie, 2022.

Secure, stable, and diversified critical mineral supply chains are necessary to prevent the risk of interrupted manufacture of goods and economic growth of many nations. However, critical mineral supply chains often cut across multiple nations and as a result can be subject to sudden geopolitical disruptions (e.g., the price of nickel doubled to $100,000 a tonne over the course of a day at the start of Russia's invasion of Ukraine[6]). Disruptions to production, processing, refining, and trading of critical minerals have a ripple effect across not only specific supply chains but also the whole ecosystem of businesses and communities that interact with them.

The semiconductor shortage, which is now in its third year[7], has highlighted many OEMs flawed approach to and over reliance on "just-in-time" supply. Lack of supply chain diversification, and heavy monopolisation of critical minerals, leaves OEMs unable to seek alternative supply chains as these do not yet exist particularly for rare earth elements (REEs), delaying production, impacting profits and brand integrity.

We expect this to become commonplace across many manufacturing sectors as the supply-demand gap widens and geopolitical tensions mount.

Although the shortage has led to some OEMs proactively engaging with their supply chains, and in some cases, investing into future supply directly from the mine (e.g. GM Motors agreement with the Australian Queensland Pacific Minerals[8], €1.5 Billion deal between Mercedes-Benz and the German-Canadian Rock Tech Lithium[9]), the lack of investment into extraction and processing or critical minerals in the past decade limits the material that is or will be available in the near term as the demand, spurred by the energy transition, grows rapidly.

Some critical mineral companies, both in the upstream and midstream are attempting to create supply chains outside of China's sphere of dominance. An example includes Energy Fuel's REE carbonate being shipped from their White Mesa Mill in Utah to Neo Performance Material's separation facility in Estonia[10]. While this is a great initial step, and showcases that alternative supply chains can be set-up, it is a drop in the ocean in comparison to **China's control of 80-90% of refined REEs**. Similar activity is seen in the lithium space with proposed partnerships between UK and Australian companies.

Supply Chain Complexities

Fundamentally, there is no shortage of metals globally, but production is constrained by geology, economics, environmental impact, and time (our biggest constraint in addressing security of supply and climate change adaptation). Mining inevitably occurs where orebodies are located. Subsequent processing and fabrication can be undertaken anywhere, subject to end market, logistics and infrastructure, and government policy. The projected shortage stems from lack of foresight, long-term planning, steady investment into the supply chain, and agility of governments to adapt to rapid changes.

In capitalist economies, metal will only be mined and produced if it is economic to do so. High energy requirements and environmental impact may render extraction processes unacceptable. Both constraints can vary with time as technology and demand change. An additional constraint is the time taken to bring a new mine into production. **A recent survey of 35 major mining projects indicated an average of 17 years between discovery and production**[11]. This should encourage development of the circular economy as recycling plants can be built more quickly, subject to planning approval. However, recycling will only produce a fraction of demand and many new mines will be needed regardless.

Location of the Midstream

The midstream tends to follow both demand and the manufacturing sector, and in recent years, gigafactories. Some electric vehicle gigafactories need supply chains which are proximity dependent, particularly in the case of lithium hydroxide, to minimise shipping costs of waste (spodumene, a lithium ore, is approximately 95% waste), and lower the carbon footprint of the end product.

Stages in the Production of Metals

Metals and their chemical compounds are ultimately converted into industrial and consumer products and production can be split into three phases:

Upstream

Primary production of ores at mines or brine sources. This includes preliminary beneficiation to a mineral concentrate or impure metal, and safe storage of valueless waste. This will naturally take place at the location of the orebody. Depending on the metal, scale of production and infrastructure, larger mines may have elements of midstream production such as smelters, solvent extraction plants, and electrolytic refineries.

Midstream

Refining of impure metals or their conversion into alloys or compounds to be used in final product manufacture. The processes can be technically complex with demanding product specifications.

Although midstream processing plants can be found at large mine sites, they are more commonly at locations with high skill levels and good infrastructure, including urban areas. Centralising midstream operations achieves economy of scale, diversity of supply, feed blending for optimisation, and proximity to end users. An important aspect of the midstream is that it is the point in the circular economy at which recycled material is also introduced.

Downstream

Conversion of the refined metal or its compound into a final product such as electric vehicle battery cells or rare earth metal magnets. Waste inevitably produced in downstream operations can be recycled to the midstream.

Feed Blending

Metallurgical refineries receive feed material from different sources. The nature and chemical analyses of each feed material may be different, particularly with respect to deleterious (or "penalty") elements. Also, some constituents may generate more heat in the process, thus reducing the energy that must be added from fuel or electricity.

The efficiency of the refinery and the quality of the final product are improved if the feed to the process is reasonably consistent, and avoids high levels of impurities that must be removed. A homogenous feed, optimised for the process, is prepared by blending material from different sources in the ratio required to give the optimum chemical composition.

Figure 3

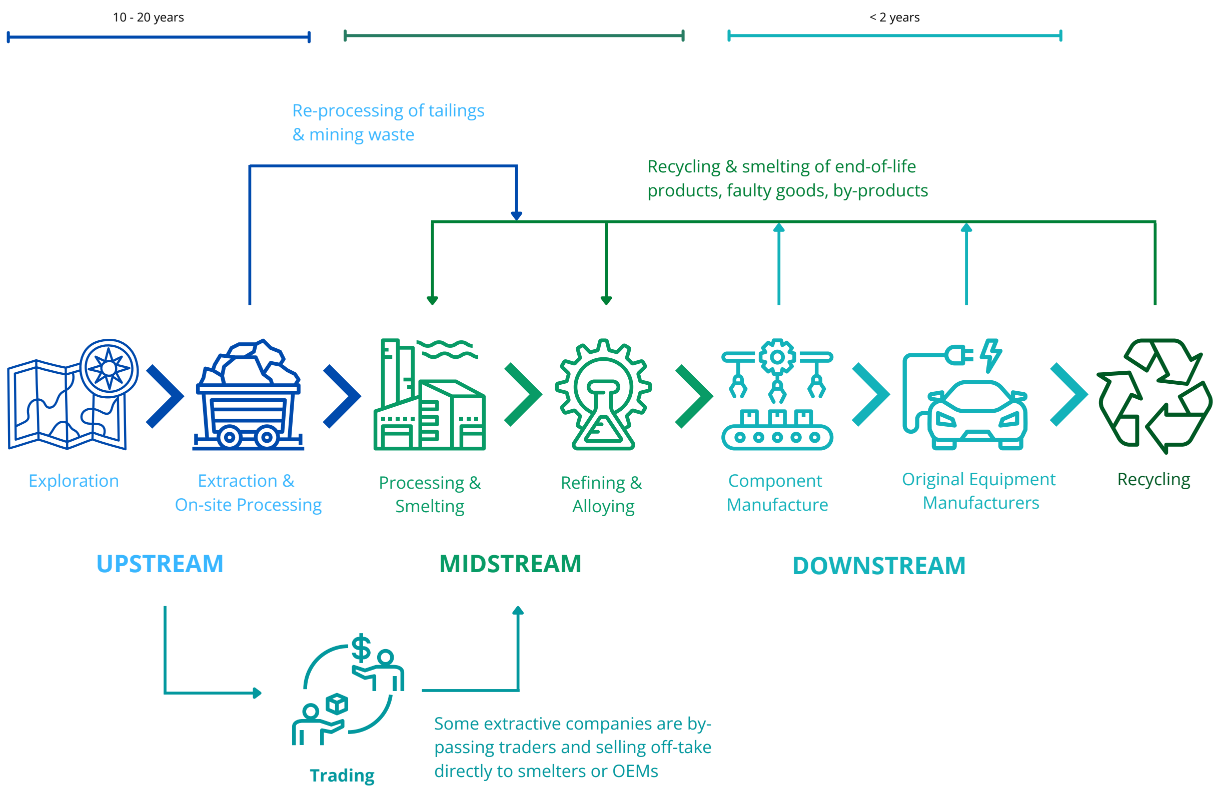


Figure 3: Overview of the typical stages from early greenfield exploration, through to extraction (mining, in solution or in-situ), processing and smelting, refining, component manufacture, OEM manufacture / component assembly, and recycling. Traders typically bridged the gap between upstream production of minerals and the midstream processing and refining. The concern over security of supply has prompted some OEMs to secure offtake directly from miners, some smelters and refiners also source feedstock directly from miners.

Source: Minefield.

Minerals Processing and Refining

Many of the processes used to beneficiate critical mineral ores and refine their concentrates are industry standard. Others are complex, ore specific, and require multiple stages. A simple overview of some of the methods used are described in Appendix 1. This provides an indication of some methods available and is not an exhaustive review of all alternative processes. Operations may be vertically integrated with primary concentration and refining conducted at the same location, typically the mine site. Others may be dedicated midstream plants located closer to end users. Simple explanations of metallurgical terminology are given in Appendix 2.

Many complex critical mineral mineralogies require techniques that have been developed and pioneered by China to be cost effective. These are often not directly transferrable to the Western world where labour, environmental, and health and safety standards are more stringent, in addition to higher labour costs and employee expectations. Investment into research and development is necessary to identify fast, safe, and reliable technologies compatible with Western expectations and standards.

Challenges in secondary processing or recycling include the small quantities of some metals in end-of-life goods, the cost and complexity of disassembly to access components containing critical minerals, and the risks of diluting specialist alloys and steels with less valuable waste. Energy prices are also a key factor given the energy intensity of refining processes.

Modern midstream plants capture virtually all their potential emissions. Off gas from smelters is treated to recover heat, remove particulates, and convert sulphur dioxide to sulphuric acid that can be used in metallurgy and other industries such as fertiliser manufacture. Liquid effluents and dusts are similarly captured and treated so that no harmful waste is discharged to the environment. Major metallurgical refiners operate midstream plants successfully and compliantly in countries with some of the highest environmental standards[12 13 14]. Any new midstream plants built in the UK would use the latest technology for safety, efficient operation, and minimal environmental impact.

Some of the processes require high energy inputs to melt materials, or for electrorefining. This can favour locating midstream plants where there is a cheap, clean, energy source such as hydro-electric or wind power. Some processes require the use of carbon as a reductant. Research in ongoing to reduce power requirements and find alternatives to carbon, but existing methods will have to be used until new processes have been commercialised.

Role of the Midstream

The midstream sector is the key to security of supply and any future circular economy – **significant value is added during the processing and refining stages** as valuable critical minerals are separated from waste.

Historically, the upstream, midstream, and downstream industries operated in silos with traders bridging the gap and moving the feedstock on from mine to processing and refining facilities. This is still the case but there has been an emerging trend of Western car manufacturers, who are concerned about rising prices of critical minerals and limited forecasted production, directly sourcing critical minerals from miners, and in some cases mines that are yet not producing.

The OEMs who have the foresight to form these partnerships will be better placed to navigate the forecasted supply deficit. However, there is a limited number of new mines coming on stream in the Western world, due to decades of outsourcing to developing nations. Secured offtake of one commodity will not necessarily translate to avoidance of supply chain disruptions.

The Western world has significant manufacturing capacity with **the USA, the UK, Germany, Italy, and France accounting for 27.9% of global manufacture**[15]. Australia and Canada have significant raw material production capability. The USA and the EU are waking up to the need to explore and bring new mines on stream[16]. But the West and allied nations are missing the crucial piece of the puzzle, leaving both miners and OEMs reliant on a Chinese midstream industry, their pricing and market conditions.

How Chinese companies process and refine critical minerals has raised red flags in the media around environmental and human rights abuses[17] [18]. Ongoing lack of transparency and inability of Western companies to validate data provided by those companies that do share it render assessment of ESG practices difficult. This poses two challenges:

- Firstly, the ESG work undertaken by explorers and miners in Western countries becomes undermined once feedstock is shipped to and enters China, due to the energy and chemical intensive processes used. Instead, ESG best practices should also be applied to the midstream.
- Secondly, the OEMs can no longer guarantee that the raw materials they are using are responsibly sourced, meaning that many alternative technologies to fossil fuels are built at a high cost to the environment and people. This renders the 'green energy transition' a greenwashing campaign if the critical minerals in renewable technologies are made from minerals and metals that considerably contribute to climate change. Further, posing ethical considerations of what price governments, companies, and consumers are willing to pay for lower carbon footprints.

To reduce emissions and environmental impact on the planet (including water usage, biodiversity, pollution etc), the circular economy will be imperative to recycle and re-use as many raw materials as possible. There is an opportunity to source critical minerals from secondary sources but to do this successfully, a midstream industry needs to exist to re-process and refine waste including:

- End-of-life products
- Faulty and sub-quality items
- By-products from processing and manufacturing processes
- Tailings from legacy mine sites
- Slags and sludges from steel industry
- Metals from landfill sites

Without a functioning, government-backed midstream industry, like many Western nations, the UK will fail to deliver its net zero and decarbonisation goals.

Net Zero Agenda

The Western world's disconnect between climate change-driven policies (e.g. the legally-binding Paris Agreement adopted by 161 parties to limit global warming to well below 2°C[19]) and intricate dynamics of critical minerals supply chains need to be addressed urgently. A transition towards fossil fuel alternatives cannot happen without critical minerals. Some climate-driven policies are disadvantaging the industries needed to extract, process, and refine these necessary raw materials. For example, removal of red diesel rebates[20] created uncompetitive market conditions for development and refining companies attempting to operate outside the current monopoly, which the UK Government inadvertently perpetuated[21]. Western companies are already at a competitive disadvantage in comparison to Chinese counterparts, many of which are government backed, and do not have to adhere to Western ESG expectations. To transition at pace towards fossil fuel alternatives, policy must be aligned with industry practicalities and long-term vision.

The UK government's 2021 policy document **'Net Zero Strategy: Build Back Greener'**[22] states that:

"The government is committed to working with industry and with international partners to safeguard these supply chains and our future economic resiliance'

The UK Government has committed **£32.5 million to support the decarbonisation of construction, mining, and quarrying**[23]. However, far more Government support is required to accelerate decarbonisation including significant investment into the creation of cheap and reliable alternative energy sources, such as hydrogen, wind, hydro, and nuclear.

The UK's economic resilience, like many Western nations', relies on the ability to source critical minerals (or components containing them) needed for their manufacturing sectors. The UK will not meet its climate goals without being able to access critical minerals necessary for renewable energy technologies. At the same time, the UK will not be able to produce and source the necessary critical minerals needed to build alternative technologies with current climate-driven policies disadvantaging the sector. This creates a loop of minimal progress toward economic growth and building climate resilience.

Current market dynamics, of significant shortfall in supply versus projected demand, indicate that the UK will likely face one of the following scenarios:

a. UK manufacturers will be unable to source responsibly produced critical minerals, undermining the energy transition as "green" technologies will be built from raw materials extracted, processed, and refined irresponsibly at detriment to environment and communities.

b. UK manufacturers will have to pay a significant premium to secure any critical minerals, with end-products being outpriced from the market.

c. UK manufacturers will face difficulties complying to climate and emission standards, keeping operations feasible due to rising energy prices, and securing critical minerals in a timely manner, delaying if not stopping production.

    i. In this worst-case scenario, the UK manufacturing industry would collapse, and larger OEMs would migrate to more competitive jurisdictions (e.g., BASF has begun scaling down operation in the EU due to lack of competitiveness and soaring energy prices[24]) causing mass unemployment, deepening the recession, and delaying the UK's energy transition.

The West must keep in mind that globally, nations are not aligned on climate change and achieving net zero. Net Zero is a Western ideology, and despite best efforts, cannot be achieved by singular nations, but has to be approached collectively.

However, it is unlikely that net zero will become a priority for developing nations in the short-term (although this is not the

Automakers are already swapping the UK for China. In November 2021, BMW announced that the Mini EV production will move from Oxford to China stating that the Oxford plant was not geared towards EV production[25] case across the board), which often contribute far less emissions in comparison to the developed world, and powerhouses such as China that are focused on growth (e.g. China's 14th 5-year plan set a GDP growth target for more than 6% for 2021[26]).

If Western governments are serious about the energy transition and want to deliver it in a just way to communities and the environment, then significant multi-billion dollar investment will be required into set-up of alternative midstream and downstream processing hubs, as well as strategic procurement of feedstock from allied nations to process and refine responsibly in line with Western standards and regulations.

It is imperative that these fundamental industries receive significant support from governments in decarbonising. Materials produced with far fewer fossil fuels carry an inherently lower footprint down the supply chain. **If the foundations of our supply chains are responsible, the rest of the value chain will follow.**

Mining, processing, and refining domestically is equally important to localise supply chains, reduce carbon footprints of shipping materials globally, and create alternative, secure mine-to-product supply chains. This also introduces employment and boosts local and national economies. The UK has a mature manufacturing sector, and existing as well as emerging midstream operations but only a few extractive projects approaching production in the next five years. The EU and USA are in a similar position.

