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SECURING TECHNOLOGY-CRITICAL METALS FOR BRITAIN

ENSURING THE UNITED KINGDOM'S SUPPLY OF STRATEGIC ELEMENTS & CRITICAL MATERIALS FOR A CLEAN FUTURE

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Disclaimer

This report is the product of a multi-stakeholder inquiry convened by The Birmingham Energy Institute's Centre for Strategic Elements & Critical Materials and the EPSRC Critical Elements & Materials (CrEAM) network, and funded jointly by the University of Birmingham, Birmingham Energy Institute, EPSRC CrREAM Network and EPSRC Impact Acceleration.

The Commissioners have agreed its conclusions and recommendations. Individual points within the text do not necessarily represent the views of individual Commissioners. Nothing in this report can be taken as representing the views of the Commissioners' employers.

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BIRMINGHAM CENTRE FOR STRATEGIC ELEMENTS AND CRITICAL MATERIALS

The Birmingham Centre for Strategic Elements and Critical Materials (BCSECM) was established to unite the significant research activity at the University of Birmingham in the area of strategic elements and critical materials and provide a forum to promote interdisciplinary collaboration in this field.

The BCSECM was launched in March 2017 and it encompasses expertise from across the University of Birmingham and the Birmingham Energy Institute in Biosciences, Chemical Engineering, Chemistry, Earth & Environmental Sciences, Economics, Law, Materials Science, Physics and Social Science. The experts within the centre all have the common aim of addressing the challenges posed by supply constraints for strategic elements and critical materials.

CrEAM NETWORK

The overarching aim of the CrEAM network is to safeguard UK industry against shortages of strategic/critical elements and materials by bringing together leading UK academics from a wide range of disciplines alongside key industrial users. The network was established to develop strategies to mitigate supply risks of these materials and, where possible develop alternatives.

The CrEAM network is raising awareness of critical materials and supply chain issues, and identifying and connecting UK research and development activities on selected strategic/critical materials to strengthen possibilities for multi- and interdisciplinary research. This research is helping to protect UK commercial interests dependent on materials supply by connecting expertise throughout the supply chain to work on solutions to the problems identified.

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The Birmingham Energy Institute is the focal point for the University of Birmingham and its national and international partners, to create change in the way we deliver, consume and think about energy. Bringing together interdisciplinary research from across the University of Birmingham and working with government, industry and international partners, the BEI is developing and applying the technological innovation and original thinking required to create sustainable energy solutions.

Our global community is consuming more energy than ever. As we run out of time to contain climate change the BEI is upscaling their innovative technology solutions for applications across the globe and influencing and shaping policy on critical issues such as waste management, materials supply and decarbonisation of heat to shape the energy solutions of tomorrow.

The UK government is committed to bringing all greenhouse gas emissions to net-zero by 2050. The Midlands region is renowned for its ability to drive technology revolution and its nationally leading manufacturing and engineering base. The Birmingham Energy Institute is working with business, industry and policy stakeholders across the region to realise the transition to net-zero.

BIRMINGHAM POLICY COMMISSIONS

CHAIR'S LETTER

We embarked upon the journey to formulate this Policy Commission, in what now seems like a different world. The UK had not yet left the European Union and the Coronavirus pandemic was not yet upon us.

In the past year, we have witnessed some dramatic changes that have reshaped the UK's relationship with the world and our trading partners, stress-tested our supply chains and logistics capabilities and changed our society in many profound ways. Some of these changes will be transitory, but others will have longer lasting effects.

Yet there are also long-standing challenges that have remained a constant - our ongoing mission to curb carbon emissions and attempts to combat climate change remain. Our ability to deliver on our international commitments will doubtless be enabled or constrained by our access to the technology-critical metals that underpin the clean energy transition.

This Policy Commission was initiated from the starting point that our trading relationships would be changing and the UK would need to consider its position and strategy in relation to technology-critical metals as a sovereign country. There have been many lessons over the past year that have shown us the consequences when supply and value chains are strained. It is important to recognise the consequences that supply constraints on technology-critical metals could have on our future prosperity. Whilst there are immediate challenges that we face, we can anticipate more in the future - it is essential to be prepared.

During the process of compiling this report, much has changed. We embarked upon this process prior to the UK reaching a deal with the European Union, before the pandemic and prior to the election of a new President in the United States. In some ways, it feels that we initiated the Policy Commission in another time. However, the challenges we set out to identify remain and the themes explored are still as resonant as ever, if anything, the changing situation has only served to highlight the timeliness of this report and the writing team have updated the text to reflect our new global context.

There are promising signs that we are headed in the right direction - whilst the UK has not yet published a publicly articulated strategy around technology-critical metals, we note through our networks that there is vigilance around this issue and plans afoot to formulate policy in this area. Furthermore, the academic partners that initiated this report have been successful in securing funding for the 'UKRI Interdisciplinary Circular Economy Centre for Technology Metals'(Met4Tech) - this will undoubtedly build upon the successful collaborations around the CrEAM network that have been instrumental in delivering this report.

It is our sincere hope that this report will serve as a catalyst for raising the profile of this crucial area, indeed our leadership in this area has the potential to unleash solutions that will benefit not only the UK, but also the many other nations grappling with the same challenges that we face.

Sir John Beddington

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FOREWORD

The Birmingham Centre for Strategic Elements and Critical Materials (BCSECM) was launched on the 29th of March 2017. One of the main catalysts for the formation of the centre, was the realisation that the UK's relationship with the rest of the rest of the world would be changing in ways which were then unforeseen and undefined. Mr Reinhardt Bütikofer MEP, Co-Chair of the European Green Party, spoke at this event, noting that the "European Union has been a very successful driver of raw materials policy". Indeed, until Brexit, our critical materials policy had largely been defined as part of the EU. We realised that there would be an urgent need for the UK to establish an independent policy and technological leadership in this area. The BCSECM brought together a highly interdisciplinary team of experts in physical sciences, engineering, business and law which has proven enormously beneficial in addressing this multifaceted challenge.

Since the Centre's inception, we have collaborated with many organisations across the UK with complementary capability. In partnership with Exeter University we established the EPRSC Critical Elements and Materials (CrEAM) Network, which for the first time brought together academic and industry expertise from previously siloed, but related, sectors such as mining, materials processing, manufacturing, and recycling. This Policy Commission is one of the fruits of that joint enterprise, providing a comprehensive end-to-end assessment of our use and dependence on critical materials and unbound by sector-specific considerations. The UKRI Circular Economy centre for Metals for Technology (Met4Tech), led by the University of Exeter and only recently announced, will further strengthen our partnerships and collaboration.

Ground-breaking projects developing solutions at scale have been a feature of our mission. The Faraday Institution ReLiB project, led from Birmingham and addressing the recycling and reuse of lithium-ion batteries, has helped us to forge strong partnerships with several leading UK universities. Our EU (SUSMAGPRO) and UKRI projects (RaRE and REAP) on recycling of rare earth magnets have brought together whole supply chains including recycling companies, alloy producers, magnet manufacturers through to end users.

Moving forwards, our Policy Commission began its work on the 28th of October 2019, with an aim to report six months later. We could not have anticipated how Coronavirus would change the world, and the launch of the report was accordingly delayed after several attempts to organise an in-person launch event were prevented by the changing situation.

Around a similar time, the Birmingham Energy Institute & Energy Research Accelerator launched a related Policy Commission, chaired by Lord Teverson, entitled Energy from Waste and the Circular Economy: Net Zero & Resource Efficiency by 2050. Although the emphasis of that Policy Commission is on waste more broadly, and the potential to generate energy from waste, there are many synergies with our report.

One of the key recommendations is the creation of "Resource Recovery Clusters", hubs for innovation around transforming waste into valuable resources for our economy. Indeed, the Birmingham Energy Institute is working to develop the Tyseley Energy Park, an ambitious energy and resource nexus close to the city of Birmingham. It is here that many of the technologies for the processing and recovery of technology-critical metals are being developed. Indeed, a key challenge addressed in this report, is the need to develop sophisticated technologies for recycling of technology-critical metals. This is exactly the approach that we hope to validate with our scale up of new innovative technologies at Tyseley.

We are very positive about the enormous opportunities for the UK to define a fresh strategy for technology-critical metals. These are generational opportunities that stand to benefit not only the UK, but also the world as we join forces as a planet to decarbonise. That said, we caution that so too are the potential threats to our industry, jobs and global standing if we hesitate or do not act in time. We hope this report and its recommendations will prove useful to government, industry, and universities as we embark on the journey to a zero-carbon future.

Professor Allan Walton and Dr Paul Anderson

Acknowledgements

We wish to thank the many people who have devoted considerable time and effort to the work of the Commission.

We wish to extend our gratitude to Sir John Beddington, who chaired the Commission with the insight and vision needed to keep the proceedings on track. Also thanks to Jane Fellows for her support throughout the process in facilitating meetings and collaboration with Sir John.

We would like to express our appreciation to our Commissioners, who have contributed their tremendous knowledge of technology metals, critical materials, materials processing and refining technologies, economics, markets, policy, law and regulation.

Additionally, we are indebted to our witnesses and others who attended individual meetings and workshops. The Commission greatly appreciates the depth and quality of the input from those who contributed to the evidence gathering sessions and from those who submitted written evidence.

We would also like to extend sincere thanks to the events teams at 10 St. James Square, the Royal Society, Royal Academy of Engineering and the Institute of Materials, Minerals & Mining for their help in organising the witness sessions.

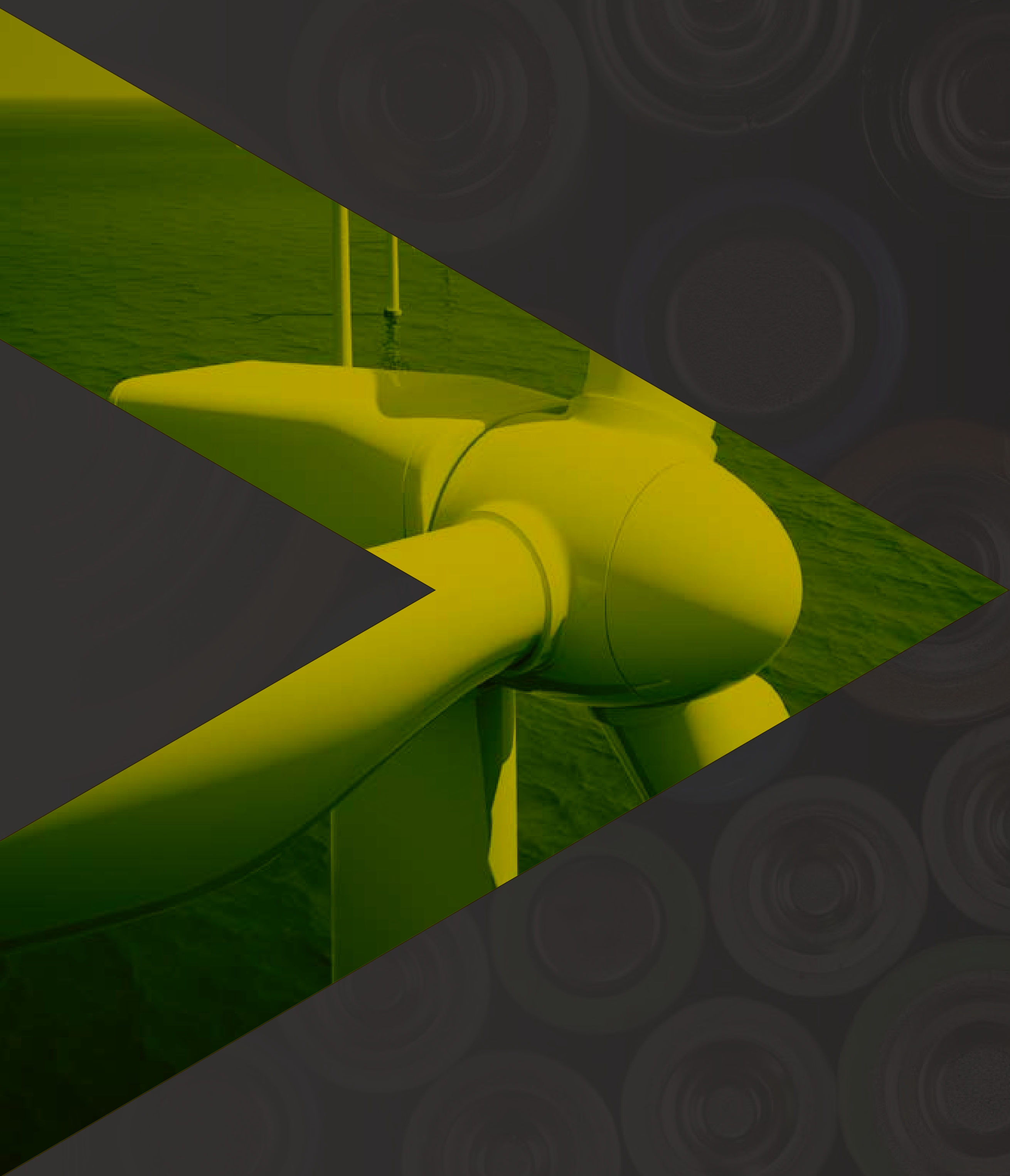
We are also grateful for the support of the following people, who have contributed to the work of the Commission, but whose work has not been acknowledged elsewhere: Professor Tariq Ali of the University of Birmingham, for his assistance with the Policy Commission and attending meetings; Professor Martin Freer and Dr. David Boardman for support through the Birmingham Energy Institute.

Many people have contributed to the shaping and proof reading of the report including Dr. John Speight, Mr. Dave Kennedy and also to Romana Ogrin and who provided editorial support to Dr. Paul McGuinness

The presentation of this report and its associated materials are testament to the hard work and creativity of Think Creative, and their team of staff, notably Simon, Fran and Betty Grigg, and Alistair Grant who have worked with us on the design of the Commission report and accompanying video.

We are also grateful to Dr. Vicky Mann for leading the management team who put the Policy Commission together. This included Dr. Matt Finerty for his contributions to the management of the commission, and Karen Seehra, Beck Lockwood, and Jeremy Swan for their work and advice on communicating the outcomes of the Policy Commission report.

This work was supported by the Engineering and Physical Sciences Research Council Critical Elements and Materials Network grant EP/R020140/1.



EXECUTIVE SUMMARY & KEY RECOMMENDATIONS

EXECUTIVE SUMMARY & KEY RECOMMENDATIONS

In the next 5-10 years the UK is going to see dramatic changes to many of its large industrial sectors, such as automotive, aerospace and energy generation, as we move from a fossil-fuel-driven society to an electrically driven one. Many of these industries will be dependent on technology-critical metals (TCMs), for example, cobalt and lithium for the batteries in electric vehicles and rare-earths used in the magnets for electric motors and wind turbines.

These technology-critical metals have been identified by the EU, US and Japan as being a serious supply risk[1,2,3]. In a post-Brexit Europe, it is vital that the UK develops its own strategies to access these metals so that we can achieve the planned transition to a low-carbon society and meet our climate-change targets. Covid-19 has highlighted the vulnerabilities of many supply chains and, as we scramble to shore up existing industries and expand into new job-creating sectors, the UK needs to ask itself serious questions about how it will access essential raw materials like technology-critical metals. To put this in perspective, such metals are vital to 7 of the top-10 UK export markets, with a value of more than £150 billion annually. The Faraday Institution predicted that the transition to manufacturing electric vehicles (EVs) could support 220,000 jobs by 2040.

The ability to create and retain these jobs will depend on the UK's access to critical materials for batteries[4] and rare-earth magnets for EV motors and platinum group metals for the hydrogen economy.

The world's demand for raw materials is expected to double by 2060, according to a report by the Organisation for Economic Cooperation and Development[5]. The requirement for metals is expected to grow even faster, with an expansion from 8 to 20 gigatonnes over the same period. In volume terms, much of this will be readily available, and easily recycled, metals like iron and aluminium. However, high-technology industries that make, for example, batteries and motors for EVs, the generators for wind turbines and the jet engines for aircraft are dependent on many technology-critical metals. It is predicted that by 2050 the EU will require 60 times more lithium, 15 times more cobalt, and ten times the amount of rare earths compared to the current supply to the whole EU economy[1].

The new industrial strategy for the EU warned that Europe's transition to climate neutrality could replace today's reliance on fossil fuels with one on raw materials, many of which we source from abroad and for which global competition is becoming fierce.

> TECHNOLOGY-CRITICAL METALS ARE THE BUILDING BLOCK MATERIALS FOR THE GREEN ECONOMY AND **WITHOUT THEM THE UK GOVERNMENT'S 10 POINT PLAN FOR A GREEN INDUSTRIAL REVOLUTION WILL BE IMPOSSIBLE TO REALISE.**[11]

DEVELOPING STRATEGIES

Many regions of the world, including the EU, have been developing strategies to access these technology-critical metals for their key industries[6], while the UK has lagged behind. The challenges already faced around access to key technology metals are potentially complicated for the UK by the nation's exit from the EU, and the uncertainty that this has created with regard to trading relationships around the globe. It is in this challenging context that the UK must now fashion its own independent policy for access to technology-critical metals.

Technology-critical metals are often at risk of supply shortage for a number of reasons: rapidly expanding markets, geographical concentrations in certain parts of the globe, political factors (trade disputes, quotas and taxes), low recycling rates and a lack of alternative substitute materials. It should be noted that at present none of these elements are mined in significant amounts in the UK.

Accessing the raw materials, however, is just one piece of the jigsaw. Without the processing technologies necessary to convert these technology-critical metals into, for example, chemicals, cathodes, alloys or magnets, we remain reliant on other countries for the critical components needed by our industrial sectors, and in many cases a large bulk of the value and jobs are in these parts of the supply chain. Highly skilled jobs, which would otherwise provide high-quality employment, are at risk if we do not capture more of the value chain in the UK. Some regions of the world, especially China, have invested heavily in the processing capability to convert these materials into products and, by doing so, now control the downstream supply chain. This report describes some of these global supply chains and suggests opportunities for intervention.

Recycling or re-using the materials and components at end-of-life or from production scrap could provide a significant indigenous supply of technology-critical metals; however, there are technological, economic and regulatory barriers in some cases, which has meant that many of these materials are lost in the system. For example, less than 3% of rare-earth materials are recycled today worldwide[1]. This report explores such barriers and suggests action that could be taken to promote a UK-based secondary supply chain to re-use, recover and reprocess these materials and products, learning lessons from success stories with platinum-group metals and aerospace alloys, where world-leading recycling technologies have been developed in the UK.

It is important to note that the secondary supply of these materials should not operate in isolation from the primary raw-material sources. In many cases the same processing technologies exist for both and if set up correctly, both should be leveraged to support the downstream supply chain. This will provide opportunities for employment and the development of a sustainable system for technology-critical metals in order to reduce the environmental footprint of production. Several examples of this are given in the report.

There are also opportunities for primary supply in the UK and by making strategic alliances overseas. The UK has major international interests in mining, through London registered companies, mine finance, equipment supply, consultancy services, and research and education.

The EU recently updated its critical materials list which has expanded to 30 material groups. This Policy Commission is more tightly focused on groups of technology-critical metals that are vital to the UK's industrial future. In particular, we have looked at battery materials (cobalt, nickel and lithium), rare-earth materials (neodymium, dysprosium), aerospace materials (rhenium and tantalum) and platinum-group metals (platinum, palladium). The report is by no means a comprehensive list of all of the critical materials that are important to the UK economy, but it is a starting point for further discussion.

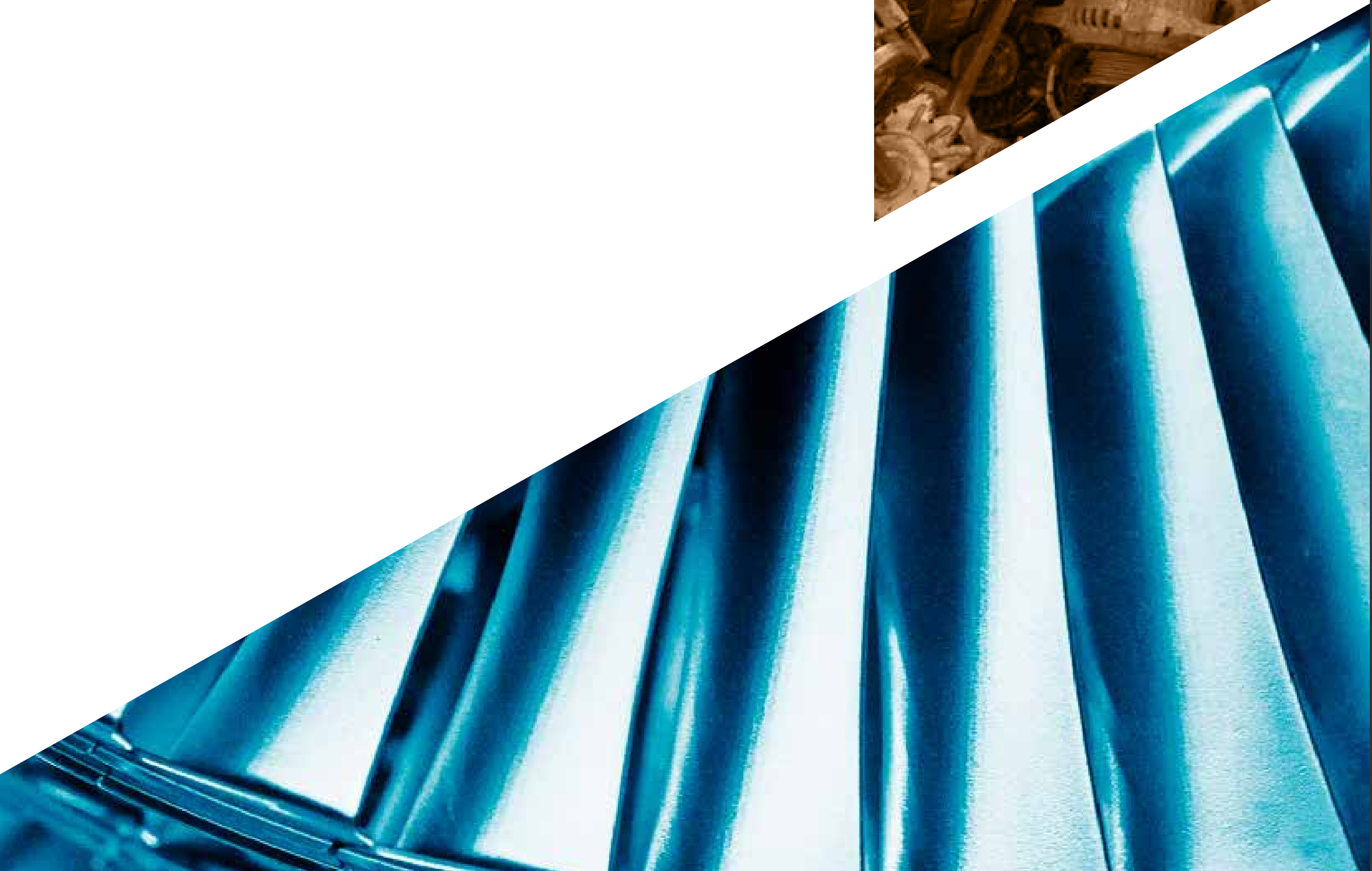
> THE WORLD'S DEMAND FOR RAW MATERIALS IS EXPECTED **TO DOUBLE BY 2060**

CONTINUED

In the intervening period since this commission was initiated, there have been a number of promising developments, which shows a recognition of this crucial issue by Government and Industry.