It takes an average of 16.9 years to bring a new mine on stream from the initial discovery of minerals resources[27] (figure 4 outlines the variation in timelines for different commodities) and **out of 1000 grassroots projects, only one gives indication of ore**[28]. This creates a significant time lag between the time raw materials are available and when offtake can be processed and refined.

In comparison, a gigafactory can be built in two years[29]. Without strategic government intervention, many Western gigafactories will be empty factories if the midstream industry is not built, and feedstock from like-minded nations is not secured. While Australia and Canada are leading in extraction of critical minerals in the Western world, little has been done to set up an alternative midstream, resulting in many critical minerals extracted in the Western world being shipped to China for refining.

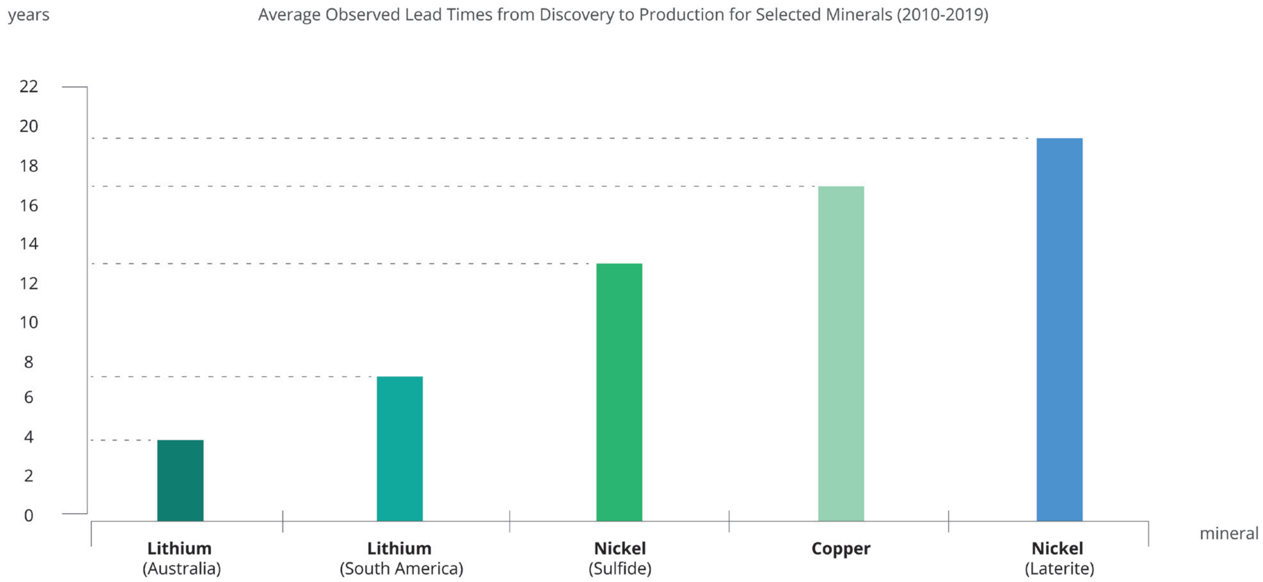


Figure 4: Disparate time horizons for commodities, deposit types, and jurisdictions.

Source: IEA.

Navigating Geopolitics

Many Western nations' economies are based on a free market approach with minimal governmental intervention. Some critical minerals cannot be bought on the "free market". Instead, supply chains are controlled by the strategic monopolisation of midstream and downstream processing and refining for many commodities. China dominates the critical midstream alongside nickel by Indonesia[30], niobium production by Brazil[31], platinum group elements (PGMs) by South Africa and Russia[32], chromium[33] and manganese[34] also by South Africa.

A collision between a Chinese fisherman and Japanese Coast Guard boats quickly escalated into supply chain disruption. The incident took place near disputed chain of islands in the East China Sea.

Nations and OEMs reliant on imports of critical minerals are increasingly weary of the disruptions caused by geopolitical tensions. China's 2010 REE export ban to Japan[35] is an example of critical minerals being used as tools of diplomacy.

Despite China's efforts to be a consistent supplier of REEs and retain its monopoly on the sector, security and consistency of supply faced scrutiny as China's 'zero covid' policy resulted in the three-year chip shortage. Any future pandemics, natural disasters, or civil unrest can have severe consequences on global supply chains, industries, and economies. This is also the case for other commodities and nations that hold a monopoly over them.

All Roads Lead to China

China's dominance is most prominent in the extraction, processing and refining of REEs used in magnets that modern electrical technologies rely on. Where it does not dominate production, China's 'go out' policy[36] and government intervention via state-funded companies has successfully supplemented the critical minerals suite flowing into the country for processing and refining.

Apart from capturing the value throughout the supply chain, the model also enables extraction at significantly lower cost than Western miners since the cost is passed down the supply chain (this typically occurs in aggregates and lower value natural resources in the Western world due to shorter, local supply chains). The dominance of the midstream also enables China to set prices for critical minerals, and since alternative markets for many are lacking, many Western producers are forced to sell their feedstock to China.

Chinese investors are also targeting strategic projects across the globe, this extends beyond just the minerals sector, through to nuclear energy (China's state-owned China General Power owns 33.5% of Hinkley Point C[37]), as well as French infrastructure[38].

This extension of power into the Western world poses several challenges. The West must navigate its relationship with China delicately as it is entirely reliant on the nation for many manufactured goods. Further, reaching net zero in the West is not sufficient without China's cooperation and the buy in of the rest of the world. The West must equally take responsibility for neglecting to secure their nation's critical mineral needs and selling off key infrastructure to Chinese investors for quick profit.

Outside of a Western-centric view, diversity of supply chains is necessary to minimise disruption to production, economic growth, and social progress. Developing nations have the opportunity to grow with responsible practices embedded as standard practices, building modern and sustainable economies. It is imperative that emerging nations are not exploited by less rigorous companies, leading to irresponsible extraction, processing, and refining of critical minerals. The race to extract critical minerals from frontier markets is on; it is imperative that this race does not swap ESG compliance for speed. Chinese companies have already displayed a "by any means necessary" approach to securing critical minerals from frontier regions to feed into their midstream and ensure steady flow of critical materials for manufacture.

China's Go Out Policy

The "going out" (Zou chuqu) policy, focused on injecting surplus capital to deepen access to foreign markets, natural resources, and advanced technologies, compliments China's "welcoming in" (Yin jinlai) policy which facilitates domestic capital formation, market reform, and technological advancement. The two distinct but interconnected pillars (consolidated in the 10th Five-Year plan) are part of the economic modernisation strategy based on foreign direct investment.

Afghanistan

China has been heavily investing in mineral extraction in Afghanistan, particularly since the withdrawal of the US army from the nation. Afghanistan is known to have significant lithium, copper, cobalt, nickel, and REE resources. Between 2004-2010 the USGS data confirmed many Soviet finds and the U.S. Department of Defense's Task Force for Business and Stability Operations valued Afghanistan's mineral resources at **$908 billion**[39].

The Afghan Government's need for funding and China's strategy of building essential infrastructure to access resources and feed them into the domestic midstream is likely to see a partnership formed between the two nations, albeit one that is more beneficial for China. China has publicly denounced the economic sanctions placed on Afghanistan imposed by non-regional forces[40]. Extraction of Afghanistan's critical minerals, with very little in the way of rule of law or enforcement, will see many of its critical minerals fed into China's monopoly.

In the coming decades, access to Afghanistan's resources will further strengthen China's position on the international stage as the West continues to play catch up and seek short-term solutions

Myanmar

Myanmar is the world's third largest producer of REEs. In 2021, an estimated 26,000 metric tons of rare-earth oxide equivalent was produced[41]. This is anticipated to be much higher due to the scale of illicit Chinese mining.

Myanmar's ongoing instability since the 2021 coup d'état is further fuelling ongoing exploitation of REEs. China's mining of REEs in Myanmar comes with a heavy price tag for the environment and local communities, with profits from the REE extraction fuelling the Myanmar military-linked militia[42]. Further information on the impact of Chinese REE mining in Myanmar is detailed in 'Myanmar's Poisoned Mountains' report by Global Witness[43], including poor processing practices, migration into the region and human rights abuses.

Myanmar temporary suspended trade with China in 2021 to stop the spread of Covid-19 across the borders in line with China's 'zero-covid' policy but it is unknown whether illicit mines continued to export to China.

Tibet

China has had its sights on Tibet since 1950, after it ended its relative autonomy. Significant infrastructure has been put in place to enable more effective exploitation of Tibet's natural resources. A push to understand the riches of Tibet included a **$50 million seven-year government survey** which identified deposits including lithium, copper, zinc, lead, and potash[44] (for comparison, the UK's CMIC only received £3 million over three years).

Since large-scale government-driven mining has entered Tibet, there have been reports of Tibetan prisoners being forced to work the mines[45].

A Race Amongst Friends

The Western world is reliant on China as a source of many processed and refined critical minerals. Despite the recent move into the midstream and downstream processing space, Western companies operating in the West face barriers including access to capital, convoluted and lengthy planning and permitting processes, higher operating costs, and inconsistent government / institutional backing, all adding to the current time lag between supply and demand. In contrast, Chinese companies can proceed at speed due to strong support of the critical minerals sector by government, including heavy investment and subsidies.

There is an emerging collaboration between nations increasingly looking to secure supply, particularly between the Anglosphere (Australia, US, Canada, Australia) tech economies (Japan, South Korea) and emerging sector economies (Saudi Arabia, India, Brazil). While each nation is racing to secure its individual critical mineral needs, there is a shared drive and thus competition to secure the regional processing and refining midstream.

This can potentially cause international tensions as each nation seeks independence without the capital and government backing to establish supply chains akin to those of China. Instead, aligned nations should look at collaborating where appropriate to play to each nation's strength and strategically agree on where alternative processing and refining hubs can be located as no nation can undertake this task on their own. Development of an alternative midstream should not however result in simply relocating the monopoly somewhere else. There is a real threat that a race to diversify the supply chain will sacrifice ESG compliance and individual or partner nation resilience.

Diversification of the midstream and downstream processing is necessary to shorten supply chains and lessen the environmental impact of transporting raw and processed materials back and forth across the globe. There is a risk that Western nations will compete against each other, to build alternative midstream plants across a cluster of the same commodities without looking to strategically diversify. If the Western world wants to lessen its reliance on China, it will need to plan decades ahead and forge strong international relationships.

Minerals Security Partnership

Canada, Australia, Finland, France, Germany, Japan, South Korea, Sweden, United Kingdom, and the European Commission are members of The Minerals Security Partnership (MSP) initiated by the USA[46]. The partnership aims to bring major aligned economies together to secure supplies of critical minerals. There has been no financial commitment to the creation of alternative supply chains by the MSP members yet.

It is imperative that any future policy outcomes or financial commitments are tailored to industry reality and not theoretical assumptions, so that they add practical value.

Australia

Australia has traditionally been a major producer of raw materials due to its vast mineral wealth, and until recently employed the "dig it and ship it" model. In a bid to grow the critical minerals sector, a **A$2 billion critical minerals facility** was established in 2022 and another **A$200 million** committed as part of the Critical Minerals Accelerator Initiative.

Western Australia (WA) accounts for half of the global lithium production and exports nickel, cobalt, manganese, and rare earths. WA's strategy has now shifted to focus on creating a "world-leading" battery industry[47]. Despite several planned processing and refining plants, it is unclear how WA will capture the battery value chain currently dominated by China (especially during downstream stages), while competing with significantly cheaper Chinese alternatives by 2025.

Queensland is leading in innovation around tailing waste, and recovery of secondary sources, as well as multi-use pilot facilities for vanadium processing.

Australia now has a desire to add value by processing onshore. This is emerging for lithium, vanadium and other battery metals. Australia is the world's largest producer of lithium from spodumene (an important ore of lithium and a source of ceramic materials). Spodumene does not travel well across great distances (approximately 95% waste) due to oxidation, making domestic processing and refining a less carbon intensive option.

However, the difficulty lies in designing plants that make domestic processing and refining economically viable in comparison to Chinese counterparts. China has developed its technology to make processing as low-cost and timely as possible. But replicating those technologies in Australia is difficult due to constraints between design and compliance with Western health, safety and environmental standards, as well as significantly higher labour costs.

Australia also lacks a major OEM sector and will need to find allied nations to sell their processed and refined critical minerals to. The natural partners are Japan, South Korea, USA, Europe and the UK. Forging new alliances can fracture the delicate relationship with China which is particularly concerning given the importance of China to the Australian economy. In 2020, China banned importation of Australian coal[48] following a fallout from the coronavirus outbreak.

Australia already has strong partnerships with Japan. JOGMEC has invested into the Australian Lynas Rare Earths, Terramin who are exploring for copper-gold, and has agreed to conduct joint research on technology to recover cobalt from waste rock of Queensland's copper mines[49]. In October 2022, Japan and Australia signed a new partnership on critical minerals to help develop a supply chain between Australia's producers and Japan's manufacturers[50].

Australia is also partnered with India on critical minerals. The Australia-India Economic Cooperation and Trade Agreement (AI-ECTA)[51] aims to support further growth and investment in Australia's critical minerals and resources sectors. In July 2022, Australia committed **A$5.8 million** for the critical minerals partnership with India[52].

However, the introduction of the Inflation Reduction Act (IRA) of 2022 is likely to make the USA a preferred partner. In 2022, the US Department of Defense (DOD) requested the Defense Production Act (DPA) to include Australian and UK facilities as recipients of funding for projects considered as "domestic source".

Canada

Canada is naturally endowed in critical minerals and is a major mining jurisdiction. Canada is geographically partnered with the USA, and there are strong similarities in their critical minerals lists. Further, Canada has the potential to recycle tailings and is already a leading waste electric and electronic equipment (WEEE) recycler. The provinces of Ontario, Quebec, and Saskatchewan are leading on critical minerals.

The province of Ontario is a leading producer of nickel, lithium, platinum, cobalt and other critical minerals. Ontario is regarded for producing critical minerals using renewable energy, and adhering to high ESG expectations. In 2022, Ontario released its own critical minerals strategy[53] committing to support the growth of the industry by committing **C$24 million to the Ontario Junior Exploration Program**, including C$12 million for a critical minerals funding stream, and a further C$5 million aimed at research for extraction and processing in Ontario's north.

Quebec was the first Canadian province to launch its own Plan for the Development of Critical and Strategic Minerals 2020-2025 and pledge **C$90 million** through to 2025 to the development of critical minerals. The strategy outlines actions aimed at making the province a leader in the production, processing and recycling of critical minerals. Quebec also has battery minerals, including nickel, cobalt, graphite, manganese, and the largest reserves of lithium in Canada. Quebec's ample supply of low-cost hydroelectric power enables low-carbon extraction of critical minerals.

Saskatchewan is endowed in potash and rare earth elements, with potential for production of 23 critical minerals on the Canadian Critical Minerals List. Saskatchewan has invested **C$51 million into a REE processing facility**, capable of upgrading rare earths-enriched monazite sand into a mixed REE product and then separate the contained rare earths into individual REE oxides[54].

The Canadian Government has been investing into critical minerals producers through the Strategic Innovation Fund, including **C$222 million to help Rio Tinto decarbonise**, and **C$27 million contribution to E3 Lithium**. In December 2022, Canada released its Critical Minerals Strategy[55] backed by **C$3.8 billion in federal funding**.

Canada is also one of the first Western nations to protect its critical mineral supply chains from investments by foreign state-owned enterprises. Any purchase of assets by such entities in the sector, will now trigger Part IV.1 of the Investment Canada Act (ICA). All such acquisitions will be reviewed based on being "injurious to national security". It is expected that other Western nations will follow suit with expectation clauses for like-minded nations.

European Union

The distribution of natural resources around the EU is variable. Scandinavian nations are taking advantage of their hydropower to produce critical minerals with lower carbon footprints, while strong "not in my back yard" (NIMBYISM) attitudes remain throughout Europe (e.g. protests against Rio Tinto's Jadar project in Serbia). The EU's mature manufacturing sector will benefit from a localised supply chain and processing and refining of critical minerals to European standards.

Finland is a favourable mining jurisdiction, and a producer of several critical minerals including cobalt, niobium, PGMs, manganese, vanadium, copper, lithium, and titanium. A vanadium processing facility is set to position Finland as a major European producer by late 2024[56]. The Finnish company LKAB is hoping to extract REEs as a by-product from iron ore production in Sweden[57], creating a Nordic value chain. The access to cheap renewable energy power in the Nordic region, positions it favourably to grow an ESG-conscious midstream centre.

Germany is the EU's manufacturing and gigafactory hotspot. However, Germany's aluminium and other smelters has been severely affected by the ongoing energy crisis. Germany is set to host its **first REE magnet recycling plant which received €3.7m in grants** including €2.5m in funding from the European Regional Development Fund and a €1.2m grant from the Ministry of Economic Affairs, Labour and Tourism Baden-Württemberg[58]. Germany has also been looking to partner with resource-rich Mongolia[59], and has been strengthening its ties with Canada[60].

France is a major producer of hafnium and some indium and has the potential to produce lithium domestically. As part of its 2030 investment plan, the **French Government pledged €500 million (matched by €500 million private equity) to foster domestic industry resilience** to metal supply chain disturbances, partly through a dedicated investment fund. France has also been strengthening its ties with Australia[61] on supply chain resilience.

Spain is a key European producer of copper and one of few EU states producing nickel ore, alongside proposed tin and tungsten projects. A 'Joint Declaration Between the Kingdom of Spain and the United States of America'[62] was issued in June 2022, to promote greater collaboration on supply chain security.

The EU announced the introduction of the Critical Minerals Act in September 2022 to drive supply chain diversification, incentivised by the ongoing energy crisis. However, conflicting EU policy and legislation is currently delaying development and production of critical minerals. The Critical Minerals Act and proposed classification of lithium compounds as hazardous exemplifies this. The EU has also announced a **€2 billion European Raw Materials Fund** to be launched in 2023, aimed at supporting the production of critical minerals to make the EU independent of China's imports.

Some critical mineral projects will not become economically feasible until energy prices return to pre-crisis levels. The Aluminium refining industry has been particularly hit by the ongoing elevated energy prices with many plants being taken offline[63]. In September 2022, a letter from Eurometaux to EU Commission President Ursula von der Leyen, stated that about **50% of EU aluminium and zinc production capacity was offline due to energy prices**[64]. Continuation of the crisis will render the EU an unattractive destination for any parts of the critical minerals supply chain. Given that the UK faces a similar situation and is disadvantaged through complex planning and permitting systems, companies (including OEMs) will begin exploring alternative locations.

United States

The US has some existing critical minerals extraction, processing capability, and a significant manufacturing sector, **contributing 16.8% global manufacturing output**. Out of recent policy changes in the Western world, US policy been most decisive and well received by industry, including the Mineral Security Act Bipartisan Infrastructure Law (BIL), and Inflation Reduction Act (IRA). This will likely spur a race to partner with the US.

The financial incentives of the IRA will also entice foreign investment and relocation of businesses to the US. This strategic move will enable the US to corner the "alternative" market and regain some security of supply. However, this poses a threat to the UK and Europe as they lag behind the US. France for instance, is preparing a Green Industry Bill[66], as a counter measure to the IRA. It is expected that the EU will follow.

The US has been increasingly active in the critical minerals space in a bid to create "Made in America" supply chains. This has included significant recent funding:

- **US$74.6 million** to 30 states for critical minerals research, mapping as part of wider US$510.7 million investment in USGS from the BIL[67]
- **US$39 million** form Department of Energy (DOE) for 16 projects across 12 states to develop market-ready technologies that will increase domestic supplies of critical elements[68]
- **US$6 billion** for battery materials processing and manufacturing projects and further $140 million[69] for a rare earths demonstration plant
- **US$1 billion**, as part of the National Defense Authorization Act, for the National Defense Stockpile to acquire REEs and strategic minerals[70]

The US has also helped finance Australian companies and projects focusing on rare earths, cobalt, and others. The US has partnered with Canada, Spain, Japan, Australia on critical minerals, and initiated the formation of the MSP.

United Kingdom

Despite a rich mining heritage, the UK has a limited number of critical minerals projects, with the only current production resulting from by-products. The UK does however have a strong chemicals industry, and a large manufacturing sector reliant on critical minerals. There are several recycling and processing facilities within the UK.

The UK is behind the curve in aligning itself with like-minded nations, despite AUKUS and trade deals with historical allies, it has been slower than others to partner with partner nations on critical minerals.

The UK Government has however announced partnerships with Saudi Arabia[71], and South Africa[72] and Canada. Saudi Arabia is hoping to pivot away from fossil fuels and create a globally renowned critical minerals sector, emphasising its focus on the midstream. However, Saudi Arabia's social history may raise questions over ESG compliance of the future sector that will need to be addressed. South Africa is heavily influenced by China, as one of its largest foreign investors into infrastructure and mining. In 2021, South Africa was the highest recipient of China's Foreign Direct Investment[73].

The CMA UK was commissioned to host roundtables in early 2022 between the UK and Australian Governments as well as industry (across the critical minerals value chain) representing both nations, to promote collaboration across five key areas: environmental, social, and governance, mines-to-magnet supply chains, electric vehicle battery supply chains, research and development, and investment and finance. The series of roundtables yielded a report to UK Government voicing the industry's concerns and call for action. The messages from industry were watered down on request of Government representatives.

In late 2021, the CMA UK also facilitated bilateral discussions between the UK and Canadian Governments on critical minerals and the circular economy. The outcomes of the project have yielded increased collaboration between the two nations. Progress towards actionable change to benefit both Canadian and the UK industry have been slow.

The UK is also working with the International Energy Authority (IEA) on critical minerals related to energy generation, and with the G7 to collaborate on critical minerals and ESG compliant supply chains.

Unlike Australia, USA, Canada, and Japan, the UK has not made any significant investments into creating localised critical mineral supply chains and provides limited diplomatic support for its companies operating overseas.

Mining companies are however eligable to apply for various Innovate UK funding rounds, as well as the British Industry Supercharger open to 300 British companies. The Department for Business and Trade and Innovate UK also announced the **£15 Million** CLIMATES programme for rare earth elements.

UK Critical Mineral Ambitions

The United Kingdom has published its first critical minerals strategy in July 2022[74], and the BGS published its 'UK Criticality Assessment of Technology Critical Minerals and Metals' report[75]. The report stipulates that the resultant critical minerals list is not forward looking. It is unclear how the recognition of the need for critical minerals in the UK will be translated into concrete actions to secure their supply, or how the list will inform policy.

To understand how the UK Government can leverage its existing industry and infrastructure to strategically address security of supply, it is important to take a future-looking approach to understanding what critical minerals are and how criticality may evolve.

The criticality of metals and minerals is commonly shown as a scatter plot of supply risk vs economic importance[76]. Materials with high supply risk and high economic importance are deemed 'critical'. More detailed analysis can be undertaken by assigning ratings and weightings to specific risk factors. Evolving methodologies in partner nations are looking at combining imports, exports, ESG considerations, market dynamics with policy and the nation's industrial goals. The UK's CMIC will require further investment to successfully support the UK's critical minerals industry across the upstream, midstream and downstream.

Materials rated 'critical' can vary with time as new sources are identified, their economic importance declines with substitution or technology change, or geopolitics disrupts their supply chain. Potash is an example of variation in criticality related to inelasticity of mineral supply. It is an important fertiliser component and has been considered historically to have high economic importance but low supply risk, so was not classed as 'critical'. However, as Russia and Belarus provide over 30% of global production[77], the 2022 war in Ukraine and subsequent trade embargo against Russia have created shortages and price increases. These are not reflected in the EU and BGS lists that predate the conflict.

Critical minerals are country specific depending on regional supply and demand. Several countries have published lists of metals they consider critical and have issued critical mineral policies including Australia, Canada, Japan, and the US. Some countries have also made significant funding available to support development of domestic critical mineral production. The BGS 2021 list of critical minerals[78] is similar to that of the European Union, which itself had changed between the reports of 2014, 2017 and 2020[79].

Table 1: Metals and minerals defined as critical in the 2021 BGS report, including BGS data for global production, main producer countries, and Gross Value Added (GVA) to the UK. There is a large variation in scale of production between different critical minerals. China dominates the supply of many metals considered critical to the UK. Western countries are trying to diversify their supply and reduce dependence on China. Russia is a major supplier but is now subject to trade embargo following its invasion of Ukraine.

Critical Metal	Main Producers	Global Production Tonnes/Year	UK GVA - Millions
Antimony	China, Tajikistan, Russia	159,258	£9,239
Bismuth	Vietnam, China, Japan	4,987	£8,480
Cobalt	China, Finland, Belgium, DRC	116,633	£8,182
Gallium	China, Russia, Germany	339	£9,708
Graphite	China, Brazil, India	1,073,814	£5,042
Indium	China, S Korea, Japan	819	£12,657
Lithium	Australia, Chile, China	65,753	£5,319
Magnesium	China, USA, Israel	984,378	£11,017
Niobium	Brazil, Canada, Russia	74, 080	£13,511
Palladium	Russia, South Africa, Canada	209	£16,073
Platinum	South Africa, Russia, Zimbabwe	189	£10,089

Rare Earths	China, Burma, Australia	200,914	£8,066
Silicon	China, Brazil, Australia	2,786,994	£8,480
Tantalum	DRC, Rwanda, Brazil	1,293	£12,846
Tellurium	China, Russia, Japan	461	£14,351
Tin	China, Indonesia, Malaysia	364,983	£12,437
Tungsten	China, Vietnam, Russia	83,935	£15,463
Vanadium	China, Russia, South Africa	83,635	£7,928

The importance of the critical minerals identified by the BGS is indicated by their range of applications shown in the table below:

Critical Metal	Applications
Antimony	Lead-acid batteries, flame retardants, diodes and infrared sensors, night vision goggles, precision optics, laser sighting, munitions, tungsten steel
Bismuth	Chemicals, low-melting point alloys for sprinkler systems and solders, glass and ceramics, catalyst in rubber production.
Cobalt	EV batteries, "superalloys" for jet engine and turbine blades, orthopaedic implants, catalysts, pigments, magnets, electroplating
Gallium	Ga arsenide as a Silicon substitute in electronics, Ga nitride semiconductor, LEDs, sensors, low melting point alloys, thermometers.
Graphite	EV Li-ion battery anodes, refractories, carbon nanotubes, graphene, electronics.
Indium	Indium-tin oxide for touch screens and flat panel displays, Indium nitride semiconductors, structural glass coating, photovoltaics (solar panels), low melting point alloys for fire sprinklers and solder.
Lithium	EV and other batteries, lightweight alloys, armour, special ceramics, lubricants, medical.
Magnesium	Lightweight alloys, refractories (as oxide), flares and fireworks, medicines.
Niobium	High strength steel, "superalloys" for aerospace, superconducting magnets, special glass.
Palladium	Internal combustion engine catalytic converters, hydrogen fuel cells, dentistry, industrial catalysts, electronics.
Platinum	Catalytic converters, hydrogen fuel cells, jewellery, chemical catalyst, electronics including computer hard drives, chemotherapy drugs.
Rare Earths	Alloys for strong permanent magnets - wind turbines, EVs, speakers, hard drives. Alloys for aircraft engines, carbon arc electrodes; studio lights, colouring glass, welding goggle glass, glass for lasers, oxide for polymerisation catalyst. Defence applications.

Silicon	Electronics/semiconductors, chemicals, aluminium alloys, solar panels.
Tantalum	Electronics (capacitors), especially in mobile phones, games consoles and computers. Surgical implants. Corrosion resistant containers. Turbine blades. Rocket nozzles. Electrodes in neon lights.
Tellurium	Solar power (photovoltaics), thermo-electric devices, metallurgy.
Tin	Solder, Chemicals, Tinplate
Tungsten	Metal milling and cutting tools, construction, and mining tools (rock drill bits), general wear resistant uses, defence.
Vanadium	Steel and steel alloys, catalyst for sulphuric acid manufacture.

Missing Critical Minerals

International assessments of criticality often show base metals nickel and copper and fertiliser mineral potash as having high economic importance, but supply risk just below the 'critical' threshold. **Nickel** is essential for EV batteries, **copper** for power transmission cables, and **potash** for fertilisers. All three are included in Canada's list of critical minerals[80]. The supply risk for potash and nickel increased suddenly with the Russian invasion of Ukraine. **Manganese** is also on the UK "watch list" but not deemed 'critical'. **Hafnium** has not been considered by the BGS despite its strategic and economic importance in the aerospace and defence industries.

The challenges in determining a future-looking critical minerals lie in:

- The availability of public data (in monopolised and opaque markets, it is difficult to obtain representative data)
- The UK's current definition of "criticality" which focuses on primary economic impact, and neglects the strategic importance of certain minerals and metals, or geopolitical risk
- Lack of strategic direction from UK Government on what its priorities are (although this could be inferred from the UK's Ten Point Plan, Industrial Strategy and Net Zero Strategy)
- Lack of support from the Ministry of Defence

Boulby Potsash Mine
Source: Shutterstock

The UK Potential

The UK was the birthplace of deep mining and many of the processes used to extract valuable metals from ores. As the UK transitioned from a manufacturing to a service economy, its need for domestic metal production decreased. Some of its metallurgical plants were old, inefficient, and environmentally questionable. By the early 21st Century, the UK was almost entirely dependent on imports for its metal supply.

Globalisation provided a smooth supply of refined metals at low cost with no domestic pollution. As a result, major zinc, copper, and precious metals refineries have closed in the UK since the late 20th Century. No new smelters and refineries were built in recent years due to a myriad of reasons including the UK not being considered commercially attractive, the permitting system too difficult to navigate, and greater foreign government support overseas. This situation is expected to change as critical minerals supply tightens.

The UK has few ore deposits, but projects are progressing to produce tin, tungsten, and lithium in south-west England through mining and brine extraction. There may also be potential to extract cobalt, nickel, and platinum group metals. Ongoing exploration efforts are also taking place in Scotland, the North-East and south-east of England. However, lack of modern datasets from the British Geological Survey (BGS) limits the ability to assess the UK for prospectivity especially for critical minerals that would have historically not been explored for. Most of critical minerals extracted in the UK will be exported overseas due to lack processing and refining capability in the UK.

Currently operating critical minerals (as per UK's Critical Minerals List) midstream plants in the UK include:

- Less Common Metals – rare earth alloys
- Vale Clydach – nickel smelter treating oxides imported from Canada
- Johnson Matthey – platinum group metals refining
- Phillips 66 – battery coke, a synthetic graphite precursor
- Luxfer Group Ltd – zirconium, magnesium refining
- Livent – lithium hydroxide refining
- JBR Recovery – PGMs refining

Figure 5 illustrates the UK's operating midstream processing, refining and recycling plants as well as proposed projects that include commodities deemed critical by the USA, Canada, Australia and the EU.

The UK produced approximately 35,000 metric tons of nickel in 2020[81], and exported 23 metric tonnes of nickel ore and concentrate in 2020[82]. In 2020, 97 metric tonnes of unwrought or partly worked platinum was exported from the United Kingdom. The UK also exported 77 metric tons of palladium and a further 18 metric tons of other platinum group metals (PGM) that year[83].

There are many smaller recycling facilities for precious metals and miscellaneous scrap[84], but research is needed by the CMIC to identify their production capacity as contributors to the circular economy. The CMIC has already published an interactive tool[85] which includes decommissioned, and planned refineries and plants.

Recognition of the importance of critical minerals to the UK's security and economy has forced a rethink on the importance of a domestic metallurgical midstream industry.