The Parliamentary Office for Science and Technology released its POSTNote on Access to Critical Materials in September 2019[7], to which a number of the Commissioners and Witnesses to this report contributed. The Critical Minerals Association was launched in January 2020 and the All Party Parliamentary Group on Critical Minerals was launched on February 2020 (mainly focussed on primary supplies)[8]. Additionally, a number of significant government investments in key sectors have recognised some of the problems the UK faces with technology metals, including the industrial strategy projects: Faraday Battery Challenge/Faraday Institution and Driving The Electric Revolution[9]. However, these are often sectoral investments, which cannot address the totality of the threat or the opportunity without engagement across multiple value chains.

While these developments anticipate certain recommendations of the report, they also demonstrate that the need for concerted policy and strategy in this area is more pressing than ever. No report of this kind can ever offer more than a contemporary perspective, pointing the way forward on the best evidence available. As the world continues to change, we must adapt with it, and so this report will receive regular updates from the Birmingham Centre for Strategic Elements & Critical Materials and partners active in the EPSRC CrEAM network.



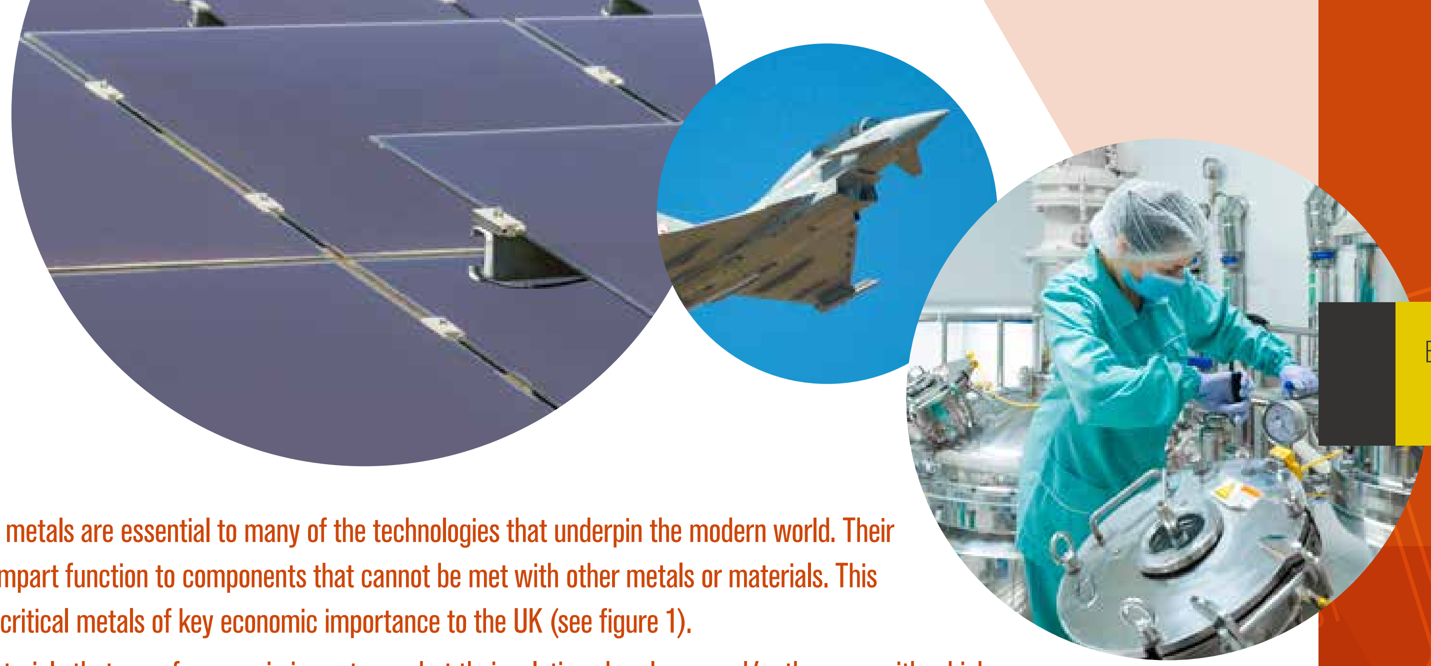
RECOMMENDATIONS

The recommendations are built upon our findings, compiled from the evidence sought from a wide cross-section of expertise, from a broad range of UK stakeholders. These recommendations are informed by the challenges that end-users in crucial British industries have faced, as well as insight from across the supply chain for a number of key technology metals. Although the specific challenges around different materials vary, there is a common clarion call from all: UK urgently needs to develop policy responses to the critical materials challenge post-Brexit.

1. **The UK should create a single body responsible for developing strategic access to technology-critical metals and effective inter-departmental collaboration at government level. This body should link the primary and secondary markets for technology-critical metals, and develop and oversee, a full UK technology-critical metal strategy.**
2. **Seek opportunities to diversify its access to primary resources of technology-critical metals, through resource diplomacy. This should form part of any new trade negotiations.**
3. **Actively attract & provide support for large-scale strategic private investments for supply chain development of technology-critical metals both at home and abroad, and aim to make the UK an international refining centre for specific technology-critical metals by 2025.**
4. **Create individual task forces bridging primary and secondary materials for targeted technology-critical metals. These should identify the investments that would be required to set up primary processing, refining and recycling facilities for these materials.**
5. **Introduce incentives to encourage recycling, refining and processing of technology-critical metals in the UK, particularly for processes that deliver a lower environmental footprint.**
6. **Consider measures to accelerate projects that seek to develop our indigenous sources of technology-critical metals (lithium, tungsten), including updating the regulatory environment.**
7. **Prioritise technology-critical metals in UK Research and Innovation strategies in areas such as the circular economy, developing substitute materials and efficient processing techniques for technology-critical metals.**
8. **Invest in the skills base in advanced materials processing and refining of technology-critical metals.**
9. **Urgently address the lack of data on material flows for technology-critical metals into and out of the UK economy.**
10. **Review waste management law with a view to promoting recovery of technology-critical metals and ensure that there are no unnecessary regulatory barriers.**
11. **Encourage information exchange through the whole supply chain to ensure the challenges for recyclers are well understood by the product designers.**
12. **Consider how appropriate governance structures might ensure sustainability and resilience in the supply chain for technology-critical metals (see detailed recommendations in the Goverance section of the report).**

SEEK OPPORTUNITIES FOR THE UK TO **DIVERSIFY ITS ACCESS TO PRIMARY RESOURCES OF CRITICAL MATERIALS**

INTRODUCTION



Technology-critical metals are essential to many of the technologies that underpin the modern world. Their unique properties impart function to components that cannot be met with other metals or materials. This makes technology-critical metals of key economic importance to the UK (see figure 1).

There are other materials that are of economic importance, but their relative abundance and/or the ease with which we can access them means they are not classed as critical. What makes a material critical is one or more factors that constrain their availability. This can be as a result, for example, of the material's geographical distribution, geo-political factors, supply-chain bottlenecks and lack of processing capacity.

If supply constraints affect the UK's ability to access critical materials, there will be negative effects on industrial sectors that are key to the UK's prosperity, such as automotive, aerospace, defence, pharmaceuticals, clean energy, machinery & equipment, robotics, transport and manufacturing . Furthermore, given that critical materials are key to many clean technologies, their constrained availability would hamper the UK's ability to project leadership on the international stage and deliver on its global commitments to the greening of UK society.

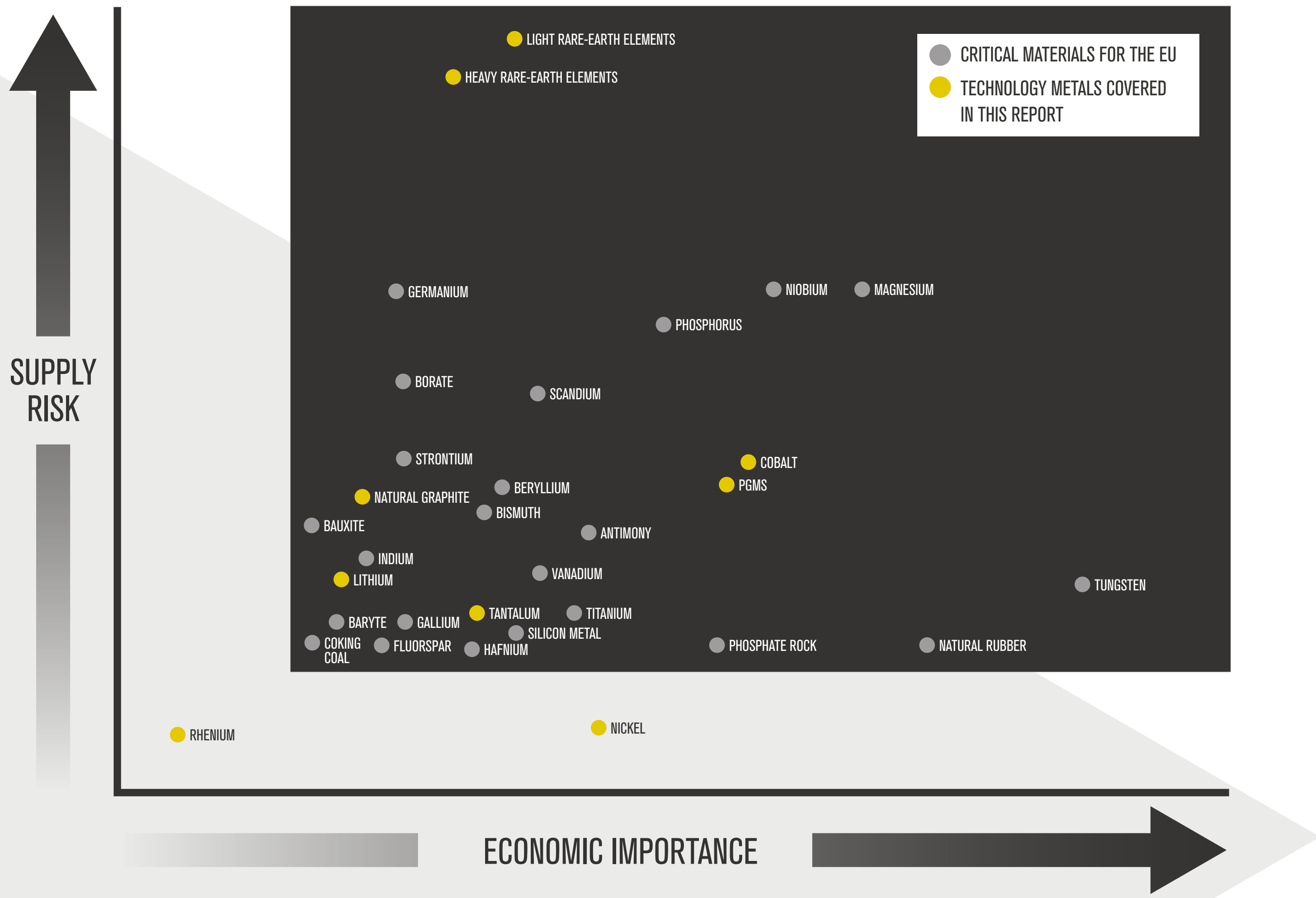


Figure 1 European Commission Study on the EU's List of Critical Raw Materials (2020), Economic Importance and Supply Risk Results of 2020 Criticality Assessment. Emphasis changed to focus on Technology-Critical Metals[1].

BOX OUT 001

Definition of a Critical Material

A material is defined as critical when it is deemed to be at risk of short supply, but is economically important either in general or in a specific region of the world (see figure 2). The EU and US have open-access lists of critical materials (see figure 1). In contrast, the UK does not currently have a strategy in this area.

Whether a material is deemed "critical" or not, is a policy determination that must be made by a nation or trading bloc, based on its own determination around access to resources, evaluation of supply risks and the impact that a supply restriction so deemed in another area would cause to that region's economy. A material that is deemed a 'critical material' in one locale, may not be deemed as such in another area.

Whether a material is critical depends on many factors, such as the quantity required, the rate of consumption, the challenges associated with purifying it, low recycling rates, ease of substitution, geographical concentration and the ease of access to the source of the material.

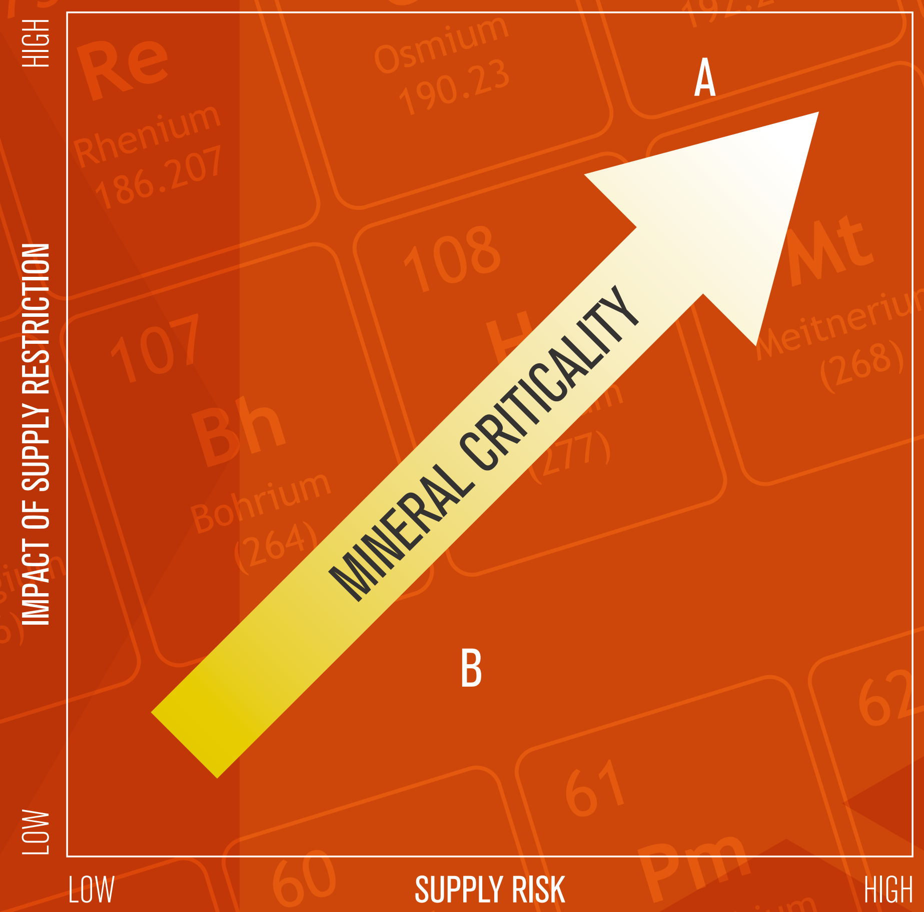


Figure 2: Classic criticality assessment developed by the US National Research Council in 2008[10]

BOX OUT 002

Definition of a Critical Material

The EU list of critical raw materials contains a wide range of elements (within 30 raw-material groups). This includes materials and elements used in farming, for structural materials and in processing gas. This report is specifically targeted at technology-critical metals, that underpin many of our key industries of the future. It is important to note that this report does not cover all of the materials on the EU list. This report focuses on four sub-groups of materials.

1. Rare-earth metals (neodymium, praseodymium, samarium, dysprosium and terbium)
2. Battery materials (nickel, cobalt, lithium, and graphite)
3. Platinum-group metals (palladium, rhodium, and platinum)
4. Aerospace metals (rhenium and tantalum)

There are many reasons why these sub-groups of metals are considered critical, ranging from scarcity in the earth's crust for platinum group metals, to political factors in the case of the rare earths. Some materials such as cobalt are largely produced as a by-product of mining other metals; as a result their supply is largely determined by the demand for these metals.

There are geographical concentrations of most of these materials around the globe, with China being the major source of many of them. This is because China has invested strategically in mineral resources, but also in the refining and manufacturing industries to convert these materials into products (see figure 3).

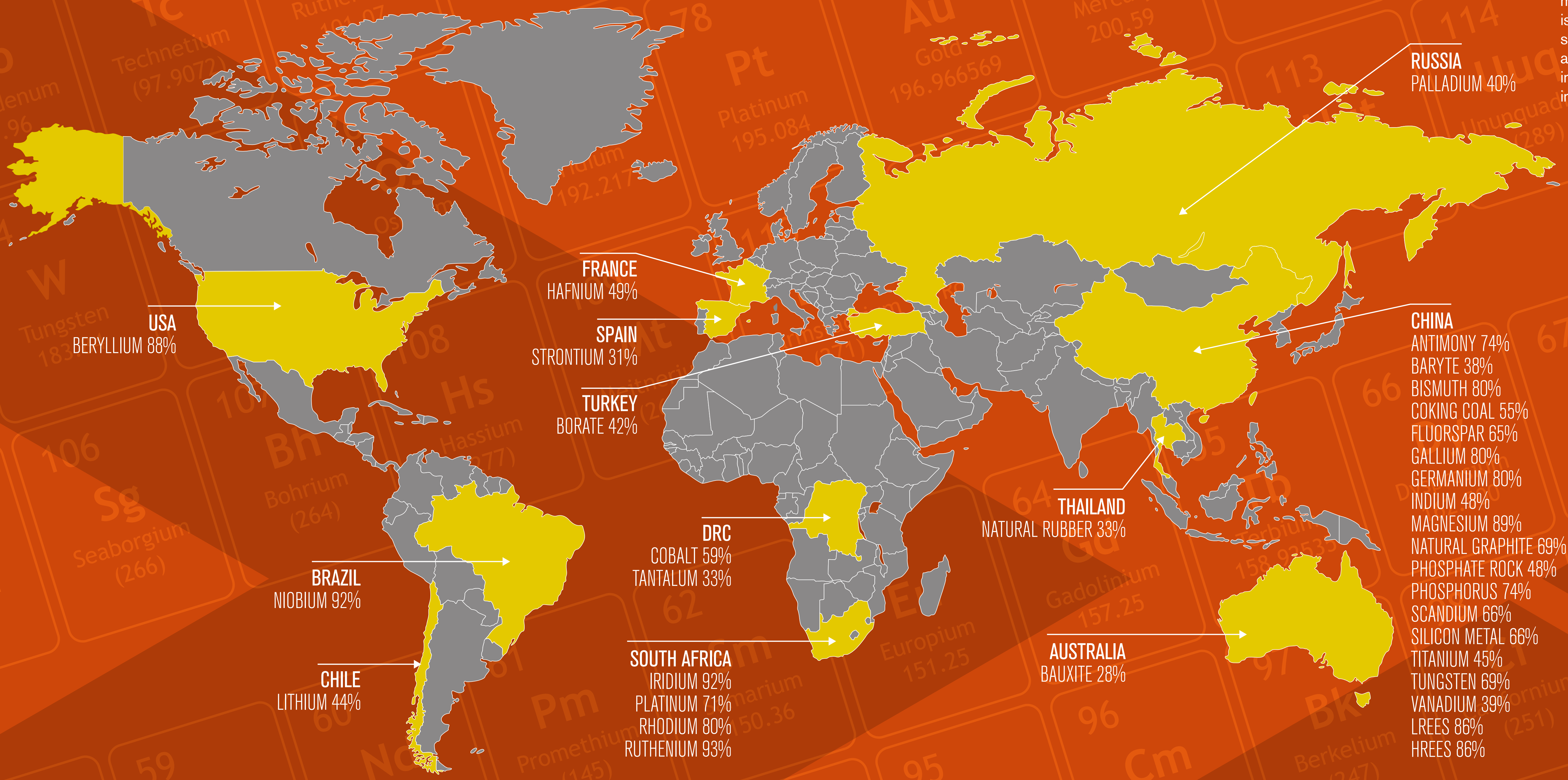
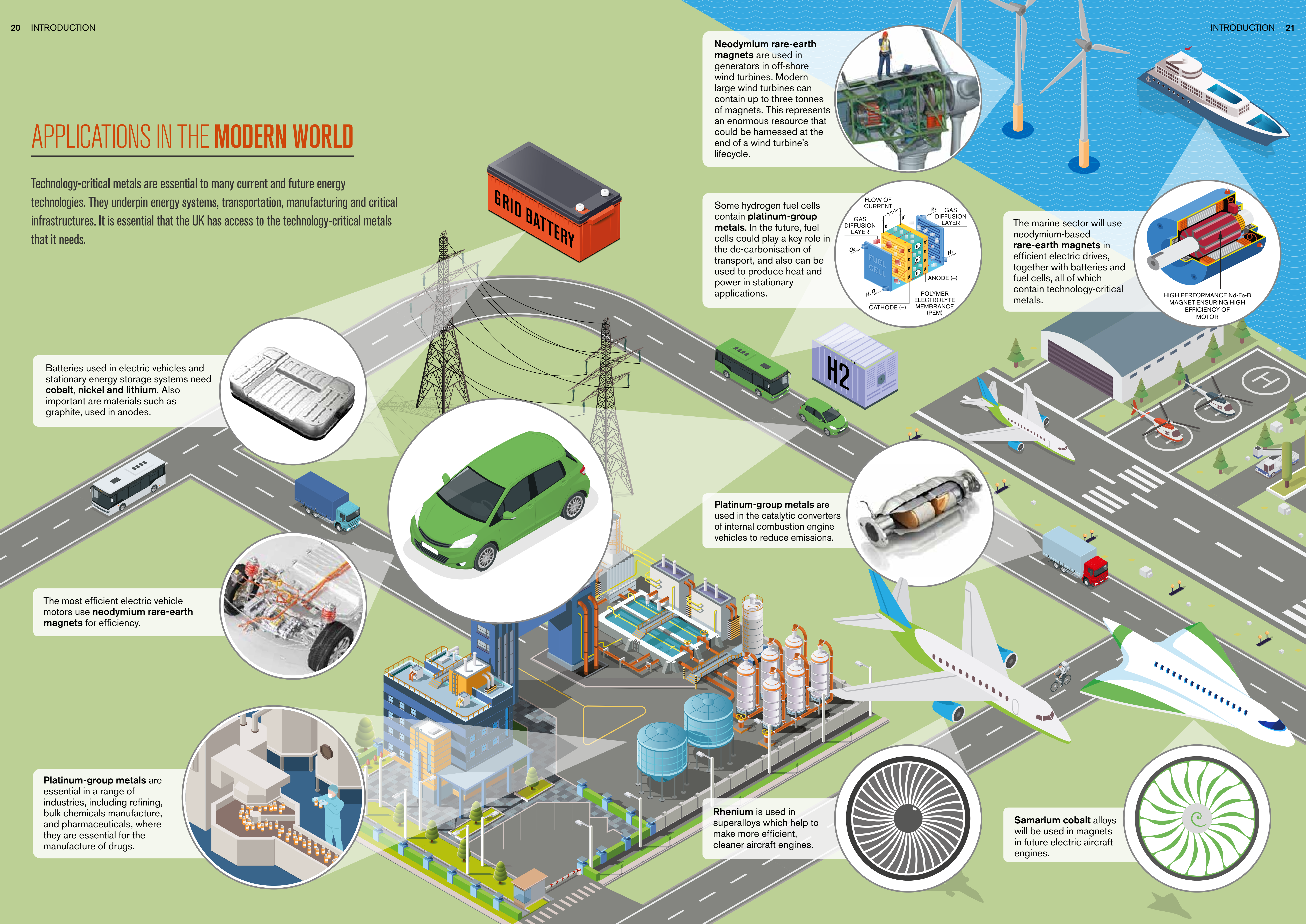


Figure 3: Primary production of TCMs - European Commission Study on the EU's List of Critical Raw Materials (2020)[1]

APPLICATIONS IN THE **MODERN WORLD**

Technology-critical metals are essential to many current and future energy technologies. They underpin energy systems, transportation, manufacturing and critical infrastructures. It is essential that the UK has access to the technology-critical metals that it needs.



Neodymium rare-earth magnets are used in generators in off-shore wind turbines. Modern large wind turbines can contain up to three tonnes of magnets. This represents an enormous resource that could be harnessed at the end of a wind turbine's lifecycle.

Some hydrogen fuel cells contain **platinum-group metals**. In the future, fuel cells could play a key role in the de-carbonisation of transport, and also can be used to produce heat and power in stationary applications.

The marine sector will use neodymium-based **rare-earth magnets** in efficient electric drives, together with batteries and fuel cells, all of which contain technology-critical metals.

Batteries used in electric vehicles and stationary energy storage systems need **cobalt, nickel and lithium**. Also important are materials such as graphite, used in anodes.

Platinum-group metals are used in the catalytic converters of internal combustion engine vehicles to reduce emissions.

The most efficient electric vehicle motors use **neodymium rare-earth magnets** for efficiency.

Platinum-group metals are essential in a range of industries, including refining, bulk chemicals manufacture, and pharmaceuticals, where they are essential for the manufacture of drugs.

Rhenium is used in superalloys which help to make more efficient, cleaner aircraft engines.

Samarium cobalt alloys will be used in magnets in future electric aircraft engines.

APPLICATIONS OF **TECHNOLOGY-CRITICAL** METALS

Our modern lifestyles are increasingly reliant on advanced technologies to keep us moving, communicating and living in comfort. Critical-metals are indispensable to many modern technologies, and their unique properties cannot easily be replaced.

As nations around the world commit to de-carbonise their energy systems, the transition away from fossil fuels will require the move to new energy vectors. Access to technology-critical metals will be fundamental to the production of those key technologies. Whether the UK has unhindered access to technology-critical metals will be decisive in determining whether it can benefit from the opportunities that come with the transition to a clean future. Technology-critical metals are the building block materials for the green economy and without them the UK government's 10 point plan for green growth will be impossible to realise[11].

The shift to renewable energy and other low-carbon energy sources means that electricity will grow in importance as a means of transferring and storing energy. Where previously fossil fuels were used to heat homes and provide a dense energy store for transportation, the shift to electricity as a principal energy vector will require significant investments in both mobile and stationary storage. Electric vehicles will require energy-dense lithium-ion batteries that need technology-critical metals, like lithium, cobalt and nickel.

Furthermore, a future hydrogen economy will require platinum-group metals (PGMs) for use in fuel-cell manufacture. PGMs also find many applications as catalysts in industrial processes and the pharmaceutical industry.

In addition to materials used for energy-storage devices and generators, technology-critical metals are also essential in the manufacture of efficient electrical drives to convert electricity into motion. The most efficient electric-vehicle motors make use of neodymium-iron-boron magnets.

Aerospace is a key UK industry that will require access to technology-metals. Superalloys used for aircraft engines include cobalt, tantalum and rhenium. But in the future, hybrid aircraft will require access to materials for batteries, fuel cells and magnets for use in electric motors.

The digital economy also requires extensive use of technology-critical metals. There are a multitude of technology-critical metals in electrical and electronic equipment. These products tend to have relatively short operating lives, sometimes just a few years, and frequently contain a large number of valuable materials including rare earths, tantalum, nickel, gold, cobalt, PGMs and lithium.

> TECHNOLOGY-CRITICAL METALS ARE THE BUILDING BLOCK MATERIALS FOR THE GREEN ECONOMY AND **WITHOUT THEM THE UK GOVERNMENT'S 10 POINT PLAN FOR GREEN GROWTH WILL BE IMPOSSIBLE TO REALISE.**[11]

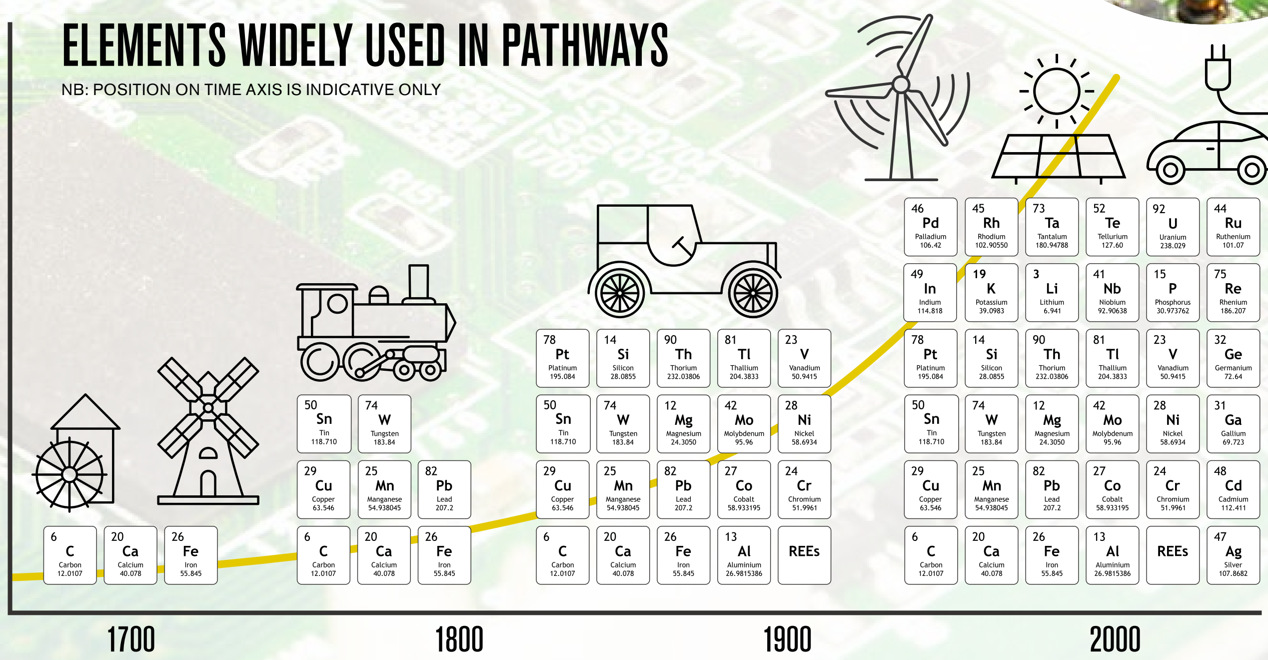


Figure 4: Representation of the range of metals used in technologies vs time.

LEVELLING UP AND **RETAINING JOBS**

For many years our national narrative has been that the UK is in the process of a transition to a knowledge and services economy. It is now clear that a mixed economy including high-value manufacturing will provide the country with greater resilience and strength than one based on services alone. The UK government's aim to see a levelling up of the economy is also an opportunity to stimulate growth in high-tech manufacturing through the 10 Point Plan for a Green Industrial Revolution [11].

Regional rebalancing will be dependent on retaining and developing highly skilled, high-value-added jobs in sectors like manufacturing. Restricted access to critical materials would do great harm to the future development of these sectors. In the very near future whole industries will be reliant on access to critical materials, and without access to these materials there will be job losses across many sectors.

The Faraday Institution, predict that in a case where the UK is successful in transitioning to the manufacture of electric vehicles (EVs), the automotive and EV battery ecosystem would grow by 29% from 170,000 to 220,000 employees by 2040, with 78,000 new jobs created in the new UK battery gigafactories and in their battery-material supply chains[12]. The ability to create and retain these jobs will depend on the UK's access to critical materials[13].

The Advanced Propulsion Centre (APC) estimates that the market opportunity for power electronics and electric machines is a £12bn opportunity by 2025[14]. Rare-earth magnets represent 40-60% of the materials cost for electric machines. So the APC identifies magnet manufacturing as a critical process in the supply chain.

While there are many factors that make the UK an attractive location for high-value manufacturing, in a competitive world those countries that can secure access to key materials will have a significant advantage. Many of these manufacturing industries are changing rapidly and therefore the time left to act is very short. Diesel, for example, will be phased out by 2035[15]. If the UK is to retain workers in this sector, not only will they have to be re-trained, but the production of electric vehicles will require access to lithium, cobalt and nickel for batteries and rare earths for the magnets in the drive motors. It is also important to realise that it is not enough to have access to the raw materials; we also require access to the processed forms of these metals in the form of alloys or chemicals. These are often complex supply-chains and for this reason the different sub-groups are dealt with separately in detail in the report.

OUR GROWING GLOBAL APPETITE FOR TECHNOLOGY-CRITICAL METALS

With the global population set to grow to 9.7 billion by 2050, we can anticipate further strain on the world's resources. Furthermore, there are additional challenges posed by the increasing affluence of the global population, and the resources required to service people's lifestyles and expectations. The 47 least-developed countries are among the fastest growing, and their populations' spending power is increasing[16]. Sales of consumer goods, motorcycles and cars have surged in many African countries, a sign that consumers have discretionary income to spend on consumer durables. In 2018, the world reached a tipping point, where half of the population, 3.8 billion people, now live in households with enough discretionary income to be considered "middle class". This number is expected to grow to 5.3 billion by 2030[17]. Achieving the UN's Sustainable Development Goals[18], and ensuring that we do so in a way that is just and equitable on a planet with finite resources and a growing population, is a challenge that will only intensify.

Figure 5: The earth's increasing population[19]

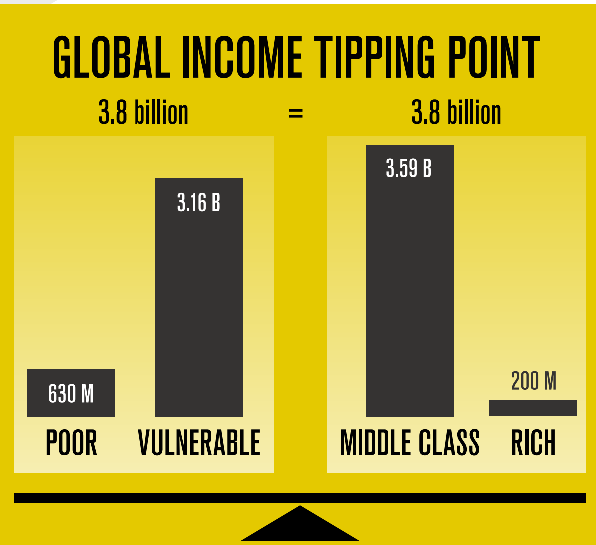


Figure 6: Global income tipping point, Sept 2018 (number of people who are poor, vulnerable, middle class and rich worldwide)[17]

BOX OUT 003

Risk of losing the SME base

As an example evidence was presented at the commission highlighting an SME that moved from South Wales because of the price rises for rare earths, during the "rare earth crisis". The company moved its operations to China, taking skilled engineers with them.

Large companies have the purchasing power to buy materials in volume, to stockpile and hedge against future price rises by buying futures in technology metals.

By contrast, smaller companies do not have this luxury which makes them more vulnerable to price volatility.

UK: New Trade Deals: Risks And Opportunities

As the UK has left the European Union, there is now a period of uncertainty and change as trade deals are negotiated with countries around the world. For countries that are rich in mineral resources, access to critical materials is an advantage and an opportunity for leverage over the UK in trade negotiations. This feeds into wider concerns about the exposure of UK industry to export quotas, as well as price fluctuations and the variability of key feedstocks.

New trade flows building on access to primary materials have the potential to be mutually beneficial, however, if the UK can offer significant downstream processing capacity. Opportunities like the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP) open the possibility to join trading blocs with new partners, some of whom have access to mineral resources, whilst others are developing the technologies to solve the challenges of materials criticality.

MATERIALS: CRITICAL FOR THE **CLIMATE**

The UK has shown great leadership on the issue of climate change. With the 2008 Climate Change Act, the UK became the first country to make a legally binding, long-term commitment to change the trajectory of national carbon emissions to tackle climate change with "Carbon budgets", the Climate Change Commission, and the development of a climate-change action plan[20].

Significant pledges were made by the members of the European Union in Paris. At the time, it was noted that the Paris pledges might slow global warming to between 2.5 and 3°C - still above a level where dangerous tipping points, might be exceeded[21].

Member States committed to reducing emissions by 55% below 1990 levels, by 2030. With Brexit, and the UK leaving the EU, there might be changes in the way that these commitments are delivered: it is unclear how policies previously developed at the EU level will be transposed into UK law. The need to reduce carbon emissions is incontrovertible; carbon budgets are set into UK law and there is a duty on the UK Government to tackle climate change[22].

The UK is on track to meet its third carbon-budget target, which covers the period 2018-2022 (the CCC); however, it is not yet on track to meet the fourth carbon-budget target covering the period 2023-2027[22] or the fifth covering the period 2028-2032. The UK has passed laws to reduce emissions to zero by 2050[23], ending its contribution to global warming. Reaching net-zero emissions will require reductions of 15 MtCO2e per year.

The significant challenge remains: the necessary emissions reductions on this scale will require the massive deployment of a wide spectrum of clean-energy technologies to aid the transition away from fossil fuels.

Many of these technologies require technology-critical metals as part of the production process. The UK is not the only customer for these materials in a global marketplace where the world is attempting to transition away from fossil-fuel-based technologies, and there will inevitably be tensions that arise in the competition for limited resources. Some have suggested the need for a better framework to facilitate the mineral resources necessary for this transition[24].

All eyes will be on the United Kingdom as it hosts the UN Climate Change Conference COP26 in Glasgow 2021. Technology-critical metals will be at the forefront of discussions as they are essential for many green technologies. Both domestic and international responses to the pressing challenge of access to technology-critical metals will be the key to developing new energy systems.

The UK is well placed to contribute to the solutions, with the innovative technologies being developed here. We should use this opportunity to showcase our contribution to the global challenge of sourcing technology-critical metals for the clean transition.

TECHNOLOGY METALS AS **LEVERAGE** IN TRADE DISPUTES

There is an uneven distribution of critical materials, and the processing capability, to refine them into usable materials, around the globe. Accordingly, there is the potential for countries that have, or have secured access to critical materials, to use this position as leverage in trade disputes and negotiations. This is something that the UK needs to be particularly mindful of, as it seeks to forge new trade deals following its departure from the European Union. As highlighted in the rare-earth crisis of 2011 box out there is precedent for supply disruption.

In the United States, successive presidents have grappled with the issue of the US' vulnerability to disruption in critical materials supply. President Barack Obama recognised the challenge critical materials presented to the US, saying "We prefer dialogue. That's especially true when it comes to key trading partners like China," But Obama also said, "but when it is necessary, I will take action if our workers and our businesses are being subjected to unfair practices[25]." The political style of his successor was notably different; however, the recognition of the problem is the same. President Trump signed an executive order, which stated that the county's "undue reliance on critical materials, in processed or unprocessed form, from foreign adversaries constitutes an unusual and extraordinary threat, which has its source in substantial part outside the United States, to the national security, foreign policy, and economy of the United States. I hereby declare a national emergency to deal with that threat."[26]

It has been pointed out that China recognises its dominance in the rare-earth supply chain as a tool for achieving geopolitical influence[27]. Other countries around the world have realised the challenges that restrictions on rare earths could pose to their industry and have taken proactive measures. We cover a number of case studies of other nation's responses to materials criticality including the US and Japan later in this report. There is concern in American policy circles that foreign restrictions on the USs' critical materials' supply could have serious implications for national security and defence[28]. China has threatened to embargo the supply of critical materials to the US[29]. In the US the Critical Materials Institute was a major strategic investment designed as a US response to this problem. There is a recognition that the supply of critical materials could lead to the movement of jobs from the US. Despite these measures, there is still concern as to whether the US approach has reduced the problem[28].

President Biden will issue an executive order reviewing US Critical Material Supply chains.[30] He pledged on the campaign trail to review US vulnerabilities[31] and has set out how this should be co-ordinated between the state and federal levels of governance. Delivering on his campaign pledges, it is anticipated that he will take many steps to address US critical materials' challenges as set out in his manifesto[32].

Whilst the efficacy of different measures can be debated, what is clear is that the US has a considered policy response in this area, which at present the UK lacks. This is an issue that will only increase in importance as the UK seeks to forge its own trade policies independently of the European Union, and the potential for critical materials to be used as leverage presents a significant challenge and potential national-security issue.

As an island nation reliant on imports of technology-critical metals, there is much that we can learn from Japan's approach to managing the impacts of materials criticality on Japanese industry (see conclusions section).

BOX OUT 004

The rare-earth crisis

Between 2005 and 2012 China introduced export quotas and taxes for rare-earth materials. This resulted in large price fluctuations for rare earths and was exacerbated by an alleged diplomatic incident in the South China sea when a Chinese fishing trawler collided with a Japanese coastguard vessel. It was reported at the time that the Chinese threatened to embargo exports of rare earths to Japan unless the fisherman was released from custody, although the Chinese have subsequently denied this. This was one of the drivers for Japan to develop a coherent critical-materials strategy to minimise the risks of future supply restrictions.

Within a year prices were back to pre-crisis levels and have generally continued to fall ever since (see figure 7). Of course, this does not mean that the problem has gone away. China still controls around 90% of the rare-earth market and the UK has no rare-earth deposits of its own (see figure 8).

The 2012 WTO dispute

In 2012, the United States filed a case with the World Trade Organisation (WTO) after the US, EU and Japan argued that China's restrictions on the sale of rare earths violated the WTO's regulations. China argued that it had environmental concerns and was legally conserving resources. The WTO ruled in favour of the US in 2014, which forced China to remove its export quotas in 2015.[33]

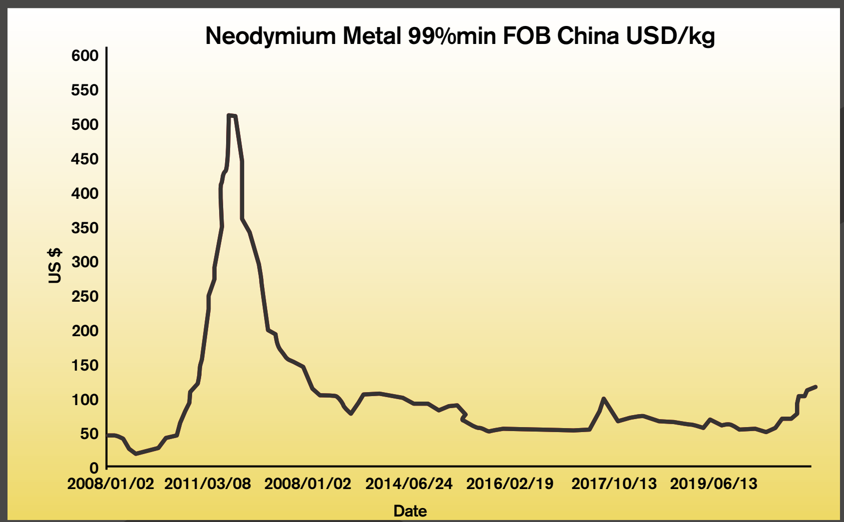


Figure 7: Rare earth price history

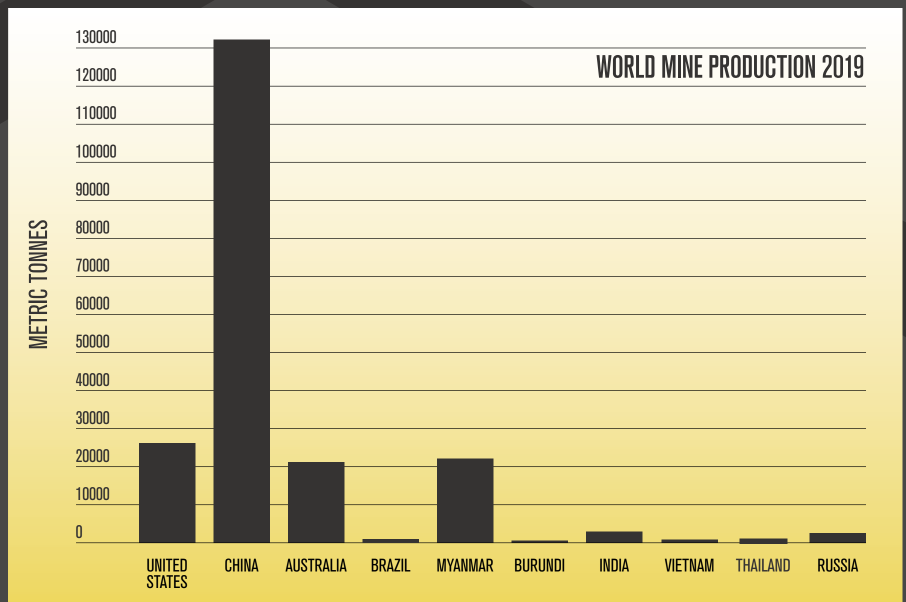


Figure 8: World mine production of rare earths 2019. Reproduced from USGS.[34]

When the Chinese President Xi Jinping visited a rare-earth processing plant in Jiangxi, just a week after the Trump administration blacklisted Huawei in May 2019, he highlighted the importance of rare earths in global supply-chains (see figure 9). This statement was widely seen as a threat to restrict Chinese exports or rare earths to the United States.