Projects under development include:

- British Lithium - battery grade lithium chemical production pilot plant in Cornwall
- Pensana - a rare earth oxide refinery in Saltend, Chemicals Park, Humber Freeport
- HyProMag - rare earth magnet recycling pilot plant in Birmingham
- Tees Valley Lithium – a lithium hydroxide refinery in Teesside shipping upgraded feedstock from Port Headland, Australia

Proposed projects include:

- Green Lithium – a lithium hydroxide refinery in Middlesborough
- Peak Rare Earths – rare earth oxide refinery
- Cornish Lithium - lithium processing and refining pilot plant

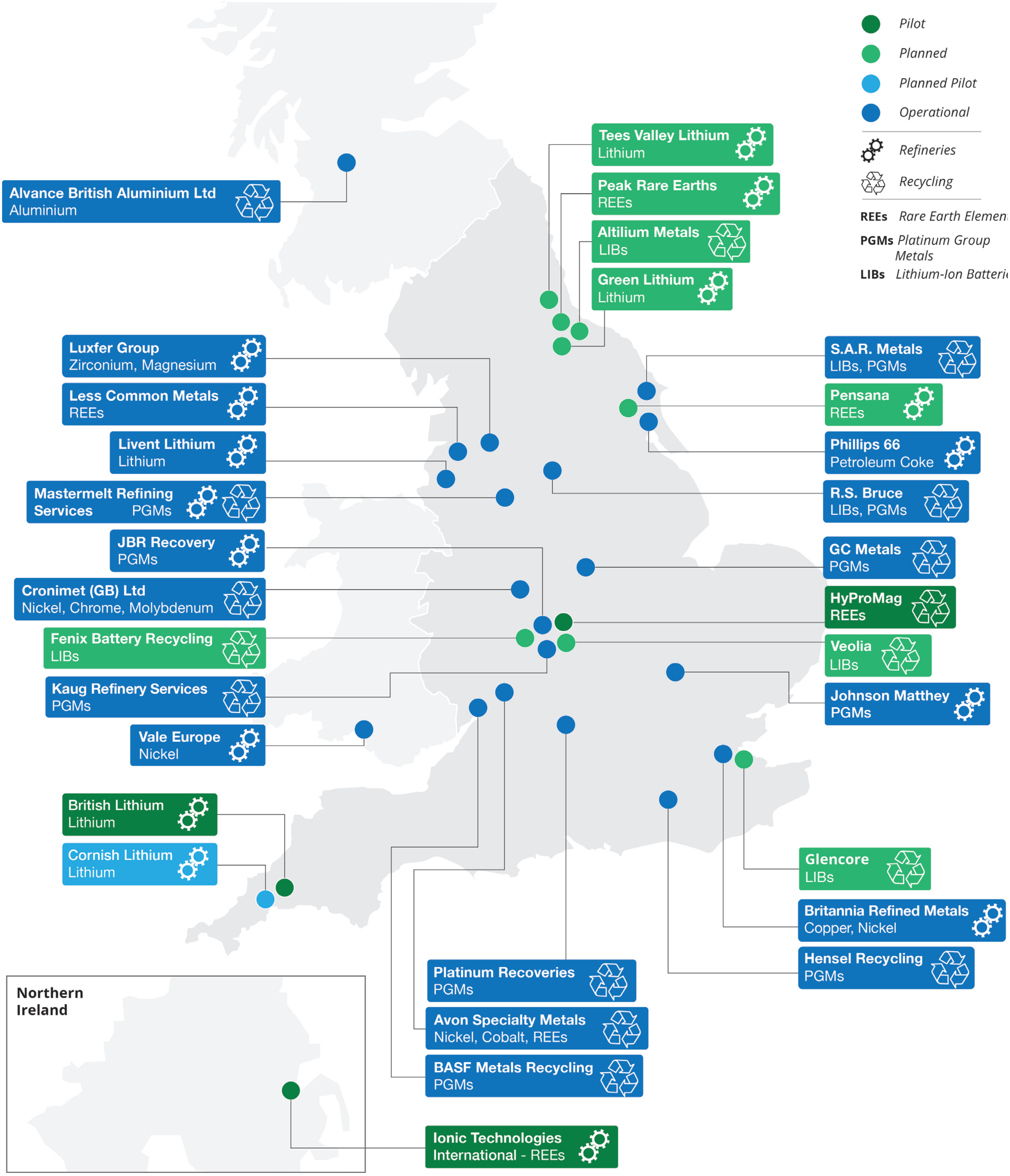


Figure 5 : 'Existing, Pilot, and Planned Midstream Projects in the United Kingdom.'
'Adapted from the CMIC Interactive Map'

Case Study - Less Common Metals

What does LCM do?

Less Common Metals (LCM), based in the North West of England, is responsible for the production of rare earth metals, and the melting and casting of rare earth elements together with other metals into alloys for magnet production. LCM is situated in the midstream and **is the only company in the western world commercially producing the highly specialised strip cast alloys**, needed to produce the highest performance neodymium iron boron (NdFeB) magnets. NdFeB magnets are the most powerful permanent magnets commercially available.

Where does supply come from?

There is a strategic vulnerability in terms of overdependence on the Chinese market. It is important that non-Chinese alternatives become established, hence LCM is very active in supporting those ventures to become viable. Prior to 2017, LCM was purchasing all of its neodymium (Nd) as metal, however, from 2017 onwards, the metal-making process was introduced onsite to commercially make Nd metal and NdPr (neodymium praseodymium) metal. Consequently, all strip-cast material processed by LCM is produced using an independent and secure oxide source. In parallel, LCM is also advancing plans to secure heavy rare earths such as DyFe (dysprosium iron) and Tb (terbium).

This makes LCM one of the very few companies in the world outside of China who can convert oxide to metal, and a strategic addition to the Western critical minerals industry. Despite thoughts that raw materials are difficult to source outside of China there are some options. It is deemed that metal processes are exclusively a Chinese process, but LCM could be taken into consideration to supply worldwide.

Where does it go to?

As a world leader in the manufacturer and supply of complex alloy systems the majority of LCM's customer base is outside the UK. LCM exports to more than 17 countries across Europe, the Far East and the USA, while expansion to further territories is in the pipeline therefore exporting is essential for the business to function. The rare earth industry is niche, and it is a challenge in itself to compete against China who have a huge 90% dominance over the rare earth market. These barriers create the need for companies like LCM to come up with new initiatives to raise the bar and be noticed by potential customers who want to support an alternative supply chain.

LCM
less common metals

Figure 6: Operator holding neodymium in ingot form at the LCM facility. Source: Less Common Metals.

Case Study - Tees Valley Lithium

Alkemy Capital Investments is publicly listed on the London Stock Exchange with a focus on projects in the battery metals sector. Alkemy has two key projects – Tees Valley Lithium (TVL) at Wilton International Chemicals Park, UK and the Port Hedland Lithium Sulphate Refinery, Western Australia the largest bulk export port in the world and the largest container port in Australia.

TVL is establishing Europe's potentially first and largest lithium hydroxide facility based in the North East of England. The facility will eventually use a low-carbon electrochemical processing route and will be powered by renewable energy. TVL has the potential to become one of the lowest carbon lithium refining projects in the world.

Alkemy aims to reduce embedded carbon in the lithium refining process by producing lithium sulphate at the Port Hedland merchant refinery in Western Australia which will serve as a hub for Australian spodumene miners, enabling direct access to the growing European battery market. The refinery will aim to become the primary source of feedstock for the TVL refinery in the UK and enable the production of low-carbon, battery-grade lithium hydroxide.

Benefits of an alternative UK-Australia Supply Chain:

- Alkemy will be concentrating spodumene to lithium sulphate near to Australia's biggest port, with plans to access to green energy (wind, solar, and green hydrogen), which is not available at the mine site. The by-products of the concentration process can be on-sold by other industries nearby or exported through the port.
- Concentrating the material to lithium sulphate reduces the weight of material shipped by 80%, saving logistics costs and reducing the carbon footprint.
- TVL's robust process in the UK can cope with feeds from multiple mining operations.
- Wilton International Chemicals Park is based in a freeport adjacent to the fifth largest port in the UK, this is an economic development zone with many financial benefits as well as being a maritime enterprise zone and customs zone.
- The 'plug & play' infrastructure at the Wilton International Chemicals Park significantly reduce the CAPEX and time taken to build a facility, as all our green power, water, demineralised water, steam, compressed air, drainage, water treatment etc have already been constructed.
- Refining by-products (sulphuric acid, sodium sulphate, CO2) can be sold to industrial players nearby, resulting in a zero-to-waste strategy. TVL's process is set up to receive recycled lithium sulphate from Day 1 to facilitate the circular economy concept.
- By selling spodumene to Alkemy, mining companies are de-risking their lithium supply chain and accessing the burgeoning European battery market.
- Conversion of lithium sulphate to lithium hydroxide, changes the source of origin, helping battery manufacturers meet the minimum domestic content limits set by the UK/EU and avoid trade tariffs and duties.

Dogger Bank is located off the North East Coast of England. The project is being constructed in three phases, A, B , and C. Dogger Bank A is expected to be operational in 2023.

TEES VALLEY LITHIUM

ALKEMY

Case Study - Pensana

Pensana Plc aims to become an alternative source for European automotive and wind turbine OEMs and ultimately disrupt the current Chinese monopoly on rare earth supply. Pensana has commenced construction of a rare earth separation facility at the Saltend Chemicals Park in the Humber Freeport. It will be one of only three such facilities in the world outside of China – the other two being Lynas Corporation's facility in Malaysia and the currently being developed in the US by MP Materials – and the only such facility located in a Freeport. This will enable miners from around the world to access the European market rather than ship to China. Initial feedstock is to be shipped to the Saltend plant as clean, high purity mixed rare earth double sulphate (MREDS) from the company's Longonjo mine in Angola.

Longonjo

- The Longonjo mine in Angola is expected to produce c. 40,000 tonnes per annum of mixed rare earths double sulphate with a 20-year lifespan and will be shipped as high purity MREDS.
- The mine and processing plants will feature hydro-electric power and a tailings storage facility meeting the requirements of the Global Industry Standard on Tailings Management.
- Pensana has already received financing from the Angolan Government, which is a 10% shareholder in the project, through the Angolan Sovereign Wealth Fund (alongside 6% other Angolan minorities).

Saltend

- Pensana's plug-and-play rare earth processing facility is located within the Saltend Chemicals Park, in the Humber Freeport.
- The facility will create over 500 jobs during construction and over 125 direct jobs once in production.
- Once established, Saltend will allow for the development of a downstream industry by using low-cost renewable electricity to convert the oxides into metal and, then teaming up with magnet manufacturing capacity in Europe.

Pensana has also announced a partnership with Equinor, which supports Pensana's commitment to the circular economy as it looks to recycle an addressable annual market of 4,000 tonnes of end-of-life permanent magnets from the Haliades X wind turbines currently being installed at Dogger Bank.

Recycling permanent magnets utilising hydrogen not as fuel, but as a reductant, whilst benefitting from the decarbonised power supply within Saltend, offers a clean alternative using 88% less energy than virgin magnet manufacture and aligns with Pensana's continued efforts to produce a sustainable supply chain for these critical materials.

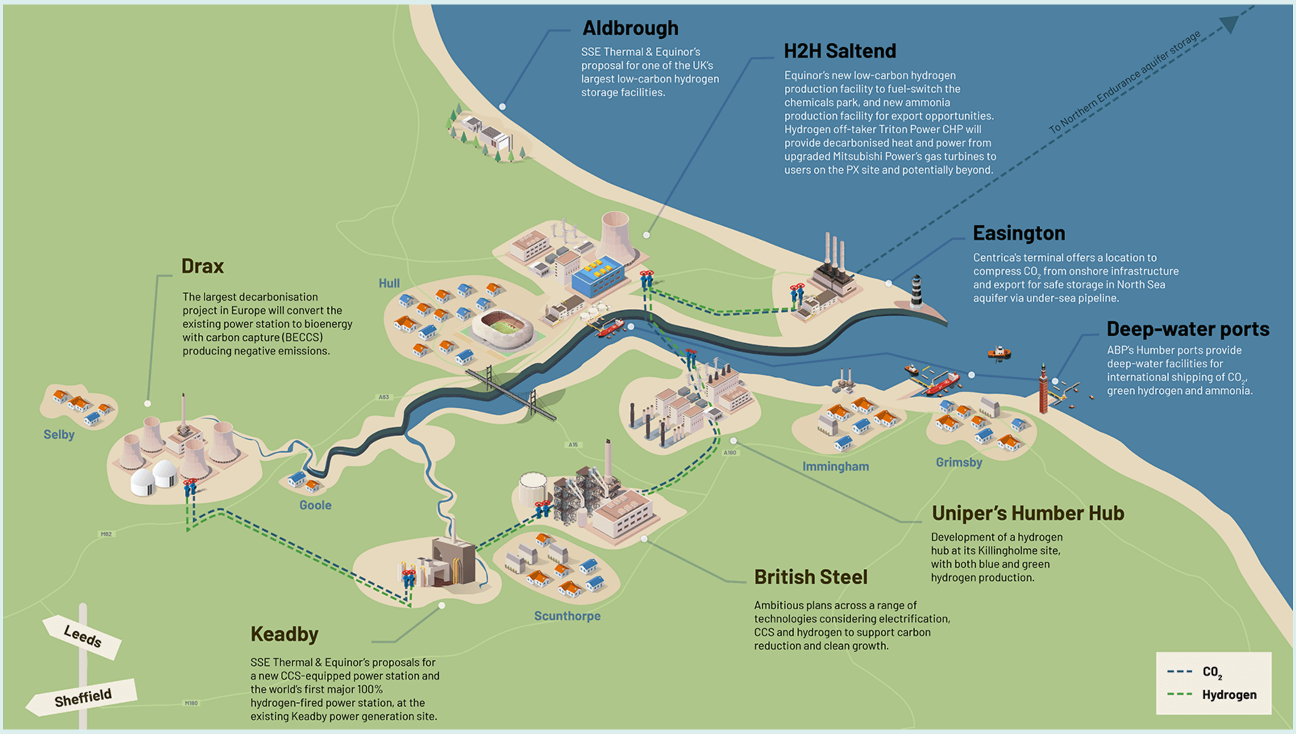


Figure 7: Source: www.saltendchemicalspark.com

PENSANA Plc

Case Study - Materials Processing Institute

The Materials Processing Institute, a not-for-profit Research Technology Organisation based in Teesside, has developed a proof-of-concept for a novel process route that will reclaim pure material streams of cathode-active materials (CAM), graphite, aluminium, and copper, via the application of existing technologies, industrial know-how and innovative 'green solvent binder dissolution'. A hydrometallurgical process will be used to process the CAM that will be used for hydrometallurgy feedstock to recover nickel, manganese, cobalt, and lithium for remanufacture.

This research was funded through the BEIS PRISM Programme and builds on a previous Innovate UK project which aimed to extract graphite from lithium ion batteries (LIBs). The Materials Processing Institute is working with Lithium Salvage, a Teesside start-up to establish a localised, circular battery materials supply chain in the Northeast.

Lithium Salvage will install a 1,500 tonnes per year system capable of recovering CAM (nickel, manganese, cobalt, and lithium), graphite, copper, aluminium, and electrolyte not only from EV LIBs, but also from waste electrical and electronic equipment (WEEE), a market that is available now for material recovery.

While the full extent of this challenge may not be felt until 2030, the UK must act now to develop a robust, circular battery supply chain to reduce our dependency on commodity imports, prevent the loss of valuable materials, reduce the energy intensity of the recycling process, and to provide recovered materials back into the battery supply chain in line with the EU battery directive[86].

EU Battery Directive

The text sets out the sets maximum quantities for certain types of metals and chemicals contained in batteries, and sets targets for waste battery collection rates, as well as financial liability for waste collection and management.

A new Batteries Regulation is under review since its proposal in December 2020. The updated framework places emphasis on lithium-ion batteries.

The proposed new regulation sets out mandatory sustainability and safety requirements (e.g. carbon footprint rules, minimum recycled content, labelling and information) and end-of-life management obligations (e.g. producer responsibility, collection targets and obligations, recycling efficiency targets).

Figure 8: Source: Materials Processing Institute.

Materials Processing Institute

Case Study - Green Lithium

The electric revolution is driving an increasing demand for lithium processing in the UK and across Europe. To help meet this requirement, Green Lithium is building one of Europe's first large-scale merchant lithium refineries at PD Ports in Teesside. Operational from 2025, this facility will play a crucial role in assuring an environmentally sound, home domiciled lithium supply chain to meet the expanding needs of the battery manufacturing and automotive sectors.

Securing the UK's critical minerals supply chain

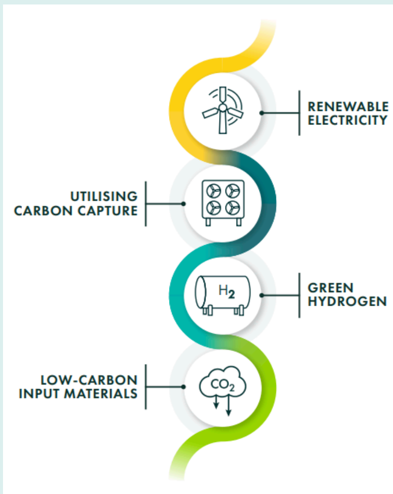
Currently, 89% of the world's hard-rock lithium is processed in East Asia, where domestic demand is expected to outstrip production by 2030. Unchecked, UK industry's continued reliance on international sources for its refined lithium chemical imports is rapidly becoming an economic risk, with national security implications given lithium's growing importance to the UK's strategic defence supply chain. Green Lithium's investment in Teesside is intended to address this.

At full capacity, the Green Lithium refinery will deliver an annual production of 50,000 tonnes of low-carbon, battery-grade lithium chemicals that will help meet UK industry's growing demand and provide an assured supply to the UK's allies and trading partners in Europe.

As a merchant refinery, Green Lithium has flexibility of feedstock, able to process lithium carbonate, lithium sulphate and spodumene from a range of international suppliers. This diversity will provide additional resilience to the UK supply. For the next decade, spodumene will be the fastest growing source of supply and our primary focus. Together with our partner Trafigura, we will source spodumene from mines in Australia, Africa, North America and, eventually, Europe.