The Trump administration has subsequently looked at accelerating the process for mining permits, increasing R&D, and more trade in rare earths with allies. The former president also asked the Department of Defence (in the US) to increase the production of rare-earth magnets, with Australia announcing that it would boost supplies.

President Biden has said that he will direct his administration to conduct a review of key US supply-chains, including those for rare earth metals.[35]

Commentators have said that while the executive order does not explicitly mention China, the directive is "likely in large part an effort by the administration to determine how reliant the US economy and military are on Chinese exports."[36]

Last year in the Senate Energy and Natural Resources Committee, Sen. Lisa Murkowski, (a Republican from Alaska) asked what would happen in the event that China decided to cut off the US from access to critical materials. Simon Moores, the Managing Director of Benchmark Minerals Intelligence replied that the move would leave the US with few options and prove devastating to the US economy.

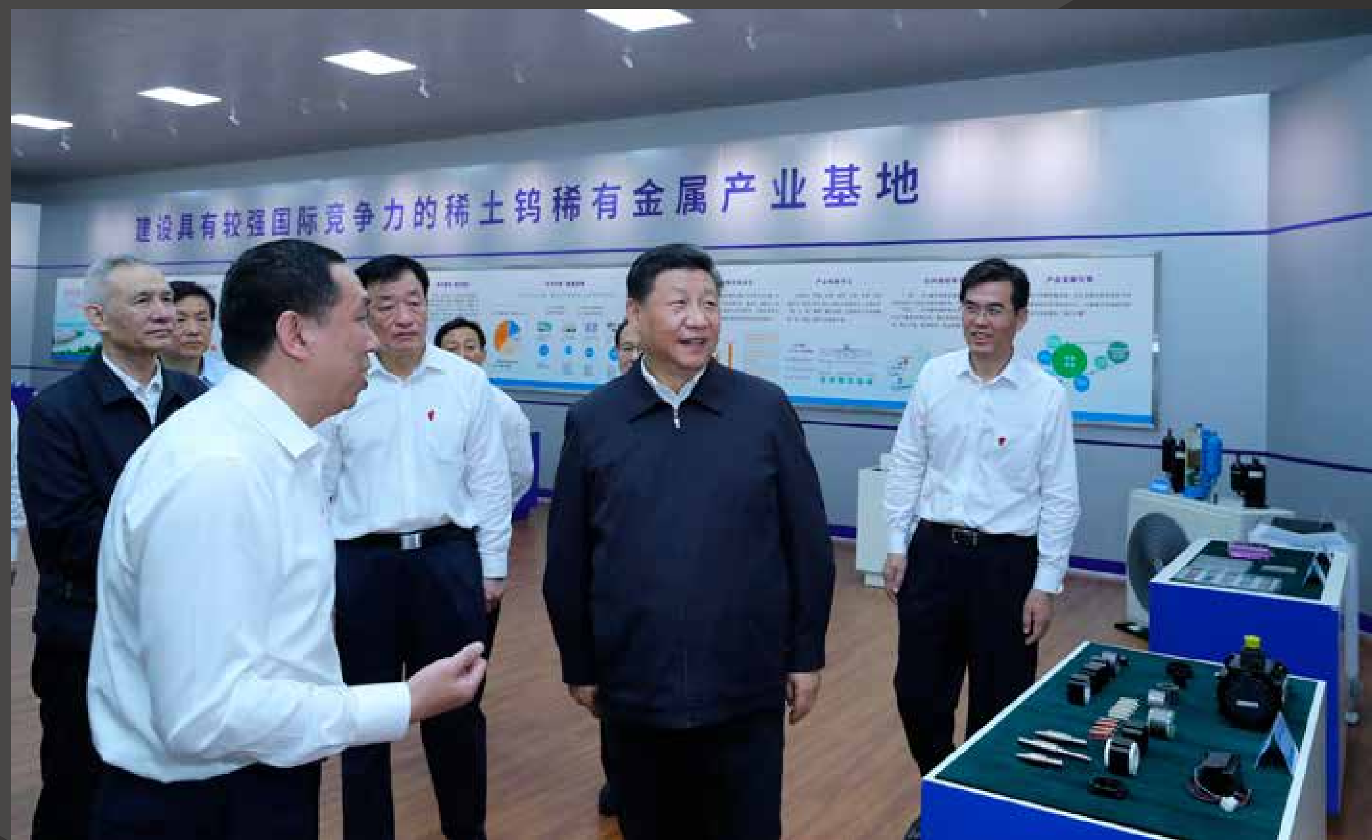
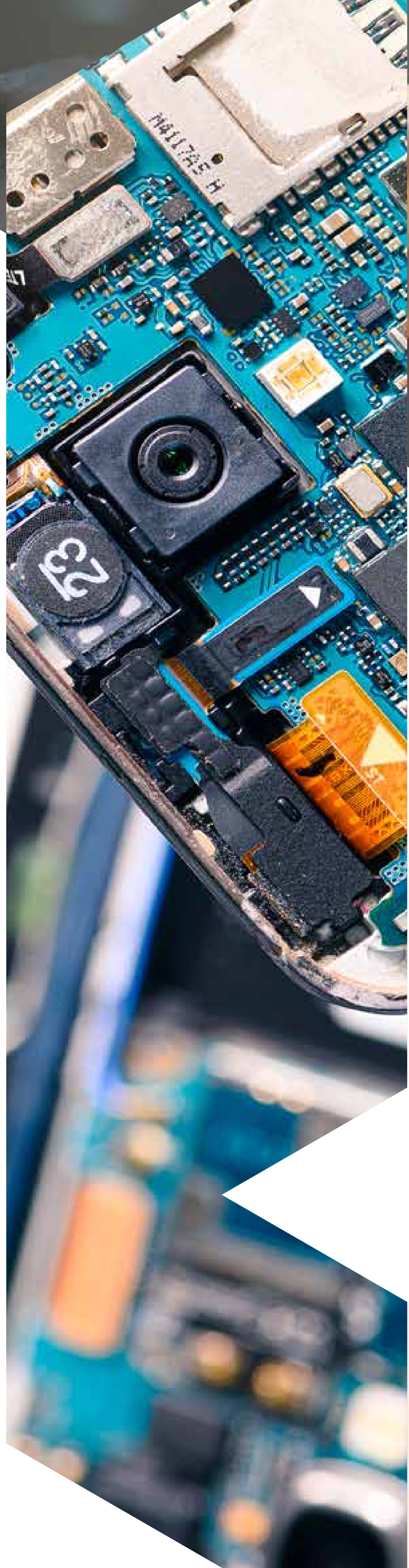


Figure 9: Chinese President Xi visits a rare earth processing plant.
On 20th May, 2019 the Chinese President Xi Jinping, the general secretary of the Communist Party of China Central Committee and chairman of the Central Military Commission visiting JL MAG Rare-Earth Co. Ltd.

ACCESS TO PRIMARY SOURCES OF TECHNOLOGY-CRITICAL METALS

One of the main challenges for the European Union is the limited opportunities to produce critical materials from indigenous resources. In many cases either the deposits of materials do not exist, or where those materials are present, they cannot be extracted at a competitive price, using methods that would be environmentally acceptable in Europe. There are a few notable exceptions to this, and efforts are underway to evaluate what primary resources exist within the European territory[37]. There are opportunities for the small-scale production of certain strategic elements, and consideration is being given to methods for extraction that might be more environmentally benign than current processes[38]. Before Brexit, the UK had considered its strategy as part of this continental alliance; however, the UK must now consider the challenges and opportunities around critical materials as a separate entity.

Focusing on the UK, there are very limited opportunities in the UK for the domestic production of critical materials, however; there are some notable exceptions. e.g., Cornish lithium[39], tungsten[40] etc. These opportunities will be set out more comprehensively later in this report.



The UK must therefore consider what its unique strengths are, and how these can be leveraged in ways that bring a competitive advantage in the quest to secure access to critical materials. There is also the opportunity for the UK to invest, as other countries have done, in developing access and extraction of other critical primary resources around the world and this should be part of our trade negotiations.

Considering the supply-chain as a whole, the UK might be better placed downstream, with opportunities to develop supply chains for processing critical materials into value-added products and partnering with resource-rich nations around the globe that have access to critical materials. Here, the UK could be well placed to create the infrastructure to process primary materials that are extracted overseas, thereby reducing our dependence on the present restrictive supply-chains and capturing the high-value-added elements for Britain.

In this respect, the UK has an asset in the City of London; as a global financial hub, a great deal of finance for mining projects flows through the city. It might be possible to leverage this position to create opportunities for new resource and project developments to secure UK access to technology-critical metals.

MOVING TOWARDS **A CIRCULAR ECONOMY** IN TECHNOLOGY-CRITICAL METALS

In many cases there are synergies between the processing of primary materials and the ability to be able to process secondary material from recycled feedstocks. Here, there is some potential to create capabilities that in the first instance could be used to process a higher volume of imported primary material, and as secondary materials become available, could switch to processing a greater proportion of secondary scrap. For some materials there is an abundance of secondary material, but the supply-chains for primary material have not yet been developed. Here, these secondary materials could be a basis for developing processing capacity in the UK in order to fill supply-chain gaps.

One example of this could be in the rare-earth supply-chain. The recycling rate for rare-earth magnets, which are used in electric motors, is very low today. However, the UK has unique patented technology to remove and to recycle these materials from waste streams. This could be leveraged to build the supply for magnets that would subsequently support the primary supply chain. Taking material from new primary resource exploration projects and secondary resources from recycling could provide supply-chain resilience for a UK magnet manufacturer. These recycling processes can process scrap material from further up the supply chain, cutting the cost and environmental burden of producing technology-critical metals.

As a product reaches the end of its useful life, it must be seen as a resource rather than something to be disposed of as quickly as possible. For simple products like glass and paper, the practicalities of this are not difficult to implement. However, as products become more complex - a mobile phone can contain two-thirds of the elements from the Periodic Table - it becomes increasingly difficult for consumers to become involved and for recyclers to operate a profitable business.

Currently, many products that cannot be recycled economically in the UK are exported to countries with low-cost economies. These products are often processed in conditions that would not be considered acceptable in the UK from a health-and-safety perspective, and in some instances involve child labour and/or poor working conditions. The extent of this exporting should not be underestimated. As much as 80% of the metal products that are classified as waste are exported from the UK, making us the largest exporter out of the EU. The UK also scraps more End-of-Life (EoL) vehicles than any other country. This is partially due to the relatively large market for vehicles in the UK, but also because, unlike Germany, for example, the UK has few options for re-selling its second-hand, right-hand-drive cars and lorries. At end of life some of the components, such as the battery and the catalytic converter, are removed and then the car is shredded with subsequent material separation and sorting. The switch to hybrid and electric vehicles will have implications for the value of recycled vehicles and materials, on the technologies which are used for separation and on the safety of workers at these facilities.

Here, there is an enormous opportunity for the UK to develop globally exportable intellectual property around recycling processes and novel approaches to mitigating against materials criticality.

In order to stem the outflow of these technology-critical metals that are found in vehicles – like rare-earth permanent magnets, lightweight magnesium alloys and the cobalt and nickel found in lithium-ion batteries – some form of intervention is required. Although the prices and availability of these materials are currently acceptable, this will not always be the case. Continuing to buy in these materials, use them until the product's EoL is reached, and then shipping them out again, often at considerable cost, is a very risky route for a country to take in the long term.

The intervention the UK requires is establishing R&D centres, university funding, joint government-private investments and a well-managed strategy to secure complete industrial value chains based on resource efficiency, recycling and closing the loop for technology-critical metals to which the UK cannot have guaranteed access over the next 25–50 years.

The main technical challenges that stand in the way of a circular economy of technology-critical metals are sensing and automated sorting technologies tailored to the recycling challenges of technology-critical materials.

Given the immediacy of the challenge, rapid co-investment is required to get these technologies to scale quickly. The dividends from this rapid technology development will be substantial, but will be realized over a longer time period as material is processed through these new processes.

To support the efficient operation of this future industry, key data and statistics on these materials streams will be required.

Regulatory and legislative changes could also support the circular economy of technology-critical metals. All of these elements are covered in more detail later in the report.

PRIMARY MATERIALS

The report is broken down into separate chapters starting with primary materials. The primary chapter begins by explaining the way in which these technology-critical metals flow through our economy and sets out the current global context for access to key technology-critical metals. It then expands upon this with a series of case studies on specific technology-critical metals employed by various sectors. Each case study covers the applications where these materials are used, demand growth, location of deposits and processing capacity, the global supply chain, environmental and social issues, and how to build a UK supply chain.

SECONDARY MATERIALS

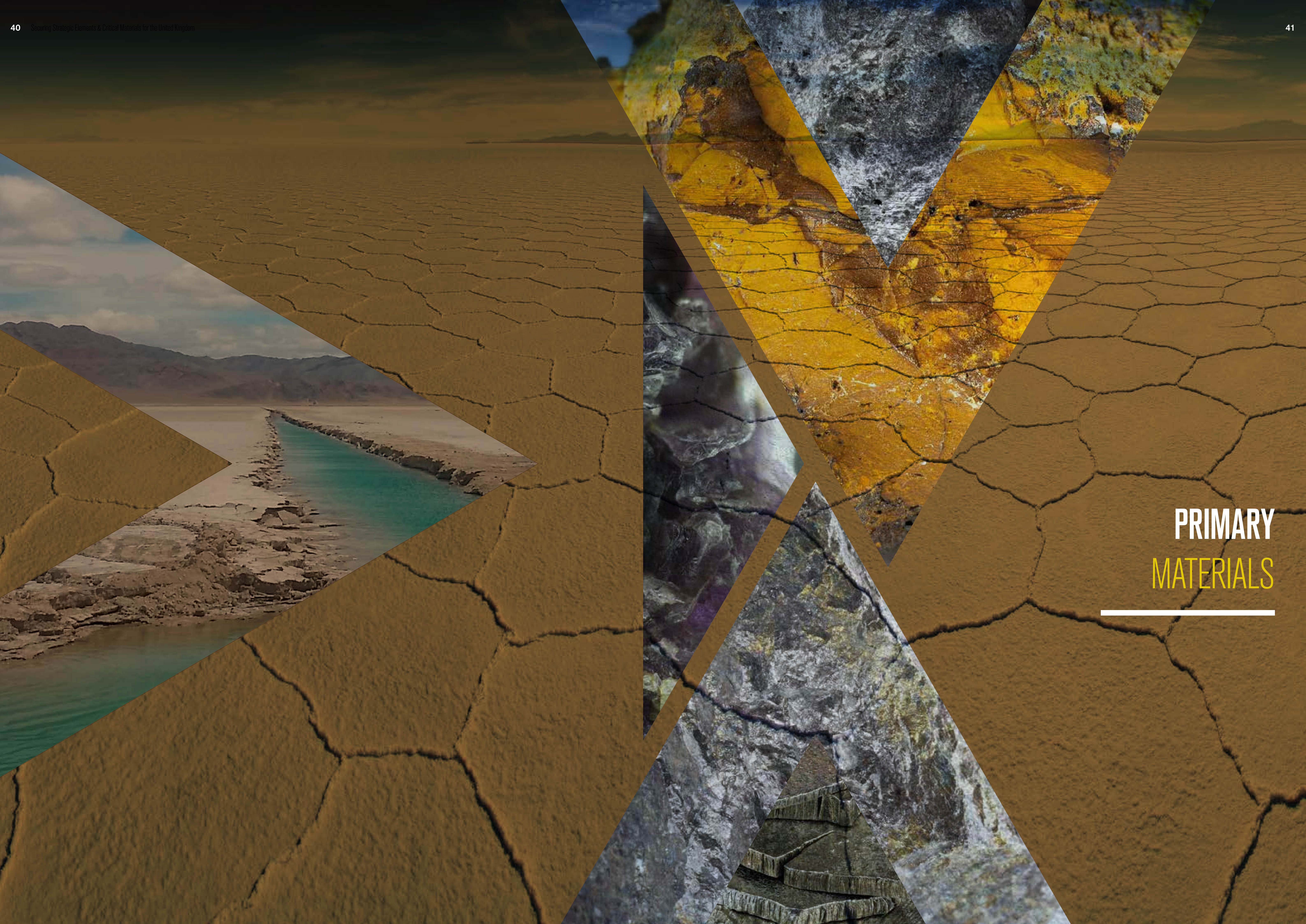
The chapter on secondary materials initially introduces the current overall recycling rates for all critical materials on the EU list. It covers the potential positive impact of recycling, the current recycling industry and processes, and the generic barriers to recycling of technology-critical metals. The chapter then focuses on case studies of the same materials sectors as the primary chapter. These cover areas including the potential size of secondary markets, the technical difficulties for reuse and recycling, design for recycle, and advanced technologies for sensing, automation, separation, purification and re-processing of these materials.

GOVERNANCE & REGULATION

The chapter on governance and regulation covers trade, the impact of REACH regulations on technology-critical metals, labelling, standards, eco-design directives, extended producer responsibility and environmental and social governance (ESG). Finally there is a case study on EU legislation for lithium-ion batteries.

CONCLUSIONS & RECOMMENDATIONS

The final chapter looks at the way that the supply of technology-critical metals is managed by a number of other countries around the world including Japan and the EU. It covers how technology-critical metals are dealt with by different UK government departments. The chapter then sets out the need for a single body to create a national strategy for the management of technology-critical metals. A detailed set of recommendations are presented that outline what a national technology-critical metals plan should include.



PRIMARY MATERIALS

MATERIAL FLOW

Technology-critical metals flow into the UK in a variety of forms, ranging from ores, elements, alloys, chemicals and other raw materials to be manufactured into products. In order to develop a strategy for critical materials, it is important to understand geographically where the raw materials are coming from, how they are processed and where and in what form the materials enter and leave the UK economy.

There are limited data on technology-critical metals flows coming into and out of the UK, as highlighted by Velenturf et al. as part of the NERC programme - Resource Recovery from Waste[41]. The Office for National Statistics is exploring the feasibility of a National Materials Datahub to provide access to reliable data on the availability of materials including technology-critical metals[42].

The UK has no current indigenous production of primary (mined) technology-critical metals and therefore is reliant on resource-rich nations around the globe. Mined materials are typically converted into metals, alloys or chemicals by refining the ores and then manufactured into specialist materials such as magnets or cathode materials, which are then used to make components such as electric motors or batteries. The primary section of this report describes the geographical locations for mining and refining of technology-critical metals, applications for each material and the global and UK supply-chains. The descriptions highlight why many of these materials are at risk of short supply. Although critical-metal definitions often refer to a restricted distribution of mines, in some cases the concentration of refining capacity in one part of the globe is even more extreme.

Responsible sourcing is rapidly increasing in importance, driven originally by the conflict minerals agenda, and now widening out to human rights and environmental performance. Tracking of materials flows and the need for supply-chain assurance are likely to increase in the near future.

Ideally, the technology-critical materials would move around the UK system in a circular economy, whereby the materials or products are reused or recycled at their highest level to minimise the environmental footprint and maximise the value of the assets. However, at present many of the technology-critical materials flow into the UK in products and pass through what can only be described as a linear economy, whereby the materials end up in landfill at their end of life (see figure 10). Other products and materials leave the UK for reuse and recycling abroad. This is not the case for all of the sub-groups of materials discussed in this report and case studies are presented in the secondary-materials section below for PGMs and aerospace materials where successful recycling is carried out.

There are multiple organisations encouraging movement towards the circular economy in the UK. DEFRA leads for the UK Government on the circular economy and the Waste and Resources Action Programme (WRAP), the Green Alliance and the Ellen MacArthur Foundation are examples of NGOs who promote a circular economy[43,44]. The ultimate aim for a circular economy is to redefine growth, create positive society-wide benefits, whilst decoupling economic activity from the consumption of finite resources.

A circular economy favours activities that preserve value in the form of energy, labour and materials. This means designing for durability, reuse, remanufacturing, and recycling to keep products, components and materials circulating in the economy.

A circular economy is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems.

In many instances we import more of the technology-critical materials into the UK and Europe in manufactured components and products than we process internally from primary raw materials. For example, the ERECON report (2015) estimated that we import around 10,000-12,000 tonnes of rare earth magnets into Europe every year, while we only manufacture around 1000 tonnes of the same material. Therefore, there is an incentive to access these large volumes of material if technologies can be developed to extract them from end of life products. However, there are technical, economic and societal challenges that need to be addressed for this to happen. The secondary section of the report explains the challenges for the secondary market and how the UK might intervene to gain a competitive advantage.

It should be noted that the processing of many of these materials from primary ores often requires the same technologies and downstream supply-chains as the secondary (recycling market). The secondary and primary markets are often seen as rivals, but in fact they are mutually beneficial and interlinked. Smelters, for example, can use either primary ore or scrap metals. Sometimes a recycling activity can be set up faster and at a lower cost than a primary-mining operation with associated processing, but the same supply-chain and processing might be able to handle both primary and secondary materials. Both scenarios will be extremely important, as although a recycled source of material could give the UK a competitive advantage this will only meet a proportion of the demand, particularly in a growing market.

Figure 10: Representation of the circular economy

Market Size

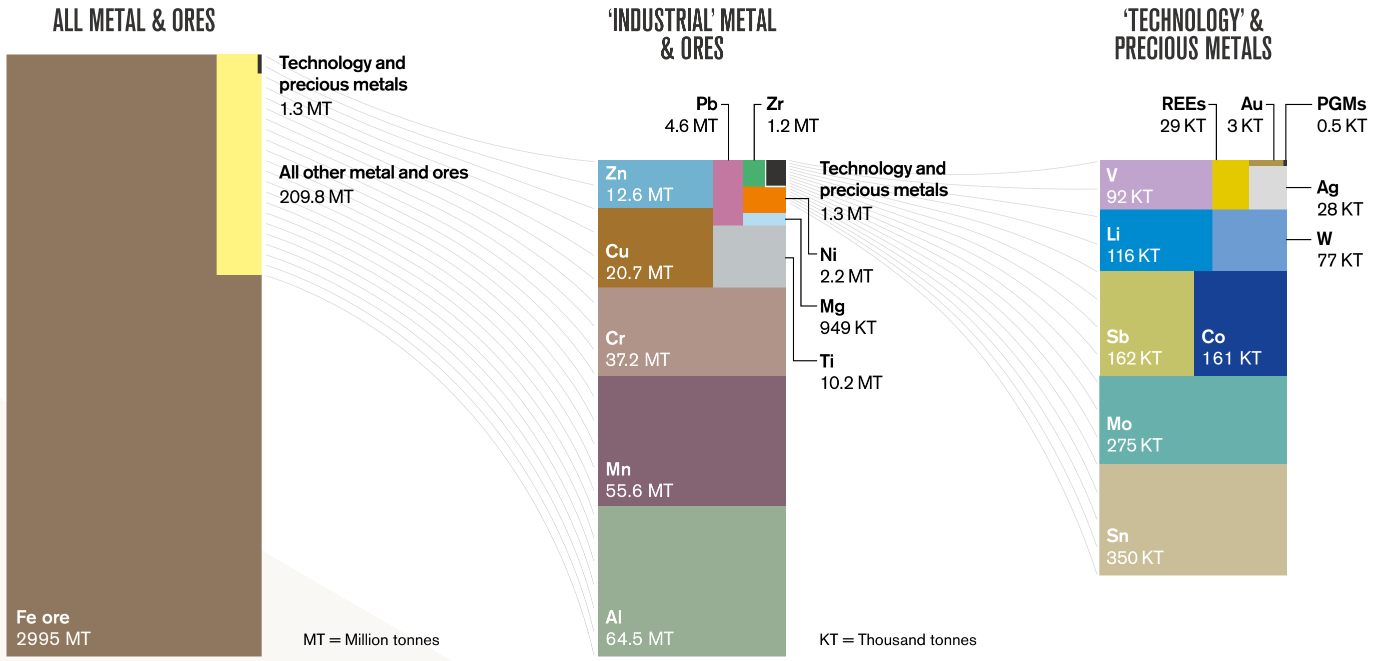


Figure 11: Global production of primary metals and ores. Source: British Geological Survey 2019.[45]

Although the demand for some technology-critical metals is growing rapidly, the overall market size for them is dwarfed by the main industrial metal sectors (see figure 11). To put this in perspective, in 2019 around 1.5 billion tonnes of iron and 64 million tonnes of aluminium were extracted from primary mined sources, whereas only around 160,000 tonnes of cobalt were produced[45]. In some instances this means that the major mining companies have not invested in technology-critical metals and most exploration and development is carried out by junior companies. Single entity mines in niche resources are more vulnerable to price fluctuations. It is also important to note however that many of these technology-critical elements are a co-product or by-product of mining operations for the major metals. These are more likely to be produced by the major mining companies, but they are vulnerable to variations in demand for the 'parent' major metal. Some of the ores of technology-critical metals, such as tantalum, tungsten, cobalt and rare earth ion adsorption deposits, are amenable to production by artisanal and/or small-scale mining (ASM) as well as large scale industrial mining. ASM is more likely than large-scale mining to lead to informal or illegal supply-chains but has also been subject of some of the best know mining industry fairtrade-style schemes[46].

As rare earth metals are top of nearly all critical materials lists outside of China[47], this section starts with these elements and then moves through battery materials, platinum group metals and then aerospace materials. Again it should be emphasised that this report does not attempt to cover all critical-materials that might form part of a UK strategy, but has concentrated on a subset of materials, to explore the issues around the supply-chain. If a broader range of materials had been covered this would not have been possible.

CASE STUDY: RARE EARTH ELEMENTS

The rare earth elements (REEs) are a group of seventeen elements that can be found mainly in the lanthanide series of the periodic table. Sometimes scandium (Sc) and yttrium (Y) are included in deposits that are economic to mine[48]. Not all of the rare earths are scarce in terms of earth abundance. In fact cerium is as abundant as copper, but their restricted geolocations combined with the difficulties in separating the individual rare earths have resulted in the concentration of production in certain parts of the globe (see figure 12)[49]. The rare earths are often split into the light rare earth elements (LREs) , including for example neodymium (Nd) and samarium (Sm) and the heavy rare earth elements (HREs), including dysprosium (Dy) and terbium (Tb) (see figure 13).

Once it became possible to obtain the rare earths as individual elements, their interesting magnetic, optical and physical properties began to be exploited. The first resources to be developed were mineral sand deposits; this was followed by the opening of the Mountain Pass rare earth mine in California. Today, China dominates the world of rare earths. China produces around 90% of the world's supply of refined light rare earth oxides (LREOs) and > 95% of the heavy rare earth oxides (HREOs)[50].

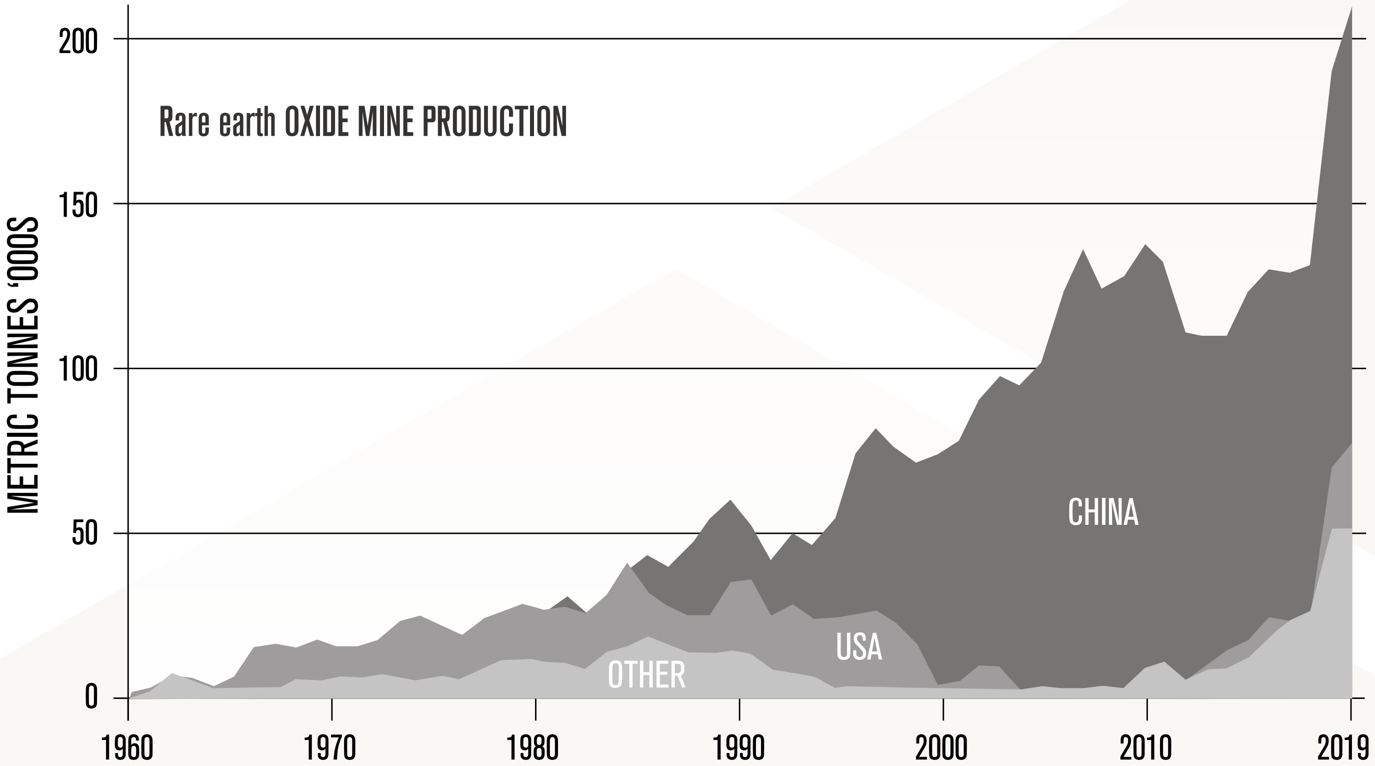


Figure 12: World mined production of rare earth oxides[34].

BOX OUT 005

Applications of rare earth elements

For a long time the rare earth elements were principally used for the polishing and colouring of glass and ceramics. They were also used in small quantities in specialist steels, in various alloys, and for phosphors used in lighting[51]. More recently they have found uses in permanent magnets and in catalysts (see figure 14).

Figure 13: The rare earth elements shown on the periodic table.

Cerium and lanthanum are used in catalysts and alloys, whereas permanent magnets require neodymium, praseodymium, samarium and small amounts of the heavy rare earths (dysprosium and terbium). By volume the magnet market represents around 35% of total rare earth demand, however, by value this represents 91%[50]. In reality, cerium and lanthanum are in over supply and therefore have a low value. If alternative applications could be found for these elements it would increase the economic viability of rare earth mining.

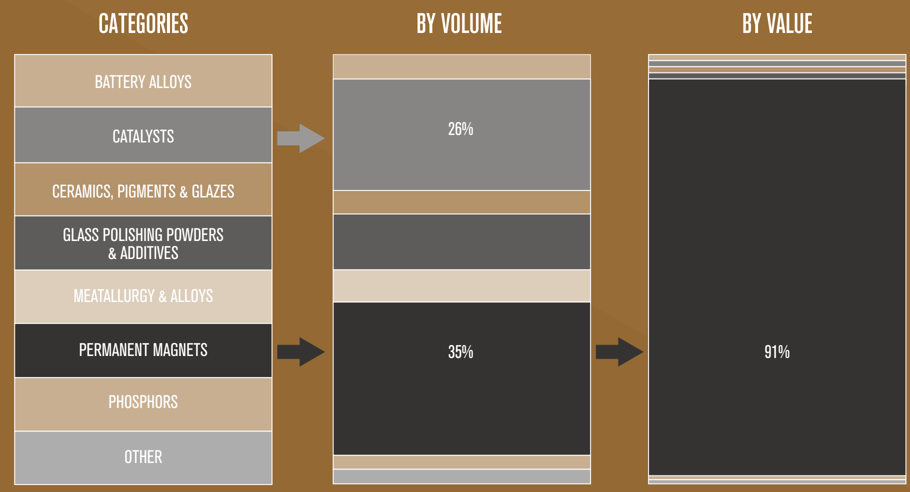


Figure 14: Applications for rare earth elements.[52]

WHAT IS A RARE EARTH MAGNET?

Rare earth permanent magnets are found in two main commercial forms: alloys of samarium and cobalt (SmCo-type magnets), which are mainly used for very-high-temperature applications such as those found in the aerospace industry, and alloys of neodymium, dysprosium, iron and boron (Nd-Fe-B type magnets). The permanent rare earths magnet market is dominated by Nd-Fe-B magnets, where around 130,000 tonnes are manufactured per year[53]. Around 88% of these materials are produced in China, with the second largest producer being Japan; less than 1% are produced in Europe[54]. Nd-Fe-B magnets are produced in a few different forms, including fully dense sintered magnets produced from an alloy powder[55], hot-pressed magnets[56.] or in the form of resin-bonded magnets by mixing Nd-Fe-B powders with a polymer[57] (see figures 15 & 16).

Figure 15: Fully dense sintered Nd-Fe-B magnets

Figure 16: Resin-bonded Nd-Fe-B magnets

Rare earth magnet applications and demand growth

Rare earths magnets are used in a vast array of electrical equipment and it is predicted that we will require around 270,000 tonnes by 2030, an increase of over 140,000 tonnes compared to current production. The magnet function can be roughly split between holding magnets, motors and generators, which are then used in a vast number of commercial sectors. They are a key component in electronics (e.g., - loudspeakers, vibrators and small motors), offshore wind turbine generators, electric and hybrid vehicles (e.g.,- drive motors, power steering, generators, actuators), cordless power tools, electric bikes, efficient pumps, robotics, separators, filters, loudspeakers, MRI scanners and many more[50.]

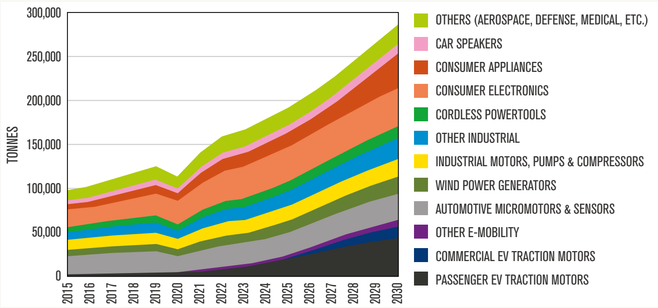


Figure 17: Historical global consumption and forecasted demand for Nd-Fe-B magnets by end-use category[50] (recreated from Adamas Intelligence)

Rare earth magnets are a building block material for electrical devices, many of which will be used in clean technologies to tackle climate change. For a permanent drive motor around 40-60% of the cost/value is from the rare earth magnets[58].

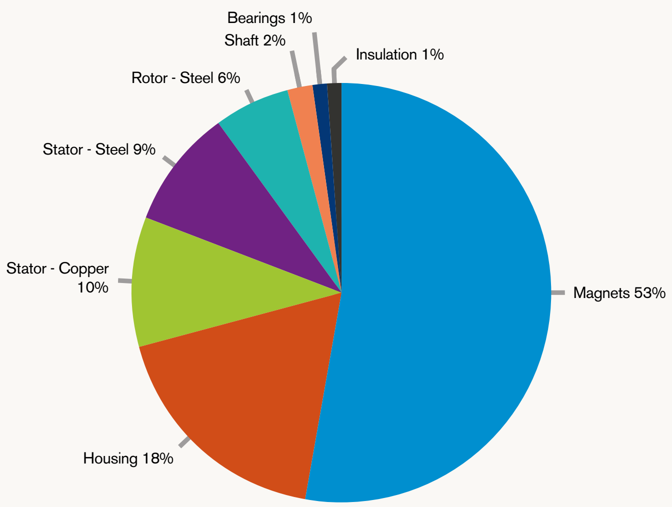


Figure 18: Cost breakdown (%) of a typical permanent magnet motor

LOCATION OF RARE EARTH DEPOSITS

The name "rare earth" is a misnomer as there are rare earth deposits all over the globe. Around 210,000 t of rare earth elements were mined in 2019[59]. Production of rare earths has more than tripled in the last 35 years, and although China has quotas for official production, there are also producers operating illegally to satisfy demand.

China has invested heavily in its rare earth market and in the processing of these materials all the way along the value chain and now dominates. At present, around 70% of neodymium is mined in China, followed by 11% from the USA (Mountain Pass), 9% from Australia (Mount Weld), and 6% from Myanmar. However, the vast majority of the extracted material (produced worldwide) is processed in China. China now produces around 92% of the world's rare earth alloys and 88% of the world's rare earth magnets. The major non-Chinese refiner is based in Australia, producing oxides from Lynas Rare earths, from the Mount Weld mine via a processing plant at Kuantan, Malaysia[60]. The main non-Chinese magnet producers are based in Japan.

It is important to understand that there are rare earth resources in many regions of the globe which could provide a supply to the UK if economic extraction can be developed (see figure 19).

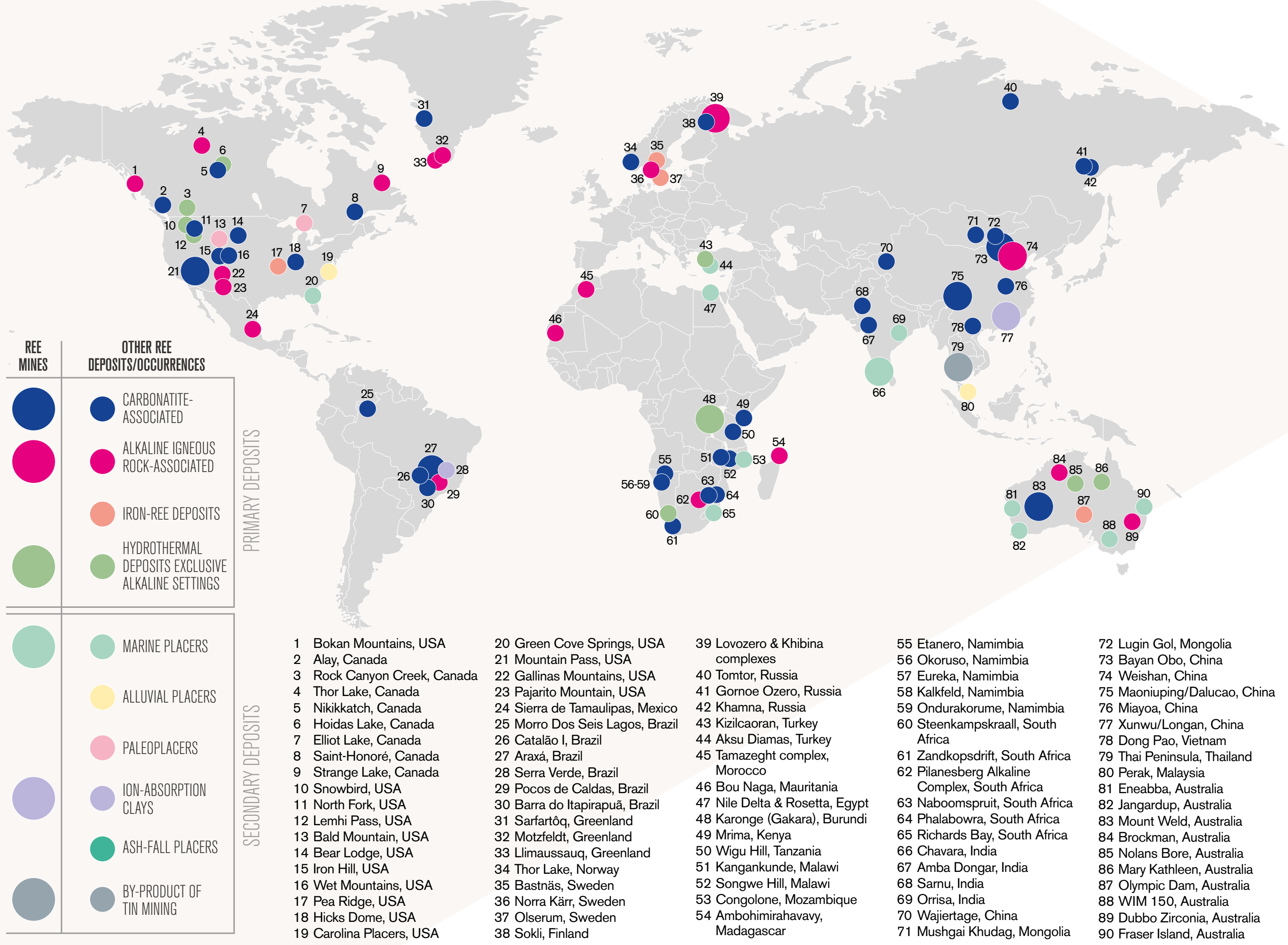
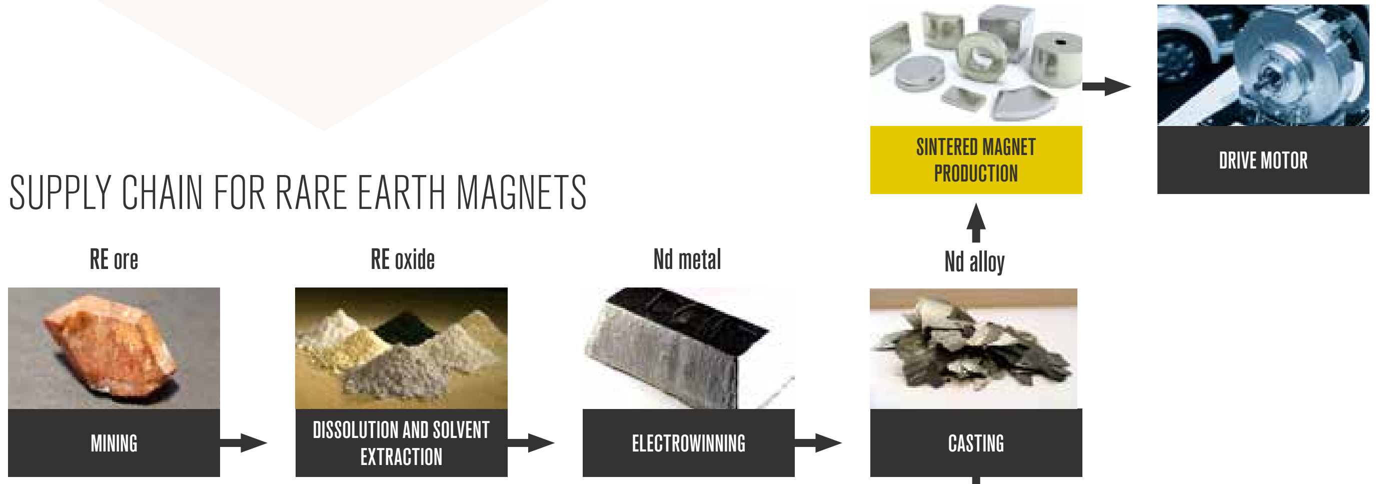


Figure 19: World deposits of rare earth elements (recreated from the British Geological Survey 2021[49]

The ore that is extracted from the ground contains a mixture of rare earth elements in different ratios. Typically, the ores are rich in the light rare earths (e.g.,- lanthanum (La), cerium (Ce) and neodymium (Nd)) but lean in the heavy rare earths (e.g., - dysprosium (Dy) and terbium (Tb)). This creates what is often described as the balance problem, where the largest downstream markets (ie.,- magnets) require more of the elements that are less abundant in the ore. This presents a particular challenge for mining companies, as only a proportion of the rare earths are profitable.