Growing the UK's green economy

The construction of the refinery will help drive the UK's levelling up agenda as well as supporting local and regional development on Teesside. Over 1,000 jobs in the local area will be created during the construction phase and 250 full-time local and highly-skilled green jobs once in operation. Recognising the economic impact on the local and national economy, the UK Government has backed Green Lithium with a grant of over £600,000 through the Automotive Transformation Fund.



Low-carbon refining – 80% lower CO2

Green Lithium is committed to transforming the refining process, historically an energy-intensive supply chain component by establishing leading ESG practices, targeting net zero on Scope 1 and 2 emissions by 2035 whilst working with supply chain partners to minimise Scope 3 emissions and reducing its carbon footprint to significantly lower than existing international refineries. This will be achieved through integrating low-energy processes with renewable electricity and by ensuring the refining plant is capable of utilising hydrogen gas and is carbon capture enabled. Additionally, there will be no wider environmental impact due to the refinery's use of a non-acid leach process flowsheet with zero liquid discharge and no sulphates in its output.

A Case for UK Midstream

The UK is falling further and further behind on critical minerals. However, our nation can leverage its strengths across the financial sector, existing manufacturing capacity, and world-renowned research and development. The UK needs to take urgent action to secure a reliable supply of critical minerals to prevent an exodus of manufacturing to more competitive jurisdictions.

Demand

The dramatic increase in demand for critical minerals to meet the needs of net-zero technology, control of supply chain by a few countries, and logistics failures have created a global shortage. Companies and countries are competing to access critical minerals to meet their strategic and commercial needs. Many countries and groups of aligned countries have published critical minerals strategies and are evaluating ways to secure their supply through partnerships. Logistics philosophy has changed suddenly from "just in time" to "just in case". This requires either larger inventories and working capital commitment or increased domestic production.

UK OEMs will be left competing with foreign government-backed companies to secure the necessary critical minerals needed for production. As the gap between supply and demand widens, nations which hold a monopoly over certain critical minerals may choose to prioritise their own needs first. Without a consistent supply, the UK manufacturing sector will be crippled.

Supply

The UK does not have significant primary ore reserves of critical minerals. It can, however, import partially upgraded critical minerals from like-minded partners to further process in domestic midstream plants. Such refineries could also recycle end-of-life goods containing critical minerals.

The first generation of electric vehicles and wind turbine generators will start to reach end-of-life by 2030. This will suddenly and significantly increase the quantity of battery active metals and rare earth metals available for recycle in the UK. By 2040, **~235,000 tonnes per annum of lithium-ion batteries** (LIBs) will have reached EOL and be available for recycling, alongside **10-15,000 tonnes per year of production scrap** from each gigafactory. This switch is creating a demand for critical materials that cannot be fulfilled as the supply and demand gap for graphite, cobalt, and lithium production reaches 30-60%[87]. A much more immediate threat is the disposal of **1.3 million single-use vaping products per week in the UK.** Each of these contains a LIB, using **10 tonnes per year of lithium[88].**

Advanced Propulsion Centre state that by 2030 the UK could recover enough nickel and lithium required for LIB manufacturing by recycling battery production waste, but not cobalt (the most expensive element in LIBs) with the difference potentially being sourced from EOL mobile phone batteries; 45 million iPhones contain 500 tonnes of cobalt[89]. Statista found that the UK have almost 90 million mobile phone subscriptions, which could make up to 900 tonnes of cobalt available for recycling: enough cobalt for 45,000 electric vehicles (20kg per 100 kWh pack). Green Alliance[90] found that potentially >50% of UK cobalt demand could be met by 2035 if the recycling capacity existed.

As the current supply chain mechanism exports all EOL LIBs to Europe for pyrometallurgical-based recycling, **the UK already loses around £13.63 million per year of materials[91].** This loss of valuable materials and lack of upstream mineral production means the UK must onshore a recovered raw material supply chain to support the transition. Graphite, burned off in pyrometallurgy based recycling, has increased in price by 56% between September 2021 and June 2022 driven by demand by for LIBs and electric vehicles, with predictions of a supply deficit[92].

A domestic critical mineral midstream would increase the UK's security of supply and create direct and indirect employment. Secure domestic supply would safeguard major industries such as automotive and defence that will rely increasingly on critical minerals. However, for the recycling capability to function at a commercial level, the UK Government will need to make strategic investment into the set-up of a UK midstream industry.

Environmental, Social and Governance Compliance

The UK government's 2021 policy document **"Net Zero Strategy: Build Back Greener"**[93] states that:

We are actively supporting the adoption of transparent, ethical, and responsible mining practices, reflecting environmental, social and governance (ESG) considerations, and re participating in the development of global standards through the British Standards Institution.

Public awareness in the UK and the Western World of ESG issues has led to expectations that UK companies comply throughout their supply chain, not just in the UK[94]. Compliance adds to costs and can reduce competitiveness of UK companies compared to those in less well-regulated jurisdictions.

However, it can also create a competitive advantage as those who do not comply are kept out of the market by public opinion, legislation, or denial of finance. Transparency and ESG compliance would favour UK midstream operations. Blockchain ledgers and related measures can track the provenance of imported raw materials. The UK contributes significantly to international standards and best practice for mining, metals, and critical minerals.

Finance

The UK is a global leader in mining finance (although New York is increasingly appealing to the critical minerals sector) and related services including legal, insurance, metal trading, and consultancy. Increasingly, companies that do not comply with ESG expectations find it difficult to obtain finance. This can benefit UK registered mining and midstream companies that are ESG conscious.

The UK Government has provided various funds to support net zero ambitions and critical minerals suppliers. These include:

- Automotive Transformation Fund (ATF) to support zero-emission vehicle development including batteries and drives.
- Industrial Energy Transformation Fund (IETF) and Energy Intensive Industries (EII) schemes to help high-energy consumers such as those producing critical minerals.
- National Security Strategic Investment Fund (NSSIF) to support technologies also related to security and defence.
- The UK Infrastructure Bank (UKIB) to support projects tackling climate change.
- UK Export Finance (UKEF) to support critical minerals projects with export potential for goods or services.

Playing to the UK's Strengths

The UK must navigate the challenges to build resilient supply chains but can leverage existing initiatives, partnerships, projects, and infrastructure to successfully build a resilient midstream industry. The UK has a strong manufacturing sector including a world-class chemicals industry. Access to renewable energy sources is also increasing, in 2020 renewables accounted for more than 43.1%[95] of the UK's total of electricity generated.

Freeports

Freeports[96] are being created around the UK to provide sites with efficient logistics, upstream and support industries, and power supply from wind turbines. They are good locations for midstream plants. Projects of national strategic importance could be given priority and support in accessing valuable real estate.

Freeports are Special Economic Zones with various incentives to relocate business there including tax reliefs (Business Rates, Stamp Duty Land Tax, Employer National Insurance Contributions, Enhanced Structures and Building Allowance, and Enhanced Capital Allowances) customs, business rates retention, planning, regeneration, innovation and trade and investment support. Customs relief is negotiated on a case-by-case basis with HM Treasury for each Freeport.

Domestic Primary Ores

The UK has limited domestic primary ore resources, but exploration is being encouraged and geological data made available. Well-established projects are already progressing in Cornwall and Devon to mine tungsten and tin, and to produce lithium from geothermal brines and micaceous granite.

Lithium will be processed in the UK to battery grade for use in domestic gigafactories. Preliminary minerals processing will be performed at the tungsten and tin mines, but concentrates may be exported for refining at existing midstream plants in Europe.

Source: Tungsten West

UK-Owned Mines Overseas

A UK mining company plans to import rare earth concentrates from its mine in Africa to upgrade to magnet grade at a new refinery to be built on Humberside. There should be opportunities for other companies to do the same, creating an ESG compliant supply chain from mine to market.

Supply from Strategic Partners

The UK is cooperating with the multinational MSP on critical minerals supply. It also has bilateral cooperation with Australia and Canada with whom there are historic cultural ties. Both countries have primary ore deposits of critical minerals and are also looking to develop their own midstream. There is scope for cooperation.

Membership of such alliances should improve the UK's security of critical minerals supply. It may also create opportunities to refine primary products from these countries at midstream operations in the UK. It is beneficial for midstream plants to be located close to the end user, especially when these produce waste materials that must be recycled. The UK has such end users in the automotive, gigafactory, advanced manufacturing, and defence industries.

Circular Economy

The UK hosts companies that use critical minerals in advanced manufacturing. Recycling of waste generated at such facilities is important for profitability, and recycling facilities should be located close to the source of waste.

From approximately 2030, there will be a sudden and significant increase in the quantity of first-generation electric vehicle batteries and drive motors, and wind turbine generators, reach end-of-life. To minimise transport carbon footprint, ensure safety when handling lithium-ion batteries, and to secure UK supply, it is essential that these materials are recycled in the UK.

The UK generates a great quantity of WEEE. Each item contains small amounts of several critical metals. However, equipment design may mean that valuable metals are embedded in other materials making them difficult to disassemble[97]. These factors can make recycling uneconomic[98]. In addition, there is currently no recycling classification for WEEE in the UK, and collection of WEEE is poorly organised. Until recently much WEEE has been exported.

WEEE and other sources of critical minerals have been discarded to landfill[99] in the UK. The potential for "urban mining" from such sources was recognised by the House of Commons Science and Technology Committee in 2011[100].

Secondary Sources

Historically, processing wastes were discarded without consideration of their potential by-product content. There are historic tailings dams in the UK that may contain recoverable by-products[101]. Flue dusts from steelmaking have been land-filled but contain zinc and possibly associated critical metals[102] [103] [104].Coal waste dumps may contain rare earth elements[105] [106] , and their exploitation is being evaluated in the USA. Steel slags may contain vanadium. The quantity and contents of such waste deposits may not be fully understood, and merits research to determine if critical minerals could be recovered. The UK does not have large electrolytic refineries, so there is no domestic production of anode slimes from which certain critical minerals can be extracted. However, that does not prevent UK companies importing anode slimes to process domestically.

Challenges faced by the Midstream

Until very recently, midstream metallurgical plants had been closing in the UK. Rapid increase in critical minerals demand has led to new projects for domestic primary lithium, tin and tungsten production, proposals for a rare earth processing plant, and expansion of scrap recycling facilities. Despite these encouraging developments, there are constraints on midstream development in the UK.

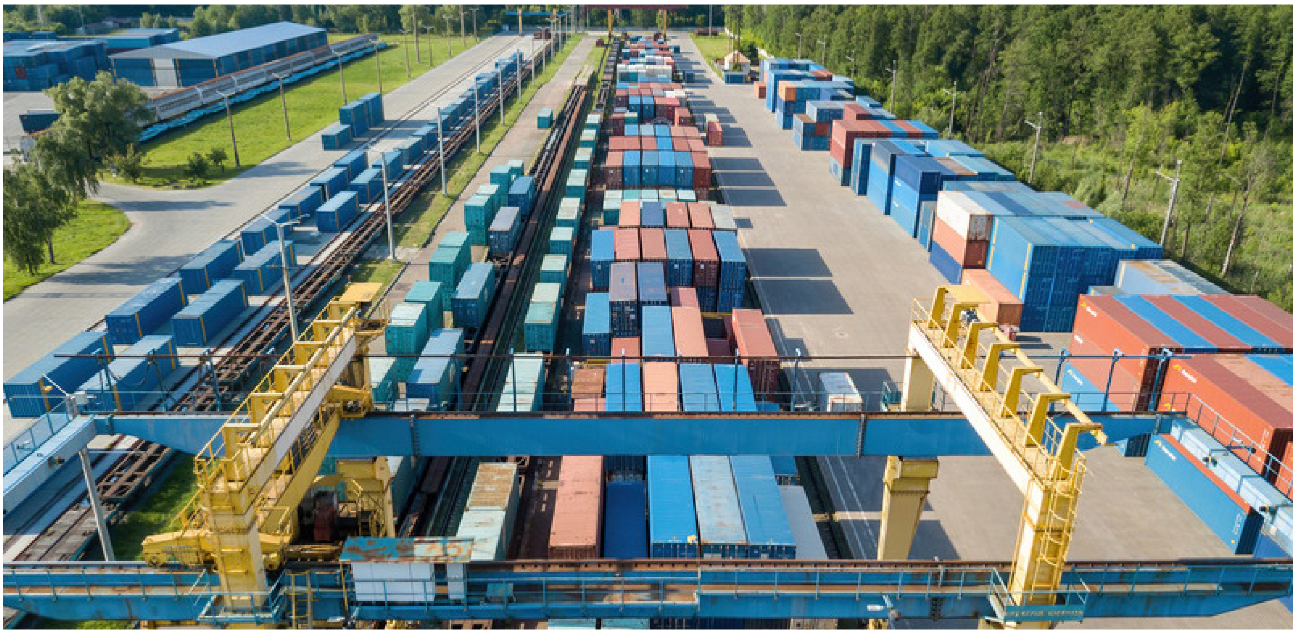
Feedstock

To expand midstream metallurgical processing in the UK, it would be necessary to import raw materials such as concentrates, partially refined metals, or scrap. Import risks will include international competition, export controls by supplier countries, and logistics problems. UK midstream operators would also need to ensure their raw materials are ESG compliant throughout the supply chain.

Alternatively, the UK must significantly increase domestic recycling of critical materials. There will be a sudden and significant increase in the quantity of electric vehicle batteries, drive motors, and wind turbine magnets as older units reach end-of-life at the end of this decade. For safe handling and security of supply, these materials should be recycled in the UK. There is potential for recycling waste electronic equipment, but classification, legislation and collection need urgent attention. Recycling alone will not meet the UK's needs, and materials from primary mining will still have to be imported in increasing quantities.

Steel is recycled in the UK, but much is exported. A new electric furnace in Scotland powered by wind turbines will increase the UK's domestic steel recycling capacity[107]. Sorting of scrap steel by composition would avoid loss of high specification steels containing critical minerals through dilution with basic steel scrap.

Wastes from coal processing and steel plant flue dusts have historically been discarded without thought of reprocessing. Article 20 of the EU Mine Waste Directive, to which the UK was committed, states that 'Member States shall ensure that an inventory of closed-waste facilities, including abandoned waste facilities, located on their territory which cause serious negative environmental impacts or have the potential of becoming in the medium or short term a serious threat to human health or the environment is drawn up and periodically updated. Such an inventory, to be made available to the public, shall be carried out by 1 May 2012, considering the methodologies as referred to in Article 21, if available.' It is possible that such wastes may contain critical minerals and other metals such as zinc that could be recovered. Research is needed into the potential to convert these wastes into resources to supplement domestic supply.



Waste Electrical and Electronic Equipment (WEEE) Recycling

WEEE recycling is challenging because of the small quantities of critical material contained in each device, and design that necessitates disassembly to access the valuable components. Both factors reduce the economic viability of recycling WEEE, despite the need to recover critical minerals.

WEEE recycling rates are also low, estimated at **less than 20% globally**[108]. There is significant scope for this to be increased in the UK. Many electronic devices are hoarded in homes[109], partly because of residual personal data retained in them, and due to the lack of recycling facilities. The UK has six categories of waste for recycling, but WEEE is not one of them. Collection facilities are generally restricted to a specific section at council recycling centres to which owners must take their defunct WEEE. This requires personal transport and possibly reserving a time slot. Many people may find it less troublesome to discard WEEE to the general waste collected from their homes, which is sent to landfill. There are no overt campaigns to encourage recycle of domestic WEEE. Until recently, much of the WEEE collected by councils was exported for processing. The Waste Electrical and Electronic Equipment (WEEE) Forum estimated that 45% of WEEE is exported illegally from the European Union. According to a report, the UK is the worst offender in illegally exporting WEEE to developing nations.[110]

Regulations and Permitting

The CMA publication 'Environmental, Social, Governance & UK Critical Minerals: Planning & Permitting', describes challenges posed by UK planning and permitting to new critical minerals projects. The report states in Issue 3[111]:

"Decision making on planning and permitting is devolved to the local level. However, many Local Planning Authorities (LPAs) generally do not have:

- The capacity to review documents
- The in-depth understanding of mining and associated technical issues needed to assess projects
- A 'mining' focused mindset when it comes to evaluating projects (e.g., assessing a mining project through the same lens as an infrastructure project)
- An understanding of the mining sector, transnational processes and stakeholders that influence mining projects (e.g., investors, financial institutions, global standards, downstream manufacturers)
- Knowledge of the key ESG risks in mining (e.g., water impacts, closure plans) which can be managed in the mine design or the context of international responsible mining standards
- Confidence to take decisions and / or face political consequences of making the wrong ones

One council agreed with these above points and mentioned that these have also been raised by other groups, in particular the Planning Officers Society Mineral & Waste Group and the Royal Town Planning Institute (RTPI)."