SUPPLY CHAIN FOR RARE EARTH MAGNETS

There are different types of rare earth deposit including hard rock, ion adsorption clays and mineral sands. If this ore is a hard rock deposit, then once it is extracted from the ground it is crushed, milled and pass through a range of physical sorting techniques (e.g.- screening and magnetic separation). The separated rare earth-rich fraction is then dissolved with strong acid and passed through a chemical solvent-extraction process (see figure 21). The ore processing steps produce significant amounts of tailings, which are the chemical by-products of the processing (see environmental section).



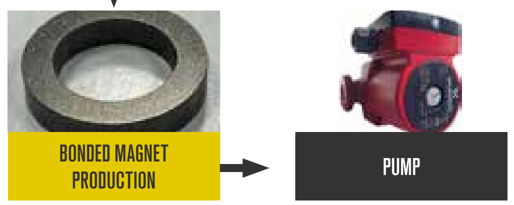


Figure 20: Supply chain for the production of rare earth magnets.

The extracted oxides are converted into rare earth metals using molten salt electrolysis, which is similar to aluminium processing but on a much smaller scale. The extracted pure metals are then converted into alloys by melting at high temperatures and rapid cooling onto a water-cooled wheel either by melt spinning or strip casting (see figure 20).[62]

In Europe, magnet companies buy in rare earth alloys and use them as the starting point for magnet manufacture, whereas in China the supply-chain is fully integrated from mine to magnet.

There are multiple ways of manufacturing rare earth magnets with various levels of control from China. Fully dense magnets can be manufactured either by breaking the alloys into a powder, pressing and sintering[65] at high temperatures (sintered magnets) or the molten alloys can be rapidly quenched and hot pressed[56] (known as the MQ3 route). The other forms of rare earth magnet are based on polymer-bonded magnets where Nd-Fe-B powders are mixed with a polymer and pressed into net-shape magnets. The only large-scale manufacturer of magnets in the UK (SG Technologies) is based upon this polymer bonded route[57]. Polymer-bonded magnets are magnetically weaker than the fully dense form as they have a non-magnetic fraction Therefore, they are used in different markets to the fully dense form of material. Where the highest energy density is required (i.e., for high-power motors) then only fully dense materials tend to be used. This includes the drive motors for electric vehicles.

Figure 21: Image of solvent extraction process

BOX OUT
006

Positive and negative environmental impact of rare earths

There has been a lot of publicity about the environmental burden of rare earth production in China[63] and certainly there has been historic concerns about the safety of the separation processes. It is one of the reasons given by China why the industry was brought under state control to clean up these operations. This in part led to the introduction of export quotas around 2005-2012 The export quotas were subsequently removed after the US, Europe and Japan took China to the World Trade Organisation in 2012. The satellite image in figure 22 – shows the largest rare earth mine in the world at Bayan Obo. Next to the mine, the tailings lakes can be observed where the effluent from the leaching processes are poured onto the land. It should be noted that this one mine produces over 40% of the world's supply of rare earth materials. The ion adsorption deposit mines in southern China that produce almost all of the world's heavy rare earths as well as light rare earths also have a very poor environmental record. The Rare earth Industry Association (REIA) based in Belgium is developing standard procedures for life-cycle assessments to compare the environmental footprint of rare earth mines. Lynas Rare earths, the main provider outside of China set store by their responsible sourcing standards.

The negative impact of the materials production is far outweighed by the positive impact that rare earth magnets have on the efficiency of electrical machines. However, this does not mean that the international community should not push to limit the environmental impacts of rare earth production and technology-critical metals production, generally. Generally, a permanent-magnet motor or generator will be more efficient than an induction machine (which does not contain rare earth magnets). This is because electricity does not need to be passed through the material to generate magnetic flux. Typically the efficiency gain has been reported to be around 5% although this is very dependent upon the type and size of machine and its drive cycle. If rare earth magnets are not used in generators and motors then the impact on global CO_2 emissions would be enormous. This will be exacerbated by the growth of electrical machine use over the next 20 years. If the motor was being used in an electric vehicle the drop in efficiency would also have an impact on the size of the battery and therefore the amount of cobalt, lithium and nickel that would be required for the same range.

Figure 22: NASA image of the tailings ponds outside of the largest rare earth mine in Inner Mongolia.

Rare earth deposits have diverse geology and this gives a range of production routes and environmental characteristics. The mineralogy of the deposit is more important than the grade (i.e. how rich the deposit is in rare earths) in determining which deposits might be economic to mine, and also their environmental characteristics. Figure 23 shows a comparison of several types of rare earth ores and their characteristics. This kind of qualitative comparison can be quantified using a life-cycle assessment[64].

Most rare earths are produced from either carbonatite-related deposits (e.g. Bayan Obo and Maoniuping China, Mountain Pass USA, Mt Weld Australia) or ion adsorption clay deposits in southern China and Myanmar. Monazite is mined currently as a by-product of mineral sand deposits in India, Madagascar and Australia and this amount could be increased from other deposits around the world. The problem is that mineral sand monazite typically contains 2-10 wt% thorium as well as rare earths. This makes the concentrate radioactive and produces a radioactive waste. Given transport and processing regulations and public concern regarding radioactivity, most mineral sand monazite has been avoided, although interest has risen again recently. A new use for thorium, in nuclear reactors, for example, would be a 'game changer' in making mineral sands more favourable as sources of rare earths.

Ore type	Energy for crushing and grinding	Grain size/ Difficulty of beneficiation	Chemicals (acid, flotation reagent)	Radioactivity: ore mineral and host rock	Amount of rock to be moved*	By-products
Carbonatite	Medium - High	Variable - 10 µm	Flotation - medium	Medium	Low	Not usually
Weathered carbonatite	Medium	10 µm and finer	Flotation - medium	Low-med.	Low	Not usually
Alkaline rock	High	Variable - 1 µm and larger	Variable	Variable	High	Co-products common
Ion adsorption clay (in-situ leaching)	None	Beneficiation not needed	Leaching, so can be high	Low	Low	None
Mineral sand (placer)	None - Low	10 – 100 µm	Low	High	High	from TiO2, zircon etc production
By-product of igneous apatite	High	100 µm-mm	Medium	Low	High	from fertiliser manufacture
Red mud	Bauxite processing	n/a REE from red mud	Medium?	Low	High	from Al production

Figure 23: Examples of rare earth element deposits and qualitative analysis of their mining and processing characteristics. Characteristics shaded yellow are generally advantageous to responsible sourcing, grey are less so and unshaded cells are less favourable. From Wall, F., Rollat, A. Pell, R.S.(2017)[64].

Figure 24: Image of tailings pond at Bayan Obo .

ADVANCES IN MANUFACTURING AND SUBSTITUTION OF RARE EARTHS IN MAGNETS

Over the last twenty years there have been multiple attempts to find substitutes for Nd-Fe-B magnets which contain more earth abundant elements through major programmes in the EU, Japan and US[1,2,3]. To date a competitive material has not been found. This is not to say that a substitute material will never be discovered, but this should not be a policy decision in isolation, as the rare earths have very unique properties which are difficult to replicate using other elements.

Figure 25: Sintering of Nd-Fe-B magnets

Where there has been significant development is around the processing and recycling of Nd-Fe-B magnets (the latter is covered in the secondary section). For example, it has been shown that it is possible to substitute cerium for Nd in some forms of Nd-Fe-B magnets up to around 40%, thereby using up some of the cheaper, more abundant rare earths[54]. Also, by controlling the processing and subsequent microstructure, manufacturers have also reduced the content of heavy rare earths in magnets (which are added to improve temperature stability). This is particularly important for high speed automotive magnets, which can contain up to 8% Dy[65]. Dysprosium is typically ten times the price of neodymium[66].

There are multiple activities investigating new process routes to produce Nd-Fe-B magnets to lower the cost, increase safety, improve magnetic, corrosion and mechanical behaviour and to reduce losses during manufacture. At present the main magnet manufacturing route relies on pressing and sintering of fine powders, which are pyrophoric, and therefore burn in air, and as a consequence all the processing needs to be carried out in inert atmospheres, which increases the cost. After processing, the machining losses to cut the magnets to size can be anywhere from 20-60% depending upon size and shape[67].

There is certainly scope for UK investment into the manufacturing processes for rare earth magnets. There is now investment being put into this sector at high technology-readiness level (TRL 5-9) through the Advanced Propulsion Centre and Driving the Electric Revolution[9]. While this is important and these projects will help build up the supply chains in the UK, there is also an urgent need to invest at lower TRL levels. There are internationally leading research groups in the UK working on modelling, materials synthesis and processing of rare earth magnets, but the funding for these projects has almost exclusively been from outside of the UK

BOX OUT 007

Chinese dominance of the market

There are multiple factors which have resulted in China dominating the rare earth market. Firstly, the state has invested heavily for over 25 years in the extraction and processing of ores, alloys and magnets. The Chinese premier famously stated that while the Middle East has oil, China has rare earths[68]. Since that time, the Chinese have gradually moved up the value chain from processing of ores, to alloys, magnets and components. This has given China a strategic advantage in the downstream product markets. The largest rare earth mine in Inner Mongolia (Bayan Obo) is actually an iron-ore mine with the rare earths being produced as a by-product. This factor, accompanied by relatively cheap labour and state intervention, has meant that the rare earth alloys can be produced at a lower cost than in other regions of the world. The historically lower environmental and safety standards have also allowed China to reduce costs compared to heavily permitted mining and separation plants elsewhere in the world. Local incentives are in place in China, which subsidise the production of magnets. Western producers also have to compete with an internal VAT charge that has been implemented on rare earths alloys. It is possible to claim this 13% levy on magnets, but not on rare earth elements or alloys, which immediately puts western producers at a disadvantage. For all of these reasons, the western producers of sintered Nd-Fe-B magnets sell at the top end of the market and often not into the bulk automotive or wind-turbine markets. This makes some of our largest industries vulnerable to near-total reliance on imports from China.

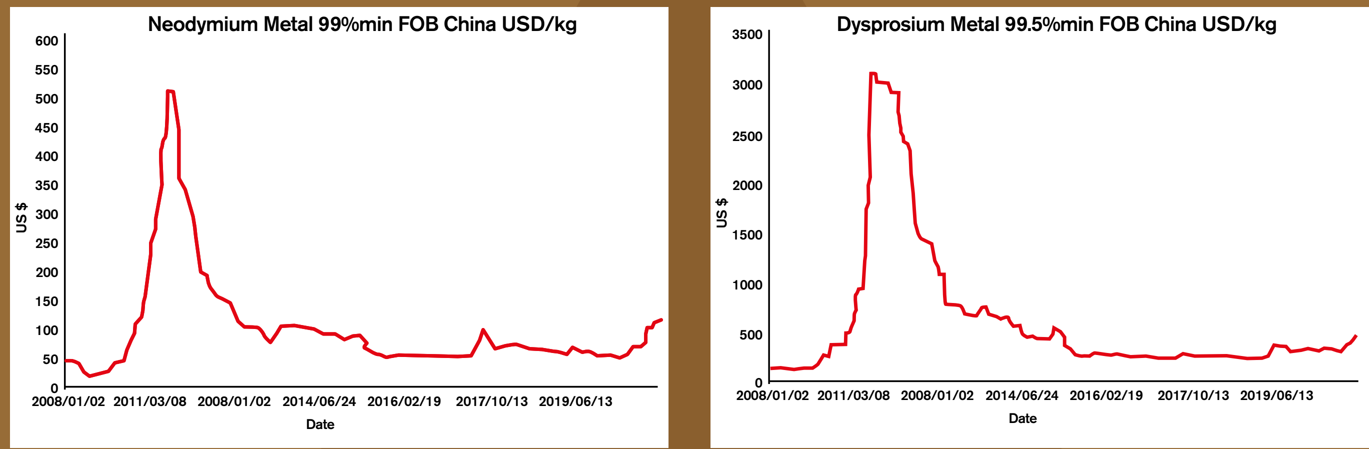


Figure 26: Prices for neodymium and dysprosium metals through time

The rare earth elements are traded on private contracts that remain confidential to the buyers and sellers. Prices quoted as market prices are derived from journalistic reports from such subscription sites as Shanghai Metals Market (www.metal.com) or Asian Metal (www.asianmetal.com). There is no public pricing mechanism that provides transparent pricing for the global metals market, as exists for dominant commodity metals (such as aluminium, copper, lead, tin, nickel, tin, and zinc) provided by the London Metal Exchange.

The prices quoted for rare earth metals and oxides may not represent the true prices paid by consumers of the materials. Prices quoted are normally in both local RMB/kg and as US$/kg (FOB – "free-on-board" delivery terms); pricing includes 13% VAT which is imposed on exports but is reclaimable locally in China (see figure 25). At this time (February 2021), Nd pricing for 99% to 99.9% pure metals is standing at RMB710/kg (or US$109/kg FOB China). Specifications for the materials are not standardised; though standardisation is under development in an international standard ISO (technical committee TC298) which has been recently joined by the British Standards Institute (BSI).

UK SUPPLY CHAIN

The UK has significant parts of the value chain for rare earth magnets. Several companies, including Mkango Resources and Pensana Rare Earths are developing rare earth deposits overseas and have potential for connection via rare earth refining to the UK value chain. Less Common Metals Ltd (see figure 27)[69] is the only company that can produce rare earth metals and alloys in Europe for the magnet market (based in Ellesmere Port) and one of the largest producers of polymer-bonded magnets in Europe (SG Technologies)[70] is based in Rainham, making a wide range of magnetic materials and components for the automotive industry. Beyond magnet production, there are a number of companies that distribute rare earth magnets, and that machine and assemble these into components, including for example, Bunting, Eclipse Magnetics and Arnold Magnetic Technologies. This then branches out into a very large number of industries and companies that will be purchasing rare earth magnets, mainly from China.

Figure 27: Less Common Metals Limited

The UK has supply-chain gaps in the chemical processing of rare earth ores to liberate separated oxides and there is no large-scale producer of fully-dense magnets (either sintered or hot pressed). However a start up company based in Birmingham (Hypromag)[71], is aiming to produce sintered magnets in the UK from recycled feedstocks (covered in the secondary section of the report). There are also start up companies that are proposing to build chemical processing facilities in the UK to convert ores to separated oxides and metals (Peak Resources, Pensana and Seren)[72,73,74].

Ultimately all the parts of this supply chain have to compete against a state-sponsored industry in China, which has made significant interventions in the market over many years.

BUILDING UP THE UK SUPPLY CHAIN.

There will be a requirement for more rare earth mines to open in the future, especially to meet demand for Nd and Pr for electric vehicle drive motors and offshore wind turbines. There is certainly scope for increased production, given the number of rare earth deposits around the globe. However there are technical, economic and geopolitical factors that need to be addressed to accelerate this. The supply of REE as by-products of other ores is attractive as a means to diversify supply and should be explored. The rare earth market value is not large and low capital operations are likely to be the ones to come on stream.

The UK should be assessing viable projects globally and securing access to ores or oxides for the downstream market. Ultimately, there is no point in accessing the ores without the downstream refining into oxides, which could be carried out abroad or in the UK. Beyond that stage, Less Common Metals has pilot facilities for producing rare earth metals (which should be expanded) and they have large-scale capacity from producing strip-cast alloys. Although the UK has a large-scale manufacturer of polymer-bonded magnets in SG Technologies it requires a fully dense magnet producer which would service the car industry for electric drives. LCM is currently working on a feasibility study with the Automotive Transformation Fund, looking at how a magnets supply chain could be developed in the UK. The UK should be working in partnership with other regions of the globe, particularly with Japan who have been at the forefront of novel magnet manufacturing, which has given it's companies a competitive advantage.

Most of the fully dense magnets made outside of China are made in Japan.

CASE STUDY: LITHIUM-ION BATTERIES

In 2019 the Nobel Prize in Chemistry was awarded to John B. Goodenough, M. Stanley Whittingham, and Akira Yoshino for their groundbreaking work leading to the lithium-ion battery as we know it today, which has already had a profound impact on modern society[75].

The oil crisis of the 1970s encouraged Goodenough, then working for Exxon, to investigate the batteries[76]. The batteries he developed led to electrification of many applications that were previously reliant on energy-dense hydrocarbon fuels. Akira Yoshino replaced the lithium anode with carbon[76], which led to safer, more practical cells. The present challenge is to scale up lithium-ion battery production and its complete supply chain to meet the demand of the automotive and other sectors. The next challenge is to develop and bring to market batteries that are cheaper, safer, longer-lasting, and with higher energy densities[76]. Work also continues apace to develop new battery technologies that are not reliant on technology-critical metals, substituting more problematic elements with those that are easier to source. The scale of this challenge is captured well in the Automotive Council Electrical Energy Storage roadmaps[77].

What is a Lithium-Ion Battery?

Lithium-ion batteries are a type of rechargeable battery that improves significantly upon previous technologies in a number of key areas. Lithium-ion battery is a common name for a large variety of battery types, not only in the shape and packaging of cells, but also in the chemistries contained within the battery. In particular, there are many different formulations of cathode material, each with different attributes. They have a relatively high power and energy density, making them useful for applications ranging from mobile phones to vehicles and grid storage. The batteries consist of individual cells. As a single unit, a cell performs functions of a rechargeable battery and the cells come in a variety of different types. A module is formed by connecting multiple cells, providing them with a mechanical support structure, a thermal interface and the attaching terminals. The modules are designed according to the cell format, the target pack voltage and the requirements of the application. A pack is formed by connecting multiple modules with sensors and a controller and then housing the unit in a case. Electric vehicles, for example, are equipped with batteries in a pack format. The packs are connected to the powertrain.

Compared to conventional batteries, lithium-ion batteries have different chemistries and constructions. Unlike lead-acid car batteries, which are easy to recycle, containing the lead and acid in a plastic housing, lithium-ion batteries are much more complicated in their assembly. This makes manufacturing more challenging and end-of-life recycling difficult in comparison to lead-acid batteries.

The main types are lithium cobalt oxide (LCO), nickel manganese cobalt (NMC), lithium nickel cobalt aluminium (NCA), lithium iron phosphate (LFP), lithium manganese oxide (LMO) (see figure 28).

Different chemistries are used for different applications because of their inherent performance characteristics, properties and cost curves. It is expected that automotive and grid storage applications will be dominated by the NCA, NMC and LFP chemistries.

Over time, it is projected that high nickel content lithium nickel manganese cobalt oxide (NMC) cathodes. [NMC-High] cells will occupy a sizeable proportion of the market for lithium-ion batteries. NMC cathodes have a lower cobalt content (less than 20%) that some other designs of cell, whilst offering many performance benefits. Cobalt makes batteries expensive, because of complex supply chains and constrained supply. Work is underway to try and reduce the cobalt content of batteries. There are cells such as LMO and LFP cells which do not require cobalt - however, the trade off is that these cells have lower energy density, and so lower performance. The projected changes in market share for different chemistries is illustrated in Figure 28 below.

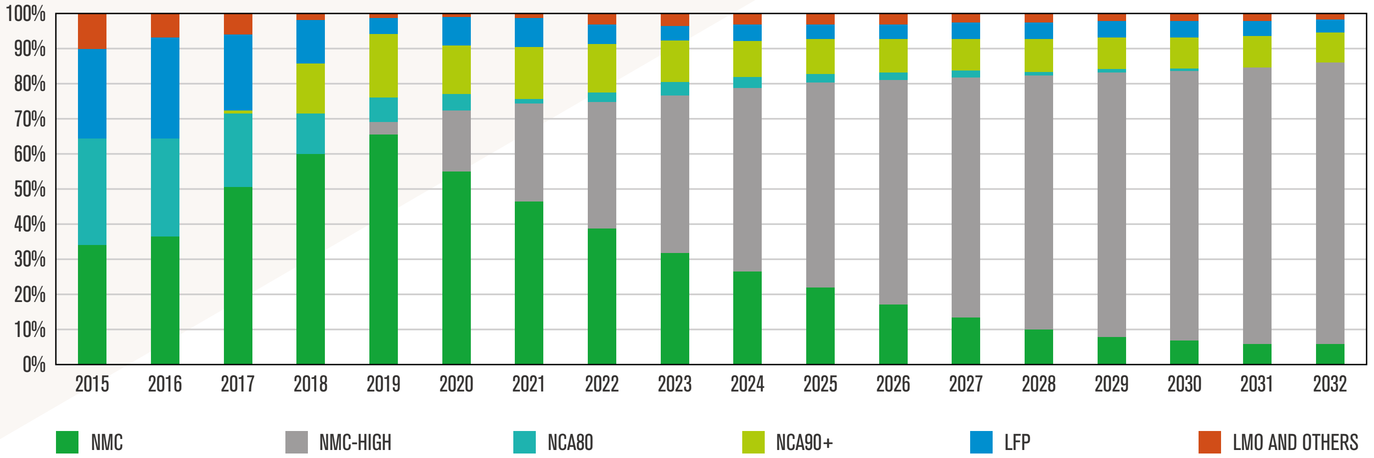


Figure 28: Long term battery technology trends. Courtesy of the APC / IHS Markit, 2021.

LITHIUM-ION BATTERY APPLICATIONS

There are a wide range of applications for lithium-ion batteries. Anywhere portable electrical power is required, lithium-ion batteries provide the lightest, densest source of rechargeable electrical power. What differs dramatically among these applications is the scale on which they employ batteries, while the capacity of mobile phone batteries in watt-hours may be in the single digits, with a small number of cells, electric vehicles will have battery capacities that are several orders or magnitude larger. To add further contrast, enormous grid batteries require an enormous quantity of batteries, e.g. the Hornsdale Power Reserve in Australia, with a capacity of 194 MWh (see figure 29). Although the number of batteries used in an application varies dramatically by several orders of magnitude, so do the quantities sold to the market of the products that contain them. In a future energy scenario, a nation might only have a handful of batteries of the scale of Hornsdale Power reserve, while millions of vehicles will be sold, and likely even greater quantities of applications such as portable electronic devices.

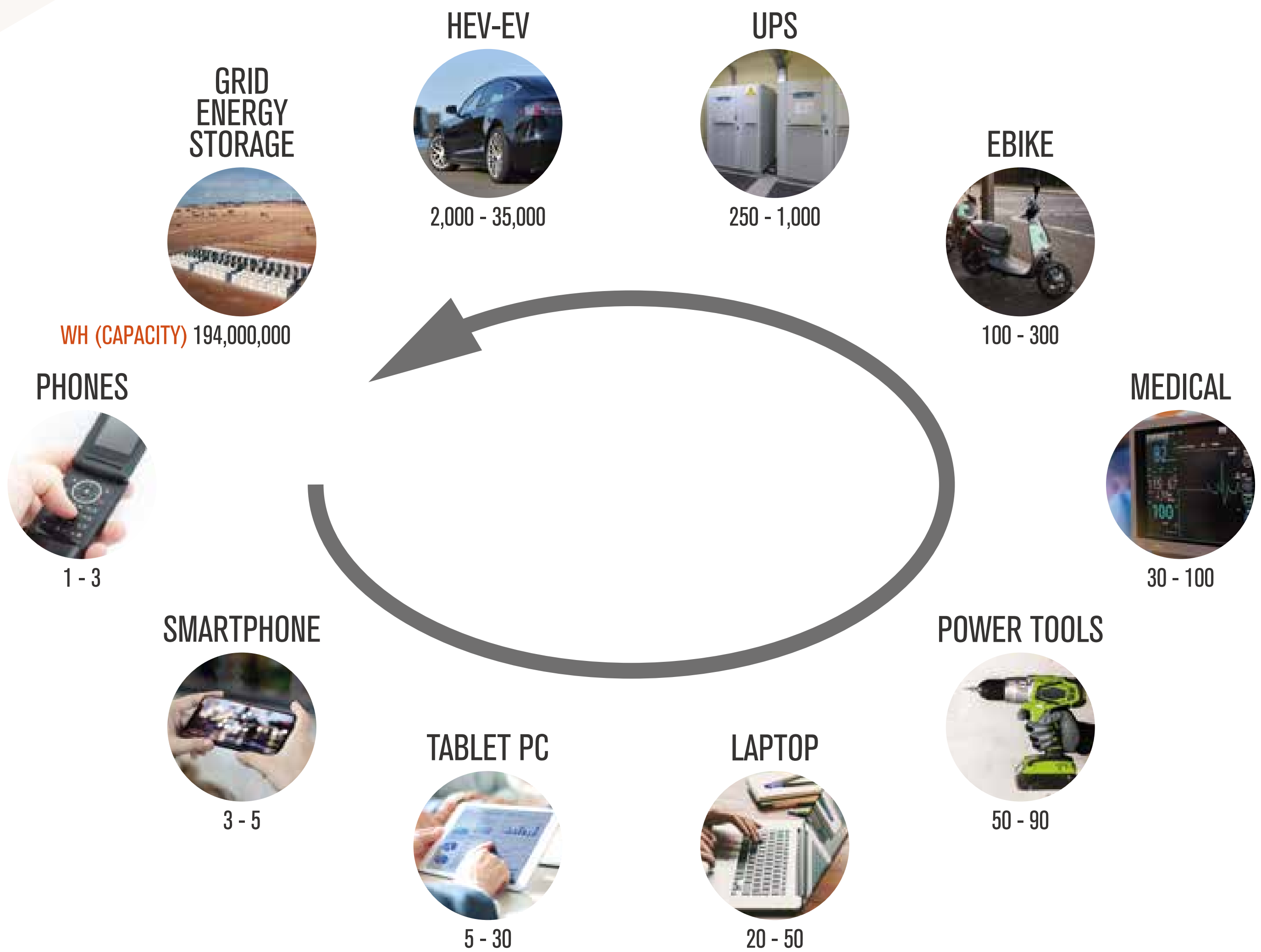


Figure 29: Approximate size of lithium-ion battery applications in Wh [78,79].

LITHIUM-ION BATTERIES: DEMAND GROWTH

Global demand for batteries in all applications is rapidly expanding. The automotive sector, in particular light duty vehicle applications, accounts for most of the current demand for batteries.

Figure 30: One type of Lithium-ion battery, the pouch cell, used in automotive applications. In the section on secondary materials, Figure 112, there is some additional explanation of different automotive battery form factors.

The market for lithium-ion batteries is forecast to register a compound annual growth rate of over 16% from 2020 to 2027. This rapid increase in use will be driven by laptops, PCs, smartphones, and above all, electric vehicles. The market for lithium-ion batteries also includes medical, marine, commercial aircraft, aerospace, and defence (see figures 30-33).

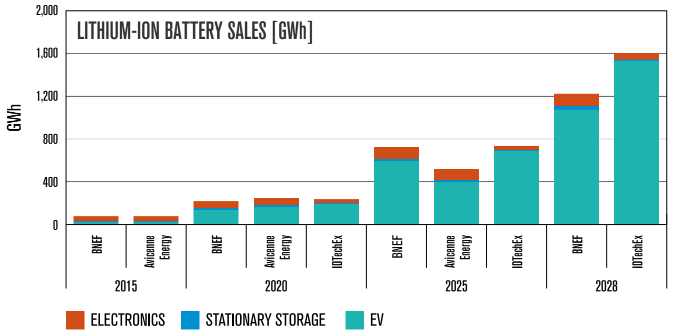


Figure 32: Lithium-ion battery sales[81]

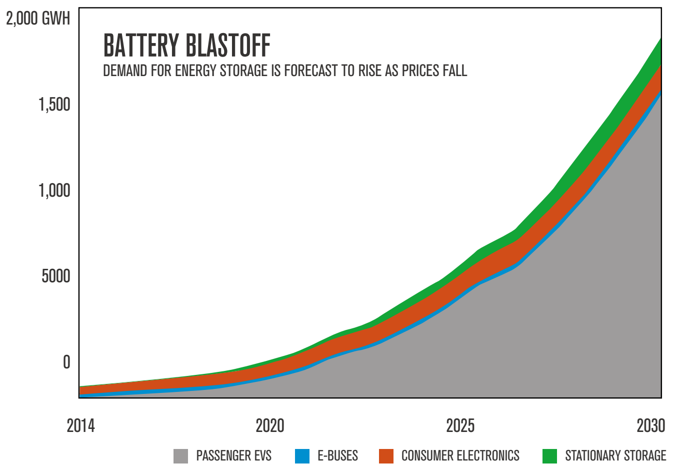


Figure 31: Demand growth for lithium-ion batteries[80]

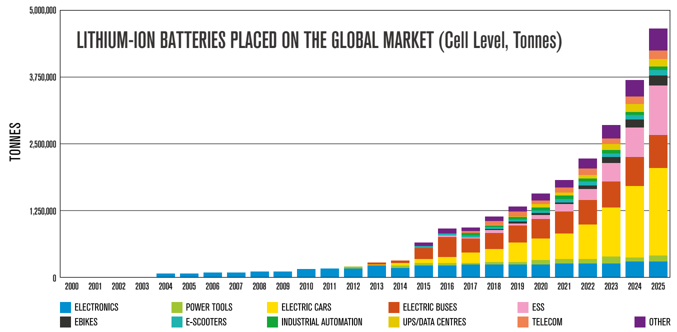


Figure 33: Lithium-ion battery placed on the global market[81]

The growth in the number of EVs is expected to disrupt significantly the market for technology metals in the coming years. Emerging economies like India and China are seeing soaring sales of consumer electronics and a rapidly expanding middle class with the expectations of more affluent lifestyles, which is driving demand in these markets for EVs.

Lithium-ion batteries are becoming pervasive in energy storage due to their high power and energy density[82]. The technology is undoubtedly a core component in our transition to a clean energy future, enabling green electricity to serve as an energy vector in many applications that previously required energy-dense hydrocarbon fuels.

Whilst historically lithium-ion batteries enabled more sophisticated portable electronics, the transition to electro-mobility is the main source of present and anticipated market growth for lithium-ion cells. This is understandable, given the large number of cells required to deliver the range consumers demand from electric vehicles.

Future energy systems that integrate storage, smoothing peaks and demands, providing backup power, stabilisation of weak-grids and off-grid power[83,84], will also be a significant market, albeit smaller than the use in portable electronics and EVs. Lithium-ion batteries will also be important to global clean energy development, bringing clean power and access to energy to developing countries in places where there is limited or no access to the grid[85].

The uptake is driven by a combination of rapidly falling battery prices, to the point where they are nearly cost competitive with conventional technology in key regions, and the need for automotive companies to meet various international and national CO_2 and other emission targets.

Estimates differ between different forecasters about the projected market growth for lithium-ion batteries, and the evolution of chemistries that will be manufactured in the future. However, there is a consensus that growth in the market for lithium-ion batteries in the coming years will be dramatic. This is illustrated in figure 34 which shows the market share of different types of vehicles containing lithium-ion batteries in the coming years. It is projected that the market share of pure battery electric vehicles will grow rapidly. Additionally, as we approach the 2030 deadline for the phase out of conventional vehicles, there will be growth in various degrees of hybridisation in vehicle powertrains. These hybrid vehicles will also use lithium-ion batteries. In Europe and China this is a pressing issue with automakers. Car manufacturers are expected to have 72% of all vehicles partially electrified, and 26% of these plug-in or pure EVs by 2025, with the trend accelerating until 2030.

In the UK, the Faraday Institution estimates that by 2040, eight gigafactories will be needed in the UK.[12,13] It projects that this could increase employment in the automotive industry and battery supply-chain from 186,000 to 246,000 jobs[4]. By way of contrast, if the UK cannot attract and develop a battery-manufacturing industry, there are significant risks[14]. The production of EVs could move offshore, attracted to locations where batteries are manufactured. UK jobs in the automotive industry and battery supply-chain could decline, with the potential loss of 114,000 jobs by 2040 according to the Faraday Institution (2019)[4].

Lithium-ion batteries are increasingly constructed using many highly refined materials, which are in turn made from semi-refined raw materials that ultimately need to be mined or recovered from end-of-life waste streams.

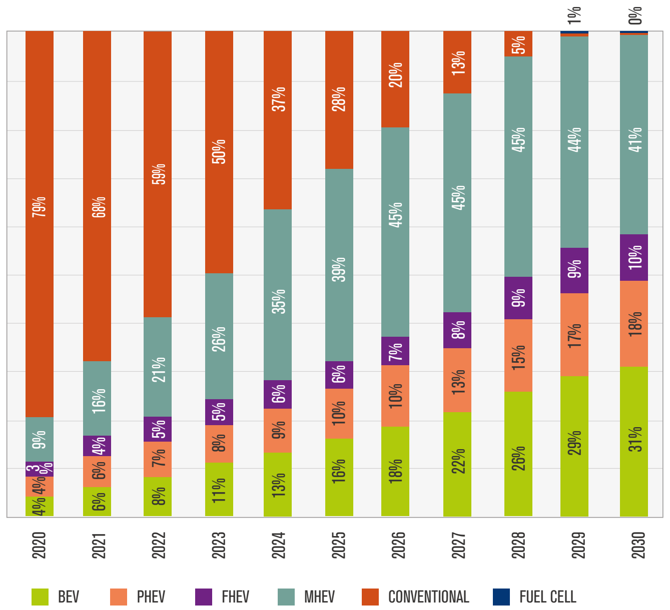


Figure 34: Future global sales of main lithium-ion battery market segments. Source: APC Demand Databases using IHS AutoTechInsight data (December, 2020) NB: Passenger cars only, excludes LCVs.

SUPPLY AND VALUE CHAIN FOR BATTERY MATERIALS CONTINUED

It matters that the supply and value chains for electric vehicles are complex, because the battery makes up more than 25% of the value of an electric car. This is more than for conventional powertrains. However, the value of the battery lies further upstream in the supply chain with over 60% of it embodied in the highly refined chemicals that make up the battery cell. The UK must devise ways to capture this value (see figure 35).

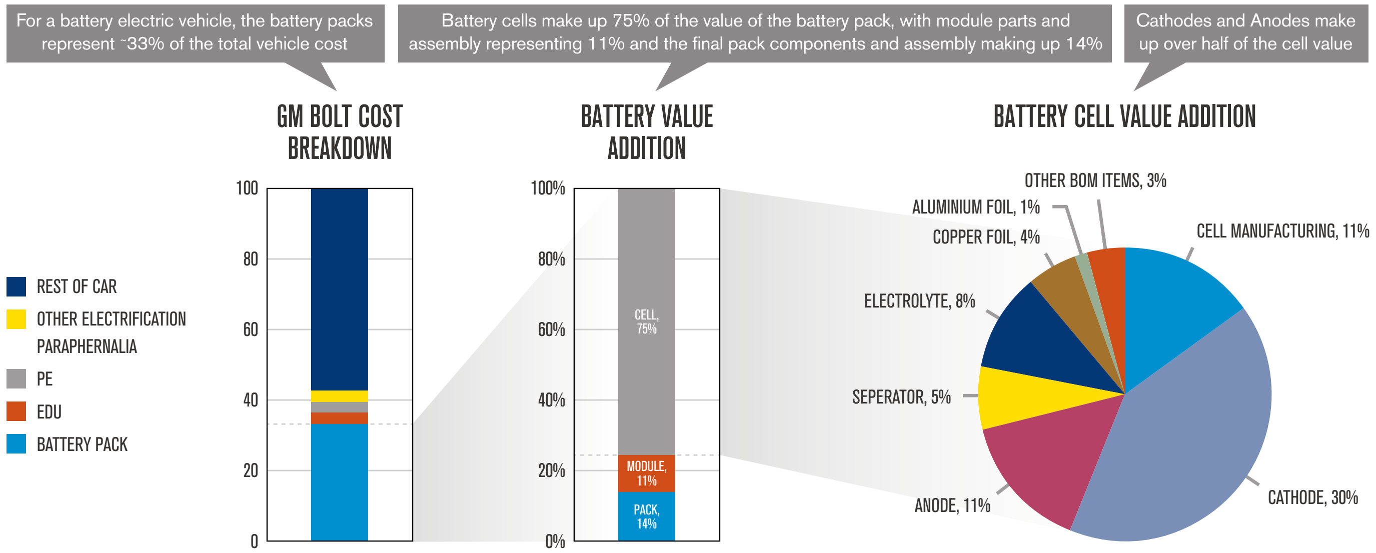


Figure 35: GM bolt cost breakdown in 2025. Source: The Advanced Propulsion Centre UK Ltd.

1 Cell and pack production
A large number of cell production facilities (giga-factory) will need to be built with a capital investment of around £1bn per GWh. (See the boxout on the global race to build gigafactories)

2 Key battery cell commodities
Battery commodity (cathode, anode, electrolyte, etc) production capacity needs to be built in Europe. APC estimates suggest that there are very sizeable gaps in capacity across the 6 main commodities, as shown in the table below

3 Refining of raw materials
Nickel, cobalt, lithium for cathodes and natural and synthetic graphite for anodes, along with aluminium and copper for current collectors are needed in large quantities and to exacting specifications.

In 2025 the demand for the batteries needed for passenger cars and vans is expected to exceed 787 GWh globally and 249 GWh in Europe. To put this in perspective, all the European Nissan Leaf and e-NV200 batteries are produced in Sunderland with a maximum capacity of less than 2GWh.

Considering this demand, one can work out the total demand for these commodities throughout the supply-chain. Assuming that most vehicle batteries will contain high nickel NMC, NCA, or the newer lithium nickel oxide (LNO) cathode materials variety, the APC forecasts the following demand for battery materials:

WORLD	EV Production (millions)	Battery Demand	Pack Value	Cell Value	CATHODE						ANODE (Graphite)			
					NMC811		Nickel	Manganese	Cobalt	Lithium	Anode Active Material		Synthetic	Natural
ALL	#	GWh	$ billion	$ billion	kTonne	$mil	kTonne	kTonne	kTonne	kTonne	kTonne	$mil	kTonne	kTonne
2020	9.6	160	21.9	16.4	225.7	6,777	120	14.0	15.0	17.7	191.4	2,500	127.6	63.8
2025	41.3	787	76.4	57.3	1,114.2	23,690	591	69.3	74.0	87.4	944.9	8,740	630.0	315.0
2030	71.1	1,349	103.9	77.9	1,908.6	32,212	1,012	118.7	126.8	149.7	1,618.6	11,884	1,079.1	539.5

EUROPE	EV Production	Battery Demand	Pack Value	Cell Value	CATHODE						ANODE (Graphite)			
					NMC811		Nickel	Manganese	Cobalt	Lithium	Anode Active Material		Synthetic	Natural
ALL	#	GWh	$ billion	$ billion	kTonne	$mil	kTonne	kTonne	kTonne	kTonne	kTonne	$mil	kTonne	kTonne
2020	3.0	50	6.8	5.1	70.3	2,112	37	4.4	4.7	5.5	59.7	779	39.8	19.9
2025	13.9	249	24.2	18.1	352.7	7,499	187	21.9	23.4	27.7	299.1	2,767	199.4	99.7
2030	18.6	439	33.8	25.4	621.5	10,489	329	38.7	41.3	48.8	527.1	3,870	351.4	175.7

Figure 36: Demand for battery materials. Source: IHS, The Advanced Propulsion Centre UK Ltd.

Electric vehicles make up the lion's share of this demand as shown in figure 36. This very significant demand for batteries both globally and in Europe means that the entire supply chain needs to scale up at the same time. Even if the overall scale is manageable, the speed at which this is happening is completely unprecedented. To illustrate this, in 2012 Nissan (now Envision AESC) built the first battery plant with a nominal capacity of 2GWh. It remained the largest battery plant in Europe until 2019. By 2025 Europe needs around 249GWh capacity, growing to a conservative estimate by the APC of 439GWh by 2030.

At this scale it is best to consider the market on a European basis, as in most cases it does not make commercial sense to ship batteries and their (semi) processed materials around the world in the volumes that are required. Secondly, and more pertinently, the UK-EU Trade and Cooperation Agreement (TCA) stipulates that the battery and most of its components need to be made locally from 2024 (see figure 37 for an overview). If not, the vehicle will attract a 10% tariff when exported from the EU to the UK or vice versa. Since around 80% of the vehicles made in the UK are exported to the EU, and 80% of the vehicles on Britain's roads are imported from the EU, the trade rules summarised below will need to be met.

These components include cathode active materials, anode active materials and electrolyte which in turn contain nickel, cobalt, manganese, lithium, natural and synthetic graphite. The estimated the demand for these materials is shown in figure 36. It is worth noting that these are highly refined, battery grade materials that make up most of the value of the battery as shown in figure 35. The refining process from the ore that is mined to the battery grade materials required by industry is complex, expensive, energy intensive and most important takes time and a vast investment to build.

This refining capacity will be the main bottleneck for the next 10 years especially in Europe, where hardly any of the required supply chain exists and secondly where rules stipulate local supply. To illustrate this, analysis by the Advanced Propulsion Centre suggests that in 2025 we could see capacity shortages of around 50% for cathode active materials, 80% for anode materials and 40% for electrolyte materials. This expected capacity shortfall in highly refined nickel, cobalt, manganese, lithium and graphite refers to Europe, and globally is even more significant as shown later in this report. For some of these materials such as nickel a substantial structural deficit is expected to arise in the next 3-4 years.

These deficits will need to be resolved by both mining (virgin materials) and an increased level of recycled materials. For both primary and secondary material streams a highly effective refining capability and capacity is required.

What this means for the UK

As discussed earlier, the refining steps for most of the battery materials is where the majority of the value of a battery is added. The focus for the UK should be very much on this area of the supply chain, not only for its own needs but also for export to Europe. Critically cathode active materials need to be made locally by 2024. The local demand for battery grade nickel, lithium and to a lesser extent cobalt and manganese are therefore a given. Focussing on the refining of materials enables recycled battery materials to be fed back into the supply chain, thereby creating a circular economy and easing the structural deficits in the supply of virgin materials.

	1st January 2021 to 31st December 2023	1st January 2024 to 31st December 2026	1st January 2027 onwards
Electric battery cells	70% maximum non-originating material allowance Or Change in tariff heading except from non-originating active cathode	50% maximum non-originating material allowance Or Change in tariff heading except from non-originating active cathode materials	35% maximum non-originating material allowance Or Change in tariff heading except from non-originating active cathode materials
Electric battery packs	70% maximum non-originating material allowance Or Change in tariff sub-heading Or Assembly from non-originating cells or battery modules	40% maximum non-originating material allowance Or Change in tariff heading except from non-originating active cathode materials	30% maximum non-originating material allowance Or Change in tariff heading except from non-originating active cathode materials
Electric vehicles (HEVs, PHEVs, BEVs)	60% maximum non-originating material allowance	55% maximum non-originating material allowance	45% maximum non-originating material allowance + originating battery for PHEVs and BEVs

Figure 37: Rules of origin for batteries and electrified vehicles provide a 6-year phase-in period. Source: BEIS

SUPPLY AND VALUE CHAIN FOR BATTERY MATERIALS

Figure 38 provides a simplified view of the process steps from raw materials to recycled product. The takeaway message is that there are a large number of complex refining and processing stages before the battery cell is made.