The above factors can lead to delays in approval of new projects. UK authorities could possibly learn from and adopt permitting and planning procedures from partner countries such as Australia and Canada that have more project applications and have modernised their systems.

Skills

The UK was once home to the world's leading university courses in mining and minerals processing. The lack of domestic industry reduced their relevance, and most have now closed or are in temporary suspension. It is unlikely that schools' careers advisors have an adequate knowledge of the mining and metallurgical industry to recommend it to their students seeking university courses.

Graduates from UK mining schools often gained experience overseas before returning to the UK, bringing their practical knowledge to mining company head offices, mining finance houses, and consultancies. As pointed out in a recent report, **80% of registered mining and minerals processing engineers in the UK are over the age of 50 and nearly 40% are over 66**[112]. Many over 70 are still active in consultancy due to the demand for their knowledge.

Even countries such as Canada and Australia with large mining industries face skills shortages. Mines are often in remote locations with fly-in / fly-out accommodation that may be unattractive to potential employees, even when salaries are good. The industry is cyclical and staff lay-offs can occur during downturns. Some skilled employees may choose not to return in the upturn. Furthermore, the mining industry is demonised in popular culture and "miners are always the bad guys in the movies". All these factors can deter those with the necessary talent from joining the industry.

In stark contrast, new, green industries such as electric vehicles, gigafactories and renewable energy have a positive public image. Courses in the UK could be revised to include midstream metallurgy within a wider green economy framework. The role of the midstream in decarbonisation, and aspects of the processes such as automation and programming, could make it attractive if it were better publicised.

Midstream processes are complex, and **the UK will need experienced minerals engineers** to design and operate them[113] [114] [115]. Some UK companies are already recruiting staff from overseas, while others have located their midstream plants in other countries. If the UK is to host a critical minerals midstream, it will need appropriate university courses to train its citizens. Even with courses in place, it will still take years for new graduates to replace the experience that has been lost in recent years.

Energy Cost and Avaliablity

The cost of electricity is high in the UK - and had reached the highest in the world during the latter part of 2022 – and companies are also experiencing high prices for oil, gas, and vehicle fuel (the removal of the Red Diesel Rebate further reduces the economic feasibility of many projects). This can reduce the UK's competitiveness against Canada and Nordic countries, for example, that have low-cost clean energy from hydro-electric schemes and an established midstream.

The UK Government does have the Industrial Energy Transformation Fund (IETF) and Energy Intensive Industries (EII) schemes to help high-energy consumers such as those producing critical minerals.

Finance

The UK is a global leader in mining finance. Nevertheless, inadequate funding can delay projects with good potential. Reasons are usually project specific and it is difficult to draw general conclusions. Projects seeking funding are expected to produce feasibility studies in a standard format that facilitates detailed technical and economic evaluation by potential investors.

The UK is typically seen as less attractive to investors than jurisdictions with favourable policy frameworks such as Canada, the Nordic nations and Germany for the set-up of potential processing and refining facilities. Heavy monopolisation of certain supply chains is also seen as too risky for many traditional banks and investors to put significant capital behind projects that are often of national importance.

The UK Government does not have a specific critical minerals fund akin to those of Australia, Canada, and the US, and lacks policy attractiveness such as that created by the Mineral Security Act (MSA) and the Inflation Reduction Act (IRA). Under the IRA, a tax credit equal to 10% of the cost of production is awarded to the producer of applicable critical minerals. The tax credits introduced as part of the MSA include $3.00 per pound of primary critical mineral produced in the US, and $1.50 per pound of primary critical mineral processed in the US. The tax benefits of the MSA and IRA have positioned the US as a very competitive investment jurisdiction for critical minerals value chains. It is expected that the EU will follow suit and propose similar incentivise to drive the creation of European critical minerals supply chains. If the UK Government does not propose its own counter measures to the IRA, and any future policies by the EU, it will effectively take itself out of the race to secure critical minerals.

Government Intervention

There is a strong case for urgent government intervention to support the industry and secure the UK's future. There is still a misconception amongst policymakers who are wedded to market forces. In reality, the midstream industry for critical minerals is heavily monopolised which distorts the market in the dominant player's favour. There is no free market for many critical minerals. If the UK Government is serious about protecting its industry and growing a circular economy founded on a just energy transition, then it must step in and support its companies.

Support the Domestic Critical Minerals Industry

As the mining and metallurgical industry declined in the UK its relevance to society was lost. The increase in personal technology, electric vehicles and wind turbines is starting to make the need for critical minerals better recognised. This is important as public opinion can influence planning permission for domestic critical minerals projects and recycling of domestic WEEE.

Publication of the government's Critical Minerals Strategy should increase awareness of the importance of critical minerals. However, more needs to be done by the UK Government to educate civil society about the role of critical minerals and the challenges we face ahead.

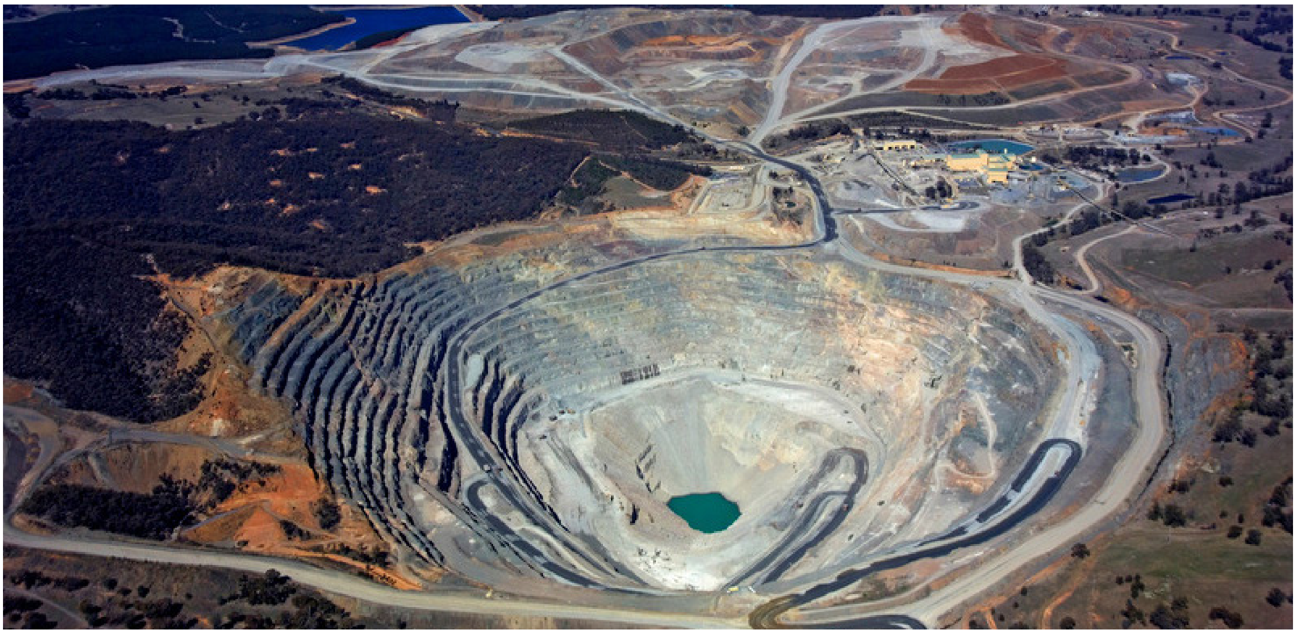
To avoid the impending skills shortage in critical minerals, the UK Government should address the closure of degree courses in mining and minerals processing. The negative image of these industries created by popular culture also needs to be countered to explain the essential role of critical minerals in a net-zero world.

Provide Diplomatic Support

The UK has considerable "soft power" and strong relationships with like-minded countries that produce critical minerals. Supplies of ESG compliant feedstock for UK midstream plants could be secured through diplomatic means and trade deals. This would however require proactive engagement of the civil service with industry and host nations. This is currently missing.

Review Permitting

The UK Government should review the planning and permitting procedures to ensure they are fit for purpose when there is an urgent need to increase domestic critical minerals supply. Best practice from countries such as Australia and Canada with higher numbers of mining and midstream projects could perhaps be incorporated. The lack of mining and metallurgical knowledge at LPAs could be addressed by centralised critical minerals project permitting. Centralised expertise could not only avoid delays, but also ensure the highest technical and environmental standards are implemented.



Encourage the Circular Economy

There is need and potential for the UK to increase recycling to recover critical minerals. Facilities to recycle EV batteries and drive motors and magnets from wind turbines need to be ready for operation by the end-of-life of first generation EVs and wind turbines from around 2030.

Recycling rates for WEE are low. National waste classifications should be updated to include WEEE and lithium-ion batteries. Facilities for collection are inadequate and deter households from recycling. Legislation to enforce WEEE recycling could perhaps be considered. Canada has developed effective systems, and these could be considered as options for the UK.

Processes for recycling WEEE can be complex. Quantities of critical minerals may be small and embedded in other materials, making them difficult to access. There are arguments that equipment design should facilitate disassembly and recycle, but the counter argument is that this would remove competitive advantage and stifle innovation. Another argument is for "durable design"[116] that would extend the lifetime of equipment and make it easier to repair and reuse. Government policy should decide between these options and determine whether to extend product life, maximise critical mineral recycle, or protect design freedom.

To ensure supply of certain critical minerals from recycling, it may be necessary for the government to provide financial support to those that are otherwise not commercially viable. Mixing scrap can dilute the critical metal content. Identification and sorting of scrap should be encouraged by the government to maximise critical minerals recovery.

Canadian companies have expertise in operating plants for EV battery recycle and minor metal recovery. With the right government incentives, they could perhaps be persuaded to establish midstream operations in the UK, or to cooperate with UK partners.

Provide Data

The UK has discarded coal mine and smelter waste that may contain critical and base metals. It is important to quantify these potential resources, and this could be a role for the CMIC.

The total demand for each critical mineral in the UK should be known, as should midstream processing capacity at the plants listed under SIC Codes 24.4.

Policy decisions should be made based on concrete data, analysis, and contextualisation with ongoing market dynamics, geopolitics, and the UK's industrial goals.

Facilitate Financial Support

Midstream plants for recycling of EV batteries will need to be ready for operation before the first generation reaches end-of-life around 2030. Financial incentives may be needed to encourage their timely development and help attract investors in the UK.

Impose Restrictions on Imports and Exports

The UK Government could prevent the import of goods and raw materials that cannot provide proof of provenance and compliance with the high ESG standards to which domestic producers are held. Similarly, UK mining finance providers should be discouraged from funding critical minerals projects that are not ESG compliant.

The government should keep in mind, that currently, it is impossible to substitute all of the Chinese critical minerals with ESG compliant alternatives. If import and export restrictions were to be introduced, these would require a phased approach that protects UK industry and does not have unintended consequences.

The National Security and Investment Act 2021 gives UK Government "powers to identify and, if necessary, intervene in acquisitions of control over entities and assets in or linked to the UK economy, including those in critical mineral value chains, which might cause national security concerns"

Concluding Statement

The UK has several exploration projects which will be reaching production in the next few years, and numerous secondary sources such as tailings, slags, sludges, and waste that could be further exploited and reprocessed to clean up legacy sites and create a more circular economy. The UK is already refining nickel, PGMs, REE oxides, and is recycling REEs from magnets – these are all occurring on small scales. Lithium extraction from granite micas and refining have been piloted in Cornwall, and there are plans to refine lithium hydroxide and carbonate in the UK, as well as to import REE feedstock to refine. Collectively, these projects will only be able to provide a fraction of the UK's critical minerals needs.

The UK has the potential to create low carbon, integrated, responsible, and diversified supply chains outside of the currently monopolised system if the UK Government collaborates effectively across departments to address challenges facing existing operators, and those looking to break into the UK market. To attract significant investment from the private sector, the UK Government must first address conflicting policies and create incentives to ensure that the UK is regionally competitive. Several of the UK's domestic critical minerals projects have been progressing despite the lack of UK Government support. With government support, these projects could be significantly accelerated.

The UK is only a small player in the critical minerals supply chain. The nation's needs and growth rely on heavily monopolised and fragile supply chains. This means that international alignment with like-minded partners in the Western world and producers in developing countries is fundamental to secure the UK's future and expanding our manufacturing capabilities. However, the UK must simultaneously address challenges at home to become an attractive partner nation in the global race for friends.

The UK Government must commit significant capital, and establish critical minerals partnerships with allied nations, to **secure the UK's future and bolster the nation's economic resilience**. The alternative is to do nothing – jeopardising the future green economy, and the UK's economic prosperity.

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Appendix 1

Processing Methods for Critical Minerals

ANTIMONY

Primary Production of Antimony

Antimony is usually produced from its sulphide mineral stibnite (Sb2S3). Lower grade ore can be upgraded by froth flotation. High grade ores can be heated to <600°C at which stibnite melts and waste rock can be separated.

Stibnite can be reduced to antimony metal by reaction with iron at elevated temperature.

Antimony is also removed from impure lead in the Betterton-Kroll pyrometallurgical refining process.

Production of Antimony

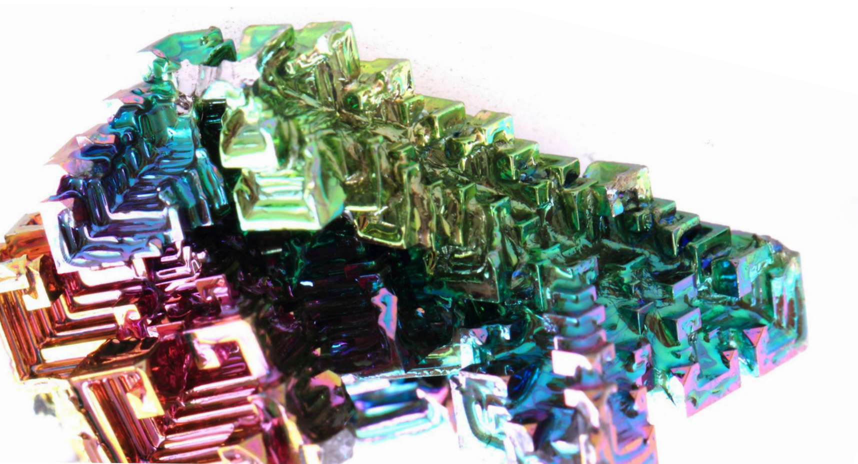
Different sources report antimony recycling rates of 10 to 30%. The main source is spent lead-acid batteries, with residues from lead, copper and zinc processing providing additional material.

BISMUTH

Primary Production of Bismuth

The most important bismuth minerals are bismuthinite and bismite that can be concentrated by flotation, gravity, and magnetic separation. Although bismuth can be a mine's primary product, it is more commonly recovered as a by-product during processing of lead and tungsten. Minor amounts are also derived from tin and copper smelting.

Bismuth is recovered from anode slimes generated in the Betts electrolytic process for production of high purity lead. The alternative Betterton-Kroll is a cheaper pyrometallurgical process, in which calcium and magnesium are added to molten impure lead. They form higher melting point alloys with the contained antimony and bismuth, which floats on the surface of the molten lead and can be skimmed off as "dross".



Recycling and Secondary Production of Bismuth

Recycling rate of bismuth is commonly reported as zero. Bismuth is difficult to recycle because of the range of its applications and the chemical compositions used.

COBALT

Primary Production of Cobalt

Cobalt can be recovered from both sulphide and laterite deposits.

Cobalt sulphide can be mined as a primary mineral, or as a by-product of copper, nickel, and platinum group metal deposits. Cobalt minerals can be recovered by froth flotation. In Central Africa, concentrate is subsequently roasted and leached with sulphuric acid. Roaster off-gas is collected, waste heat recovered, and sulphuric acid produced. Iron is removed from the leach by adding lime to precipitate gypsum that can be used for plasterboard manufacture. The remaining solution is processed by solvent extraction and electrowinning to recover copper. The solution is further purified by precipitation, ion exchange and solvent extraction to remove nickel and zinc. Cobalt is precipitated as hydroxide by lime addition, and the precipitate re-dissolved in acid before cobalt metal is recovered by electrowinning. Additional stages can include cobalt metal crushing and degassing.

This process is used widely in the Democratic Republic of Congo, the largest source of cobalt, and Zambia. Also in Zambia, cobalt has been recovered from copper smelting slags and the solution from leaching introduced into the main cobalt processing plant.

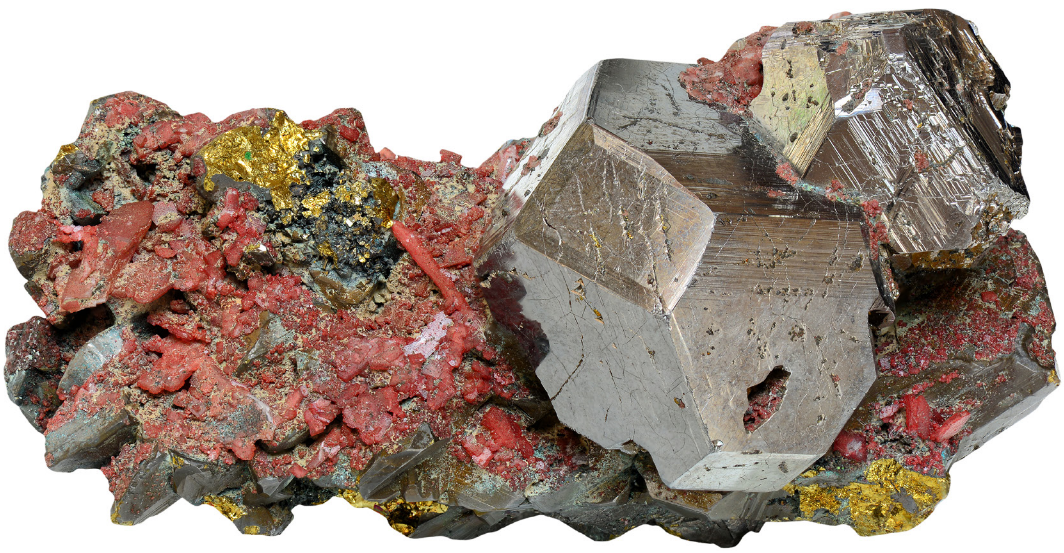
Alternative process routes include ammonia leaching (Sherritt Gordon process) in Canada and South Africa, chloride leaching in Norway, and oxidative sulphate leaching (Outotec process) in Finland.

Nickel laterites are processed by high pressure leaching and different hydrometallurgical routes in Australia, the Philippines, New Caledonia, and Madagascar. Cobalt is recovered as a by-product.

Recycling and Secondary Production of Cobalt

Reported recycling rates for cobalt range are from 20 to 30%. Sources are end-of-life alloys such as jet engine turbine blades that can be remelted, plus batteries and magnets. Scrap produced during the manufacture of alloy components is also recycled.

The quantity of cobalt available for recycle will increase significantly with the number of electric vehicles as their batteries reach end-of-life after eight to ten years. However, there are efforts to change battery chemistry and reduce the cobalt content due to concerns over the security and transparency of supply from Central Africa. Currently, the preferred battery recycling process is shredding in a neutralising solution, screening out of plastic and foil for recycle, and filtration to recover the fine solids as “black mass”, which is then leaching to dissolve the valuable battery metals nickel, cobalt, and lithium. These are separated by solvent extraction and precipitated as their battery grade salts.



COPPER

Primary Production of Copper

Copper is mined as both sulphide and oxide ores, from underground and open pit operations. Underground operations are usually higher grade and lower mining rate. Open pit operations employ economy of scale to mine high daily tonnages (>100,000 tpd) at low grade. Most copper is produced from sulphide ores, but the amount from oxide copper is increasing.

Sulphide ores are processed by standard techniques of crushing, grinding and froth flotation to produce a concentrate containing 25 to 40% Cu depending on mineralogy, and in exceptional cases 60% Cu. Concentrates may be shipped to a remote smelter for processing to anodes, which in turn are refined electrolytically to market grade cathode product.

Sulphide ores may contain by-products such as cobalt and molybdenum that can be produced as a separate concentrate during froth flotation. Trace metals such as gold and selenium are rejected in the anode slimes produced during electro-refining. Anode slimes are treated separately to recover precious metals, often in specialist refineries.

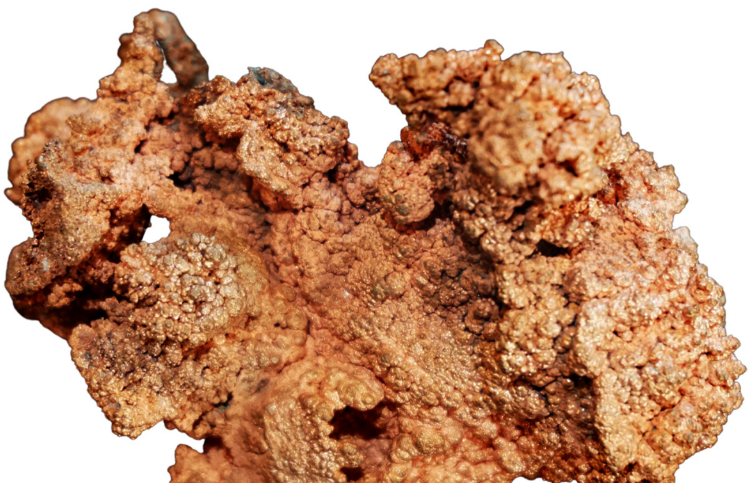
Sulphide ores of copper are generally not amenable to hydrometallurgical processing, but low-grade sulphide ores can be treated by heap leaching, which may be assisted through oxidation by naturally occurring bacteria.

Oxide or oxidised copper ores can be leached, and usually this is by heap leaching. Mounds of crushed rock are built on pads and sprayed with sulphuric acid. The acid percolates through the heap, dissolving oxidised copper en route, before being collected from the base of the heap and sent to a hydrometallurgical plant. Copper is separated and upgraded by solvent extraction and then recovered by electro-winning to produce market grade cathodes.

Recycling and Secondary Production of Copper

Around 32% of copper is produced by recycling. Processes are well-establish and relatively straightforward. Scrap can be returned to smelters and contained copper recovered as high-grade cathodes. Copper loses none of its key properties during repeated recycling.

Copper can also be recovered as a by-product of other metals. For example, cobalt roast-leach-electrowin operations include a copper electrowinning stage after leaching and initial impurity precipitation.



GALLIUM

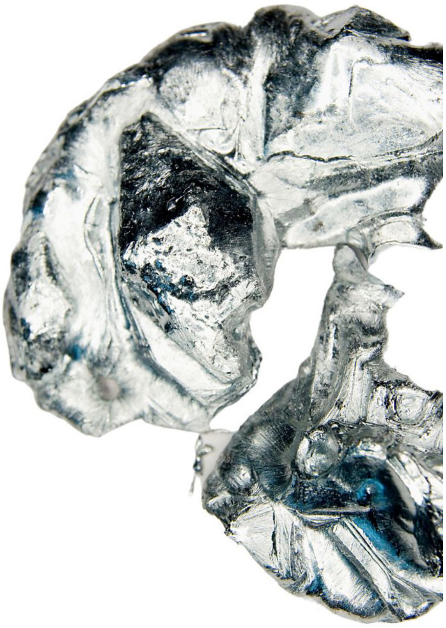
Primary Production of Gallium

Gallium minerals are too rare to act as a primary source, and all gallium is recovered as a by-product of other metals such as aluminium, or from recycling.

A major source of gallium is the Bayer Process for conversion of bauxite to alumina in the production of aluminium. Gallium accumulates in the caustic soda liquor from which it can be extracted by a variety of methods including ion-exchange.

Recycling and Secondary Production of Gallium

The recycling rate for gallium is approximately 10%. Specialist companies recycle scrap electronic and photovoltaic devices to recover gallium from gallium arsenide semi-conductors. This is complex due to the small quantities of metal and the form of gallium in semiconductors. Processes include leaching, chemical separation and electrorefining. Indium may be recovered as a separate product in the same process.



GRAPHITE

Primary Production of Graphite

Processing of natural flake graphite depends upon the impurities present. Comminution followed by froth flotation is commonly used to separate graphite flakes from waste. Gravity concentration, magnetic separation, and electrostatic separation can also be used depending on the gangue minerals to be rejected.

Graphite concentrates can be screened to separate different sizes for specific uses and can be acid-leached to remove impurities.

Recycling and Secondary Production of Graphite

Recycle of graphite is estimated to be around 3%. It is difficult to recover graphite economically and with low environmental impact, but there is considerable research into recovery from spent lithium-ion batteries. Acid curing and leaching are currently promising means to remove residual traces of cathode material and leave a pure graphite product.

INDIUM

Primary Production of Indium

Indium is produced exclusively as a by-product, predominantly from zinc ores containing the sulphide mineral sphalerite.

Primary zinc sulphide processing is by froth flotation. Concentrates are roasted and acid leached, with zinc metal being recovered from the resultant solution by electrowinning. Indium accumulates in the leach residue from which it is extracted. The indium recovery process depends on the concentration of metal. Methods include leaching of the zinc residue with sulphuric acid to dissolve indium, followed by solvent extraction or precipitation.

Recycling and Secondary Production of Indium

There is conflicting data on indium recycling rates but around 1% seems a reasonable estimate. Over 70% of indium is used in flat panel LCD displays, smart phones, and related devices. The low quantities and diffusion of indium means that high quantities of waste electronics must be processed to recover a small quantity of indium. Conventional hydrometallurgical processes can be used, and research is ongoing on new methods to reduce overall energy consumption.[118]

LITHIUM

Primary Production of Lithium

Lithium and its economically important salts are produced from both hard rock deposits of the mineral spodumene LiAl(SiO3)2 and from brine.

Spodumene ore is processed by standard mineral processing methods of comminution and flotation, and pre-concentration by dense media separation may be possible. Spodumene concentrate is subsequently calcined and leached before purification by precipitating magnesium and calcium, re-acidification, further purification by ion exchange to achieve battery grade, and precipitation of lithium carbonate final product. New processes are being developed to avoid the energy intensive calcination stage.

Extraction of lithium from micas in granite ricks is being actively pursued, including projects in the UK.

Lithium occurs in brines, particularly in South America. Brines are pumped from underground pools into surface storage areas where the water evaporates. Impurities such as sodium and potassium chloride precipitate, leaving a concentrated and partially purified solution of lithium salts. Calcium is removed by precipitation using sodium carbonate before the remaining lithium-rich material is reacted with sodium carbonate at 80 to 90°C to produce technical grade lithium carbonate. This can be enhanced to battery grade by re-dissolution and purification by ion exchange. Variations to this process include producing intermediate lithium phosphate to reduce evaporation time.

Lithium in geothermal waters, such as occur in the UK, can be treated by proprietary methods that also recover geothermal energy.

Recycling and Secondary Production of Lithium

It is estimated that approximately 10% of lithium is recycled. This is expected to increase suddenly and significantly at the end of the decade when the first generation of electric vehicles, and their batteries, reach end of life. Waste material produced during battery manufacture can also be recycled. The quantity of batteries available for recycle will continue to grow as electric vehicles replace those with internal combustion engines.

End-of-life batteries can be processed by pyrometallurgical methods, but hydrometallurgical processes are generally preferred. Batteries are fully discharged then mechanically shredded in a neutralising solution. The resultant slurry is then screened to remove structural plastic and foil, leaving a suspension of active battery components. This is filtered and the resultant “black mass” transferred to the chemical processing plant. The “black mass” is leached, and solubilised nickel, cobalt and lithium are separated and purified by solvent extraction and precipitation.

MAGNESIUM

Primary Production of Magnesium

Magnesium can be extracted from hard rock dolomite and magnesite, or from sea water, brines, or solution mining.

Dolomite and magnesite are crushed and roasted, then mixed with seawater. Magnesium hydroxide settles and is separated then heated with coke and chlorine. This produces molten magnesium chloride which is electrolysed to release molten magnesium metal that floats to the surface.

Seawater and brines contain magnesium chloride that can be separated by evaporation, then processed my molten salt electrolysis to produce magnesium.

The Pidgeon Process is an alternative energy and labour-intensive form of thermal reduction that is used by some state-owned industries. A mixture of calcined dolomite and ferrosilicon is heated in retorts in a batch process. The magnesium produced must be removed manually.

Recycling and Secondary Production of Magnesium

Approximately 20% of magnesium is recycled, predominantly through the remelting and recasting of scrap magnesium alloys.

MANGANESE

Primary Production of Manganese

For certain purposes, run-of-mine manganese ore (>35% Mn) can be used directly without processing. These include smelting with iron to produce ferromanganese or use after grinding as a catalyst in leaching processes. Lower grade manganese ore can be upgraded by mineral processing methods including ore sorters and dense media separators.

Pure manganese is usually produced by a hydrometallurgical route. Several methods have been employed at different times[120] and in different countries. A common method includes roasting of ore, dissolving the calcine in sulphuric acid, stage-wise precipitation of impurities with chemicals including ammonia and hydrogen sulphide, then electrowinning to produce a manganese metal deposit on a stainless steel cathode. After physical removal from the cathodes, the resultant manganese flakes may be heat treated to remove hydrogen to give a very pure final product.

Alternative processes[121] include heap leaching, ion-exchange and solvent extraction.[122]

NICKEL

The majority of nickel metal is produced from sulphide ores, but extraction from laterite / limonite ores has increased since viable processes were developed.

Sulphide ores are beneficiated by conventional crushing, grinding and froth flotation to produce a nickel sulphide concentrate. Sulphide concentrate grade can be relatively low, ranging from 8 to 25% Ni. Flotation can be complicated by serpentine gangue minerals, pyrrhotite., and process water chemistry.[123]

Sulphide concentrates are either smelted, in, for example, a flash furnace, or roasted then smelted in an electric furnace before conversion to intermediate nickel-iron-sulphur matte.

Matte is commonly ground and then leached by different process options using chlorides, ammonia or sulphuric acid. Leach liquor may be purified by solvent extraction to separate and purify nickel and by-product metals such as cobalt. Nickel metal is finally produced by electrowinning, electro refining, or precipitation of nickel by hydrogen reduction. Another alternative is the production of nickel pellets from matte by the Mond (carbonyl) process.

Nickel laterites are processed by high pressure acid leaching. After leaching, waste solids are removed and nickel is precipitated from the leach liquor as either a sulphide or hydroxide. Precipitates are re-leached and nickel and cobalt separated and enriched by solvent extraction. Nickel metal may be produced by either hydrogen reduction or electrowinning.

Some nickel is also produced by heap-leaching of nickel ores, followed by solvent extraction and metal recovery.

All these processes produce Nickel Class 1, with >99% Ni content.

Nickel ore may also be combined with iron and smelted to produce ferronickel alloy (Nickel Class 2) containing approximately 20 to 40% Ni.

NIOBIUM

Primary Production of Niobium

Niobium is obtained primarily from the minerals columbite and pyrochlore. These minerals are initially separated from the ore using standard minerals processing methods of comminution, followed by flotation, gravity concentration and magnetic separation.

Ferroniobium for use in high strength steel and alloys is produced in a high temperature aluminothermic process. Niobium mineral concentrates are mixed with fluxes, aluminium powder, and sodium chlorate or barium peroxide. An exothermic reaction is initiated which raises the temperature of the mix to over 2000oC producing separate molten slag and alloy layers. Impurities separate into the slag, which is removed, and the ferroniobium alloy is allowed to cool and solidify before being crushed.

To produce niobium metal powder, concentrates are leached with the aggressive hydrofluoric acid. The resultant solution is processed by solvent extraction to separate niobium, which is precipitated as its pentoxide. Metallic niobium can be produced by molten salt electrolysis, aluminothermic reduction and other processes.

Recycling and Secondary Production of Niobium

Approximately 30% of niobium is recycled. Most commonly, scrap steel with high niobium content is remelted and recast into the required product. A significant problem is dilution of high niobium steel with lower quality steel. Efficient handling and sorting of steel scrap is necessary for efficiency and maximum recovery.

PLATINUM GROUP METALS

Primary Production of PGMs

Palladium, platinum, with rhodium, ruthenium, iridium, and osmium usually occur together and are known as the Platinum Group Metals (PGMs). The ratio of palladium to platinum is higher in the northern hemisphere. They are most commonly co-recovered into a concentrate with nickel and copper sulphide minerals by conventional mineral processing techniques including froth flotation.

The concentrate is smelted to matte, which is allowed to slow cool and concentrate the PGMs. The mate is milled and leached. PGMs report to the residue which is processed by proprietary methods to recover the individual metals. The leach liquor is treated to recover copper, nickel, and cobalt. Additional PGMs and gold may be recovered from anode slimes produced during nickel electrorefining.

Recycling and Secondary Production of PGMs

Recycling rates for platinum and palladium are 25 to 30% and proprietary chemical processes are well established, with plants in the UK.

RARE EARTH METALS

Primarily Neodymium and Praseodymium

Primary Production of Rare Earths

The major sources of rare earth elements are bastnäsite and monazite, but they also occur in apatite and other deposits. Processing methods are often complex[124] and specific to the mineralogy of the deposit. Monazite mineral processing can be complicated by the presence of radioactive thorium, and tailings disposal must be carefully evaluated and executed. Rare earth elements are usually present as their oxides, in which their concentration is usually expressed.

Bastnäsite is crushed and ground and can be concentrated by flotation. It is then leached in hot, concentrated sulphuric acid. The residue is dried and leached with water to solubilise the lanthanides. Monazite can be upgraded by gravity concentration, flotation, and magnetic separation. The concentrate is leached then partially neutralised to precipitate thorium. After filtration the solution is treated by solvent extraction, ion exchange, and other methods to separate the rare earth oxides.

Recycling and Secondary Production of Rare Earths

Recycling rates for Neodymium and Praseodymium are low at 3 to 10%. This is due partly to the small size of NdFeB magnets in some goods, and the complexity of disassembly to access them. These factors can make commercial recycling uneconomic. Chemical methods can be used, and a process using hydrogen to disintegrate magnets and remove the alloy without complete disassembly is being commercialised.

SILICON

Primary Production of Silicon

Silicon is produced by melting quartz with carbon in a submerged arc electric furnace, in which carbon reduces quartz to high purity molten silicon. The furnace operates continuously. New raw material is added, and molten silicon being tapped out in batches. Further refining is necessary to produce ultra-high quality silicon.

Recycling and Secondary Production of Silicon

Recycling of silicon is currently negligible. Because of the quantities of recyclable material available, and the high energy requirements for primary silicon production, considerable research is underway to find economically viable recycling methods. Some are based on conventional minerals processing techniques including classification,

electrostatic separation, and chemical treatment to remove impurities.

TANTALUM

Primary Production of Tantalum

Tantalum can be separated its ores by comminution and gravity concentration. Refining of the concentrate is complicated by the presence of niobium, which has similar chemical properties. Concentrates are leached with an aggressive mixture of hydrofluoric, sulphuric, and hydrochloric acid, which solubilise tantalum and niobium, leaving waste in the insoluble residue. Tantalum and niobium are then separated from other solubilised metals by solvent extraction. Subsequent chemical adjustment allows the niobium to be separated into the aqueous phase.

A molten salt electrolysis method has also been developed for tantalum refining.

Recycling and Secondary Production of Tantalum

Different sources estimate tantalum recycling rates to be between 10% and 30%. Tantalum can be recovered from some tin and titanium smelting slags. Tantalum can be recovered from scrap electronic capacitors; one process includes leaching with ferric chloride.

The recycling rate for tin is estimated to be around 30%. Some scrap such as bearings and bronze are remelted directly to produce alloys. Other tin scrap can be processed by smelting, fire refining and electrolytic refining as described above.

TELLURIUM

Primary Production of Tellurium

Tellurium is recovered as a by-product of copper from porphyry deposits. Copper minerals are separated by the ore by comminution and flotation, and the concentrate smelted and electrorefined. Tellurium contained in the ore eventually reports to the anode slimes produced during electrorefining.

Anode slimes are roasted with sodium carbonate in air at 500°C. Metals are reduced and tellurides converted to water soluble sodium tellurite. Water leaching forms hydrotellurites that can be converted to insoluble telluride dioxide by the addition of sulphuric acid. Tellurium dioxide can be reduced to the metal by chemical processes or electrolysis

Recycling and Secondary Production of Tellurium

Tellurium recycling rate is estimated to be 1%. Tellurium can also be recovered from lead smelting flue dusts. End-of-life solar panels will provide an increasing source of tellurium recycle. Recovery methods include crushing the photovoltaic panels then leaching to dissolve cadmium and tellurium which can be separated by ion exchange. Tellurium can then be precipitated as the dioxide for metal recovery.

TIN

Primary Production of Tin

The principal tin mineral is cassiterite, $SnO2$. It is recovered from ores by conventional mineral processing techniques including comminution, classification into different size ranges, gravity concentration and flotation of fines.

Low grade tin concentrates may be roasted to drive off sulphur from sulphide minerals, but high-grade concentrates can be smelted direct. Tin smelting is commonly a batch process. Concentrate is mixed with carbon and heated to 1350°C. Impurities separate into the slag layer which can be separated from the molten tin which is cast into ingots or slabs.

Further fire refining can be used to increase tin purity, but electrolytic refining is used to obtain very high purity metal.

Recycling and Secondary Production of Tin

The recycling rate for tin is estimated to be around 30%. Some scrap such as bearings and bronze are remelted directly to produce alloys. Other tin scrap can be processed by smelting, fire refining and electrolytic refining as described above.

TUNGSTEN

Primary Production of Tungsten

The main sources of tungsten[125] are the minerals wolframite $(Fe,Mn)WO4$ and scheelite $CaWO4$. Wolframite is separated from its ores by gravity concentration and scheelite by flotation. The minerals are friable so care must be taken in comminution to prevent over-grinding that would result in losses.

Wolframite concentrates can be smelted with charcoal or coke in an electric arc furnace to produce ferrotungsten alloy (FeW) for use in steel production. Scheelite concentrate can be added directly to molten steel.

Wolframite and scheelite concentrates can be converted to ammonium paratungstate, an important starting point for other tungsten products. Concentrates are pressure leached in alkaline solution such as sodium hydroxide. The resultant sodium tungstate solution is purified by precipitation and filtration followed by solvent extraction or ion exchange to produce ammonium paratungstate $(NH4)10(H2W12O42)\cdot4H2O$ that is crystallised. This can be converted to oxide, which can be reduced to tungsten metal powder.

Recycling and Secondary Production of Tungsten

Approximately 42% of tungsten is recycled, mainly from tungsten carbide and high-speed steels. It is generally uneconomic to recycle electric light bulb filaments, welding electrodes and chemicals.

Contaminated or low-quality tungsten scrap can be oxidised and processed by the ammonium paratungstate route described above.

Clean tungsten carbide scrap can be melted with zinc in a vacuum furnace. Zinc is distilled off leaving tungsten sponge that an be reused.

VANADIUM

Primary Production of Vanadium

Most vanadium is produced from steel plant slags, particularly in China. A plant to produce vanadium from steel slags is to be built in Finland.

Primary ore sources include vanadium bearing magnetite such as found in South Africa. These are processed by comminution and magnetic separation to produce a magnetite concentrate rich in vanadium. The concentrate is mixed with a sodium salt and roasted to convert oxides to sodium metavanadate. This can be leached by water, purified to remove silica, then precipitated as ammonium metavanadate. After filtration the product is calcined to produce high purity vanadium pentoxide.

Recycling and Secondary Production of Vanadium.

Estimated vanadium recycling rate is reported as 2 to 10%. Secondary sources for recycling include spent catalyst, fly ash, oil refining residues, and scrap vanadium steels.

Appendix 2

Processing Terminology

Terminology used in minerals processing and metal refining is explained below. The terms are presented roughyl in the sequence they will be found in minerals processing and midstream refining.

Grade	Grade refers to the concentration of metal in the ore or intermediate product. Specific terms include:
Cut-Off Grade	The concentration of metal in a rock at or above which it can classified as ore and mined and processed economically.
Head Grade	The concentration of metal in the ore fed to the processing plant.
Concentrate Grade	The concentration of metal in the product from primary beneficiation of ore before it is refined.
Tailings Grade	The concentration of metal in the waste material rejected during preliminary beneficiation of the ore.

Mining	The process of accessing and extracting ore so that the valuable components can be separated.
Underground Mining	The method of removing ore from deposits far below the surface. Mine depths can vary from 100m to 4,000m. The orebody is accessed via shafts or declines and access tunnels. Ore is blasted and transported to surface for processing.
Open Pit Mining	Near surface ore deposits are accessed by excavating a pit to expose the ore. Lower mining costs permit the extraction of high tonnages of lower grade ore.
Placer Mining	Extraction of near surface, usually unconsolidated deposits of sands containing gold, tin, titanium bearing minerals, rare earth oxides and other minerals.
Brine "Mining"	Extraction of lithium, magnesium, and other metals from underground and geothermal waters with high dissolved mineral content.
Solution or In Situ Mining	Some metals can be leached from the orebody in situ, without transporting the ore to a processing plant on surface. The ore body may be fractured by explosives, and solution pumped into the ore, leaching out the valuable component. The solution is pumped to surface to extract the metal, and then returned underground to extract more metal. This technique can only be used where there is no chance of groundwater contamination.

Recovery	The percentage of metal in feed that reports to the concentrate. Not all the valuable minerals can be recovered due to inadequate liberation, process dynamics, and many other factors. There is an inverse relationship between recovery and concentrate grade. Processes are controlled to achieve the economic optimum.
Gangue	The commercially valueless and potentially deleterious waste minerals contained in mined ore are referred to collectively as gangue. Gangue is removed during ore beneficiation and discarded as waste rock or tailings.

Thickening

Increasing the solids concentration of a slurry in a large, raked setting tank. This can be used ahead of the next process stage, or to recover the solution containing the valuable metal. Counter Current Decantation is the use of a series of thickeners with wash water addition to recover the valuable solution.

Tailings

The fine waste produced during minerals processing of ore is usually referred to as tailings. In some countries, especially if the ore has had any kind or chemical processing, fine waste may also be referred to as residue or slimes.

Historically, tailings have been deposited as a thick slurry into impoundments or "tailings dams". The solids settle slowly and may eventually consolidate. Water is recovered and recycled to the process.

As a result of catastrophic tailings dams failures causing loss of life and environmental damage, industry bodies[126] and investors have forced mining companies to review the safety of their tailings disposal.[127] Disposal in worked-out underground or in-pit sections is preferred, and some underground mining methods rely on backfill to maximise ore extraction. When surface disposal is necessary, filtration and dry stacking with increased stability and water recovery, is becoming the new benchmark for good practice.

Leaching

The process of dissolving components from an ore or concentrate with subsequent purification of the solution by chemical methods. Usually, the valuable metal is dissolved leaving the waste mineral as a solid residue for disposal. The solution used to dissolve the metal is process dependant, but can be sulphuric acid for many metals, or cyanide for gold. The leach solution is further processed by solvent extraction, electrowinning, and other methods to purify and recover the metal. Leaching can be conducted in different ways:

Heap Leaching

Heap leaching is commonly applied to low grade copper and gold ores but has more recently been used for nickel/cobalt ores. It is not used in midstream processing. Crushed rocks are built into a heap onto which leaching solution is sprayed. As the solution percolates through the heap, it dissolves metal. This is often enhanced by natural bacteria. The solution flows to a collection pond from which it is pumped to a process plant for purification. Heap leaching is a relatively low capital cost method but is slower and less efficient than other methods. The crushed rock will typically remain on the leach pad for months or even years.

In Situ Leaching

As described above.

Atmospheric or Agitation Leaching

Atmospheric leaching with cyanide is commonly used for gold ores. It is also used with sulphuric acid for copper and uranium ores and can be used in midstream processing. A slurry of finely ground ore or intermediate product is pumped through a series of agitated tanks. Depending on the process chemistry, the slurry may be heated, and air may be bubbled through the slurry to enhance leaching efficiency. Reagent is added to dissolve the metal. The residence time of the slurry flowing through the leach tanks is typically from a few hours to one day. After leaching, the slurry is thickened or filtered to separate the liquid containing the valuable metal from the solid waste.

Pressure Leaching

Pressure leaching is used to process nickel laterites, zinc ores and other primary materials. It is used intermediate midstream products such as smelter mattes. Leaching is conducted above atmospheric pressure in autoclaves when the elevated pressure and temperature can significantly reduce leaching time or increase leaching efficiency.

Filtration

Separation of solids from liquids in a slurry using a porous membrane and differential pressurcreated by vacuum or pressure. It is required to reduce the moisture of mineral concentrates to the Transportable Moisture Limit for safe transport to midstream processing. In leaching processes, filtration is commonly used to separate liquid containing valuable metal from waste solids, applying a washing stage. Filtration is increasingly used for "dry stacking" of tailings for safe and stable disposal with maximum water recovery.

Solvent Extraction	A method for selectively separating and concentrating metals from leach solution. The aqueous, typically acidic solution containing the valuable metal(s) is mixed with an organic phase containing a reagent that selectively extracts the metal. The aqueous and organic phases are then allowed to settle and separate. The valuable metal is then stripped from the organic reagent into an aqueous phase in a second solvent extraction stage. This process is used widely for a range of metals in both primary extraction and midstream refining.

Benefication	One of several terms including minerals processing, minerals engineering and concentration used to describe processing of mined ore, usually by physical processes, to recover valuable mineral and reject waste.
Liberation	The process of preparing the ore for clean separation of valuable and waste minerals. It usually involves reducing the size of ore particles to, typically, less than 100 microns. Ideally, individual particles of broken ore should be either pure valuable mineral or pure waste, but perfect liberation is almost impossible to achieve. Some valuable metal will usually remain attached to waste reducing recovery, and some waste will remain attached to valuable mineral reducing concentrate grade.
Comminuition	The general term for size reduction of ore to achieve liberation. It usually consists of several stages of crushing and grinding with intermediate size separation or classification. Fine grinding is a very energy intensive process and modern processing often aims to reduce the mass of ore to be fine ground through pre-concentration. Ore is usually ground in water and discharged to separation processes as a slurry.
Classification	Separation of comminuted ore particles into different sizes by screening or hydrodynamic methods such as hydocyclones.
Dense Media Separation	Dense media separation is commonly used as a pre-concentration method for finely crushed ore utilising the specific gravity difference between ore and waste minerals. The dense medium is typically a suspension of fine ferrosilicon or magnetite in water into which crushed ore is introduced using various equipment designs. Metallic minerals* sink through the dense medium, whereas the waste minerals float. Both can be separated from the dense medium by screening. Ferrosilicon or magnetite concentration in the medium, and hence its density, can be controlled by magnetic separation. Dense media is also commonly used in coal processing, but low-density coal floats and waste minerals sink.
Froth Flotation	A process used to separate valuable mineral from waste. Chemicals are added to the slurry from the grinding stage and selectively coat the valuable mineral. The slurry passes through a series of agitated tanks in which fine air bubbles are generated. The coated minerals attach to the bubbles and rise with them to the surface for collection, while the uncoated waste passes through the tanks with the slurry.
Gravity Concentration	Separation and concentration methods utilising the density difference between valuable and waste minerals. Examples include dense media separators, jigs and shaking tables.
Magnetic Separation	Separation and concentration methods utilising the different magnetic properties of valuable and waste minerals.

Anode Slimes	Fine, solid particles of impurities released from anodes during electrorefining. These are collected and processed to recover metals. Gold, silver, and selenium and other metals can be recovered from copper electrorefining anode slimes. Bismuth is recovered from anode slimes in the Betts Process for electrolytic production of high purity lead.
Ion Exchange	Ion exchange has a similar function to solvent extraction, except that the valuable metal transfers selectively to an extractant attached to small resin beads. When the beads are fully loaded with metal, it is eluted from them back into solution using another chemical.

Electrowinning	Electrowinning is commonly used to produce high purity copper, zinc, and cobalt in both primary and midstream processing. Purified solution containing the valuable metal, often following solvent extraction, flows through a tank or electrolytic cell in which flat plate metal anodes and cathodes are hung. Voltage is applied across the electrodes and pure metal is electroplated from the solution onto the cathode.
Electrorefining	Electrorefining is similar to electrowinning, except that the anode is sheet of impure metal usually cast from molten metal at a smelter. In the electrorefining cell, the anode dissolves and is electroplated on the cathode. Other trace metals in the anode such as gold, silver, tellurium, and selenium fall top the bottom of the electrorefining cell as "anode slime". They are then collected and processed in specialist refineries.

Pyrometallurgy	Processes for the extraction and purification of metals at high temperature, including calcining, roasting, smelting, and refining.
Calcination	Calcination is the heating of solids to below their melting point with restricted oxygen supply to remove volatile components or to cause decomposition. The name is derived from its use in producing quick lime (calcium oxide) from limestone (calcium carbonate).
Roasting	In extractive metallurgy, roasting is heating solids to below their melting point, but with plentiful oxygen supply to decompose minerals such as sulphides to oxides making them more amenable for leaching.
Smelting	Smelting is the high temperature processing of mineral concentrates above the melting point of the constituents. Fluxes are added to form a molten slag layer into which impurities will separate, while the valuable metals remain in the denser layer. Because of the density difference, the slag can be skimmed off to remove impurities.
Exothermic	A chemical reaction that generates heat.
Aluminothermic	Exothermic reducing reactions using aluminium powder.
Preconcentration	Methods for rejecting waste at coarse size to avoid fine grinding that has high energy consumption. Preconcentration methods include ore sorting based on rock colour or radioactivity, magnetic properties, and rock density.

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