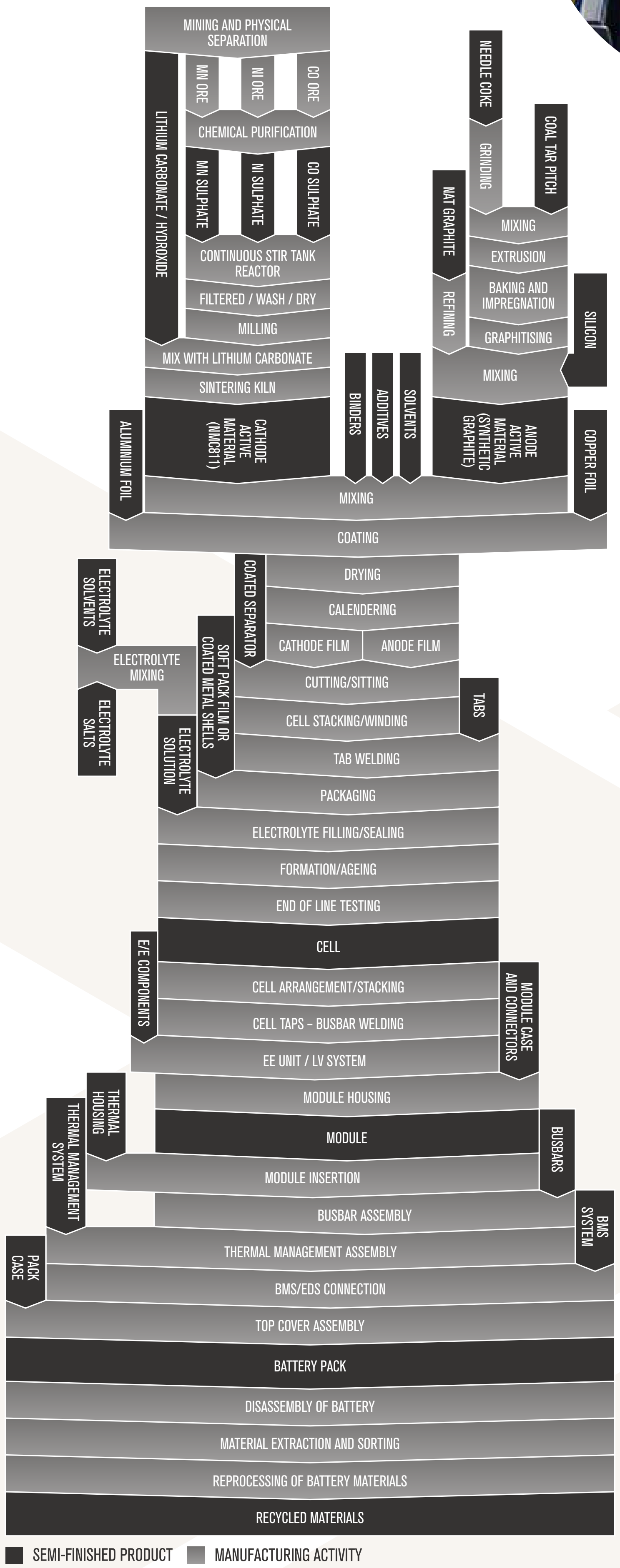


Figure 38: Battery value chain, courtesy of APC.

LITHIUM-ION BATTERY MATERIALS:
COBALT, NICKEL, LITHIUM AND GRAPHITE

Electric vehicles will replace internal combustion engines in most new road vehicles by the 2030s. They will also play a key role in decarbonising our energy systems through stationary battery energy-storage systems. As more intermittent renewables join the electricity grid and displace fossil fuels, batteries will be one of the main energy-storage technologies that helps to balance supply and demand. Their name is misleading, as lithium-ion batteries are complex products containing much more than the element lithium. The most common battery cathodes for electric vehicles (known as NMCs) are made from lithium, nickel, manganese and cobalt, while the anode is usually made from graphite (see figure 39). While manganese is widely available, cobalt and lithium have possible supply-chain problems in terms of availability, ethical mining, geolocation and supply restrictions. Nickel has not previously been considered a problem, however, as new battery chemistries decrease their cobalt content and increase their nickel content, it is increasingly seen as a technology-critical metal which should be carefully monitored. Lithium, cobalt and nickel have many commercial uses outside of the battery sector (see figure 40).

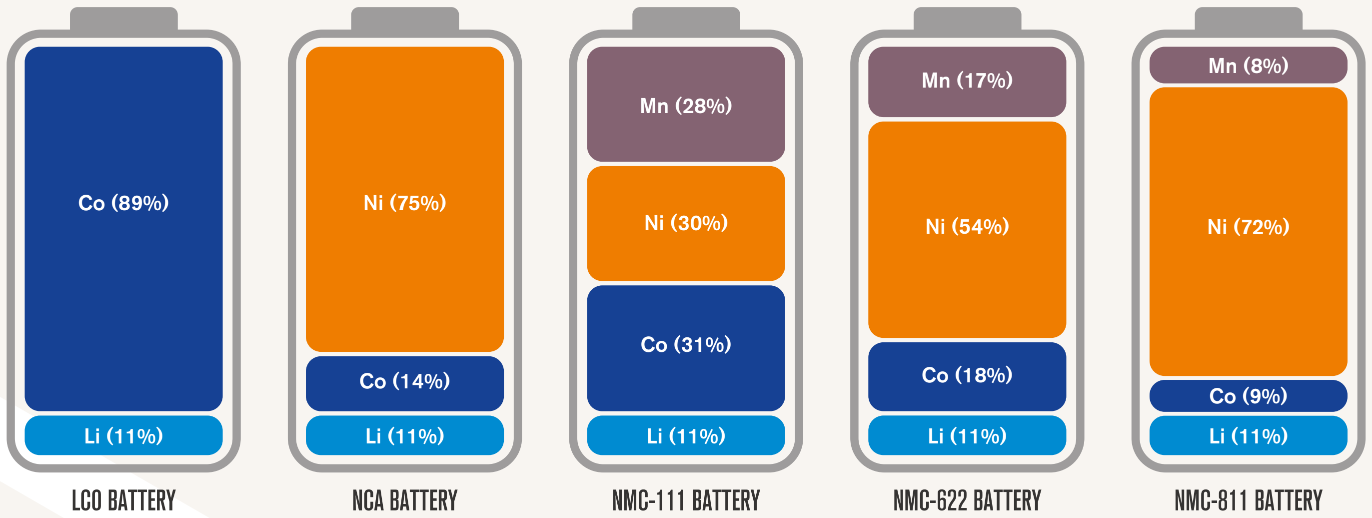


Figure 39: Image Courtesy © BGS / UKRI (2021)

MATERIAL	APPLICATION	COMMENT
LITHIUM	Batteries, Ceramics & Glass, Greases & Lubricants, Continuous Casting, Air Treatment, Polymers, Primary Aluminium Production.	Primary use is now batteries, and this is increasing rapidly. Most of the world's lithium comes from South America, where the lithium is extracted from lithium-containing brine by a process of evaporation. The variety of sources means that lithium is not a technology-critical metal, but China does refine most of the world's lithium.
COBALT	Rechargeable Batteries, Electronics, Catalysts, Magnets, Inks and Pigments, Alloys, Healthcare	Increasing amounts required for batteries. Cobalt is a by-product of copper mining in the Democratic Republic of Congo. Reports of child labour being employed in the DRC has created an interest in responsible sourcing. Cobalt refinement is currently dominated by Chinese companies.
NICKEL	Steels, Coatings, Coinage, Glass, Catalysts, Ceramics, Magnets, Batteries	Traded on the London Metal Exchange (LME), with well-established uses in steels. Batteries will dramatically increase the demand for nickel.
GRAPHITE	Writing Materials, Lubricants, Refractory, Nuclear Reactors, Batteries, Graphene Sheets	Natural graphite is a critical raw material for the UK, with China being the world's largest producer.

Figure 40: Main uses of Co, Ni and graphite

BOX OUT 008

Materials for lithium-ion batteries

Cobalt market balance

Cobalt is produced mostly as a by-product or co-product of copper or nickel mining (see figure 42). The only exceptions to this are mines in Morocco or Canada, where cobalt is extracted from arsenide ores. The supply is, therefore, largely determined by the demand for copper and nickel. The major cobalt-producing region is the Central African Copper Belt, which stretches from the Democratic Republic of Congo (DRC) into Zambia, with the highest grades of cobalt in the DRC. There are also large deposits of cobalt in Australia, Russia, Cuba, New Caledonia and Canada. There is only one mine in the world where cobalt is the main ore, and that is at Bou Azzer in Morocco. Currently, the DRC produces approximately 64 ktonnes of cobalt per year, equal to 63% of the world's output. This figure is set to reach 73% by 2025, if planned expansions are realised (see figure 41). A review of cobalt deposits in Europe identified 509 cobalt-bearing deposits and occurrences in 25 countries, 104 of which, mostly in the Nordic countries, were under exploration. Three mines in Finland produce cobalt. The geological availability of cobalt in Europe is not a problem, but exploration projects have to pass many technical, economic, environmental and social hurdles before they can become commercial.

The deep oceans are also a potential future source of cobalt. Iron- and manganese-rich nodules and crusts contain concentrations of cobalt and nickel that are of economic interest. Consideration of these deposits is still at an early stage, with more work to be done to understand the environmental impacts of deep-sea mining as well as the technical challenges. There is much debate about the pros and cons of extracting material from the ocean floor. Many countries, including the UK, have exploration licences but no mining operations have started yet. Several companies have equipment ready to deploy if licences are granted. Mining is regulated by the International Seabed Authority and revenues are required to be used for the benefit of humankind.

Cobalt has many unique properties, leading to its key roles in rechargeable batteries, electronics, catalysts, aerospace alloys and healthcare. Cobalt is also the major component in Sm-Co permanent magnets, which are used in many aerospace applications where temperature-critical performance is demanded. Several cobalt-based materials can be used as catalysts for oxidation reactions and as pigments to give a blue colour to glass and ceramics.

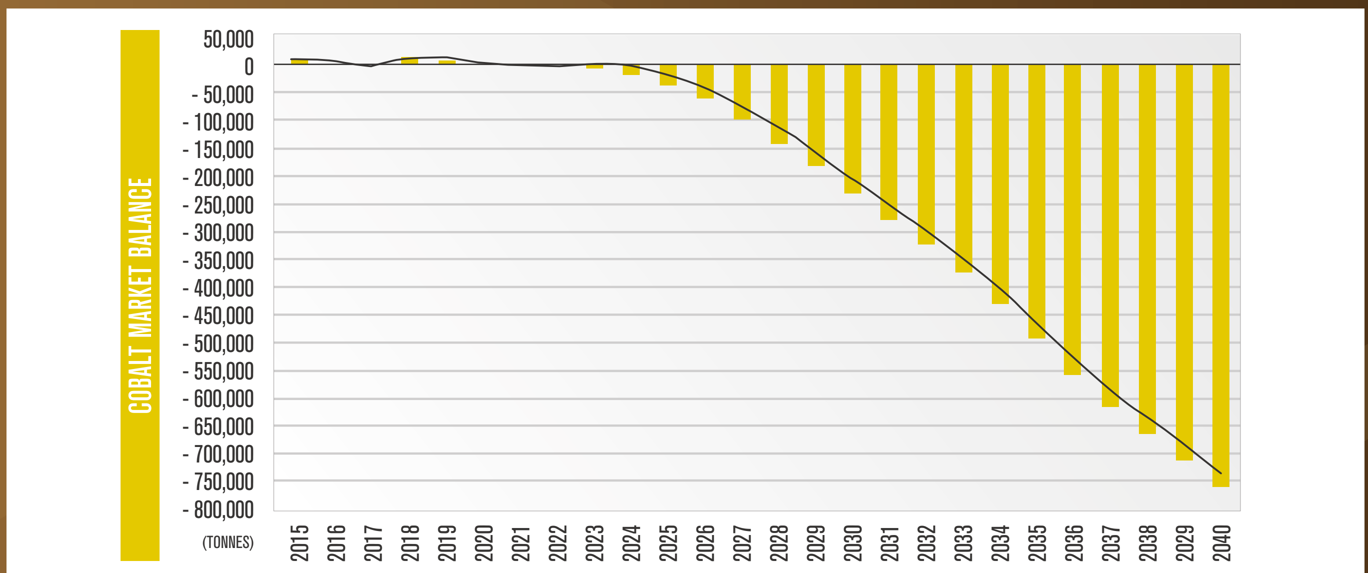


Figure 41: Cobalt market balance.

Source: Created from data from benchmark mineral intelligence

Figure 42: Aerial view of the enormous copper mine at Palabora, South Africa

Cobalt price history

Cobalt is traded on the London Metal Exchange. Major EV/HEV battery makers have been contracting with cobalt producers in order to protect supply, but these are considered to be on a market-price-index basis. One strategy available to OEMs to protect against market volatility would be to contract with cobalt producers at a fixed price over the medium term (see figure 43).

However, where cobalt is produced is only part of the story. Significant value is added at locations where the cobalt is refined (see figures 44/45). Here, China has captured a considerable part of the market, vertically integrating large parts of the supply chain for battery materials. Whilst we cannot choose where primary materials are located, processing capacity is something that could be built in the UK. In particular, there could be future synergies around raw materials from primary sources and secondary supplies (covered in the next section). Here, Umicore in Belgium provides an example worthy of consideration.

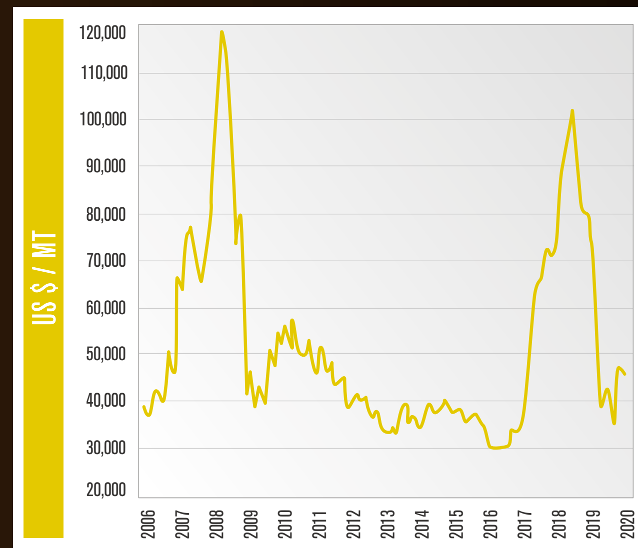


Figure 43: Cobalt price history

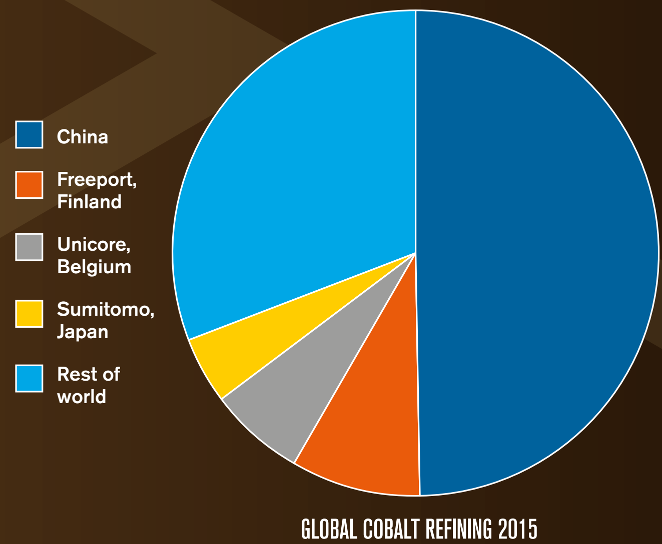


Figure 44: Global cobalt refining [86].

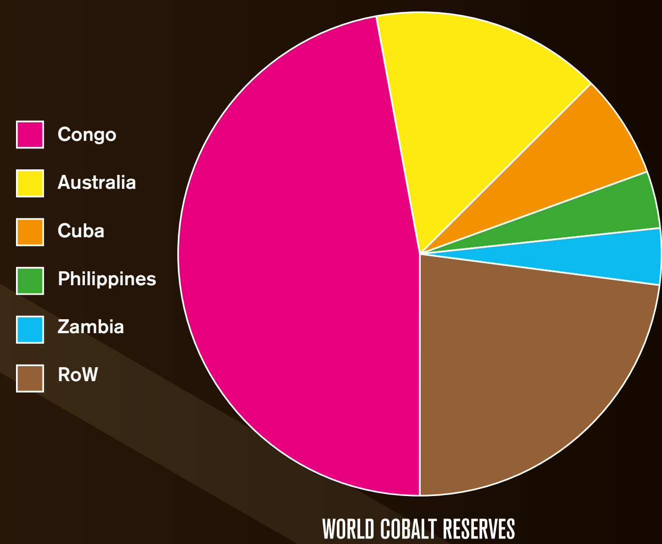


Figure 45: World Cobalt Reserves [87].

BOX OUT 009

Materials for lithium-ion batteries

58.693
[Ar]3d⁸4s²
28
Ni
Melting point: 1455°C
Boiling point: 2913°C
NICKEL

Nickel

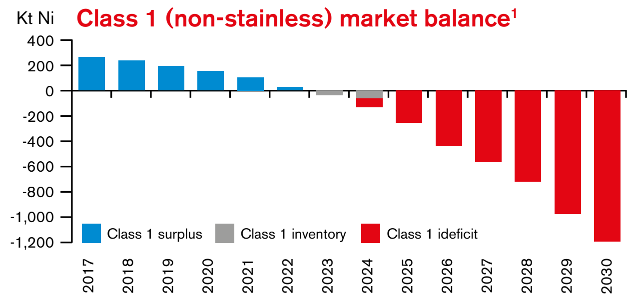
Nickel is much more widely produced than cobalt, with more than 2.3 m tonnes being mined every year. There is availability of nickel and technologies to extract it that are well known.

Capital costs are high and development cycles are long. The nickel industry will need to invest up to US$ 70 billion by 2030.Currently, prices are not reflecting the need to grow nickel mining to such an extent Indonesia is the largest supplier, with just over half a million tonnes being mined in 2019. Other countries that produce large quantities of nickel include the Philippines, Russia, New Caledonia, Australia and Canada. Nickel has two main types of ore, (nickel sulphides and nickel laterites). Nickel sulphides are formed in magmatic rocks (including meteorite impact) and are mined underground or in open pits and then usually smelted. Bioleaching is carried out on some low-grade ores. Nickel laterites, that now account for about 60% of nickel production, are formed by tropical weathering of nickel sulphides and silicates. They are extracted in open cast mines (see figures 54,55) and then subject to hydrometallurgy (chemical treatment) to produce nickel. Cobalt is a co-product of some nickel laterite operations.

Of the Nickel produced annually, roughly half is Class 1 (containing a minimum of 99.8 percent nickel) and the rest is Class 2 (containing less than 99.8 percent nickel) units This is illustrated in Figure 49. Of the Class 1 Nickel produced, a significant proportion is used for battery production. It can be seen that demand for refined nickel is predicted to outstrip supply, as illustrated in Figure 47. This is particularly acute for Class 1 Nickel, as illustrated in Figure 46. The process for extracting Class 1 battery-grade materials is shown opposite in Figure 50.

WHAT DOES THIS MEAN FOR NICKEL?

Increasing competition for suitable sources for nickel sulphate production, particularly Class 1 nickel



1 Including only highly probable projects.

Note: Considers the amount of capital expenditures needed to provide sufficient supply based on third-party source estimates (CRU and Wood Mackensie) and Vale's expected deficit by 2030 (50% Upside Case and 50% Conservative Case).

Source: LME, Barclays, BMO, Credit Suisse, Deutsche Bank, Goldman Sachs, Macquarie, Morgan Stanley, RBC, UBS, Wood Mackensie

Figure 46: Why do we care about nickel[88]

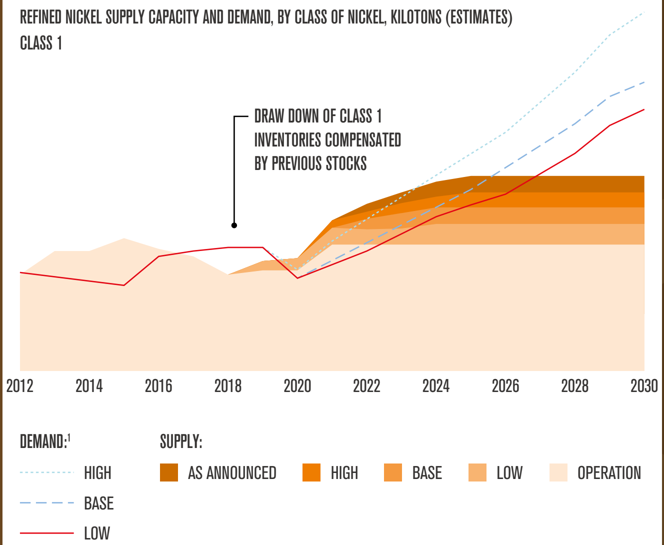


Figure 47: Refined nickel supply capacity and demand, by Class of nickel [89].

WHAT DOES THIS MEAN FOR NICKEL?

The nickel industry is lagging behind in investments due to the lack of incentive price

The downstream industry has committed over US$ 150 billion

Over US$ 70 billion needed in investments for nickel	Over US$ 40 billion needed in investments for copper	Cobalt is constrained in as much as Ni and Cu are under invested	Meanwhile over US$ 150 billion committed by the downstream industry
Ni	Cu	Co	

The nickel industry needs better prices

Figure 48: We know there will be a shortage due to electric cars

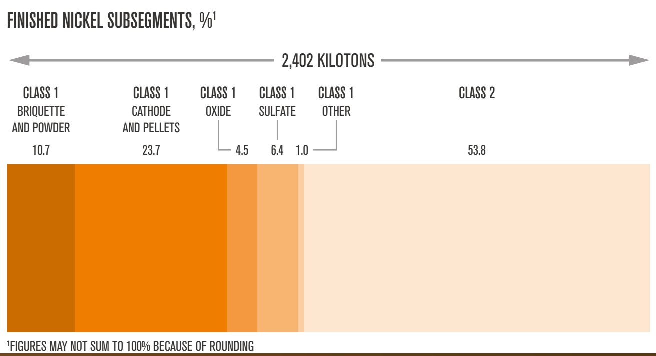


Figure 49: Majority of finished nickel production is Class 2 nickel[89].

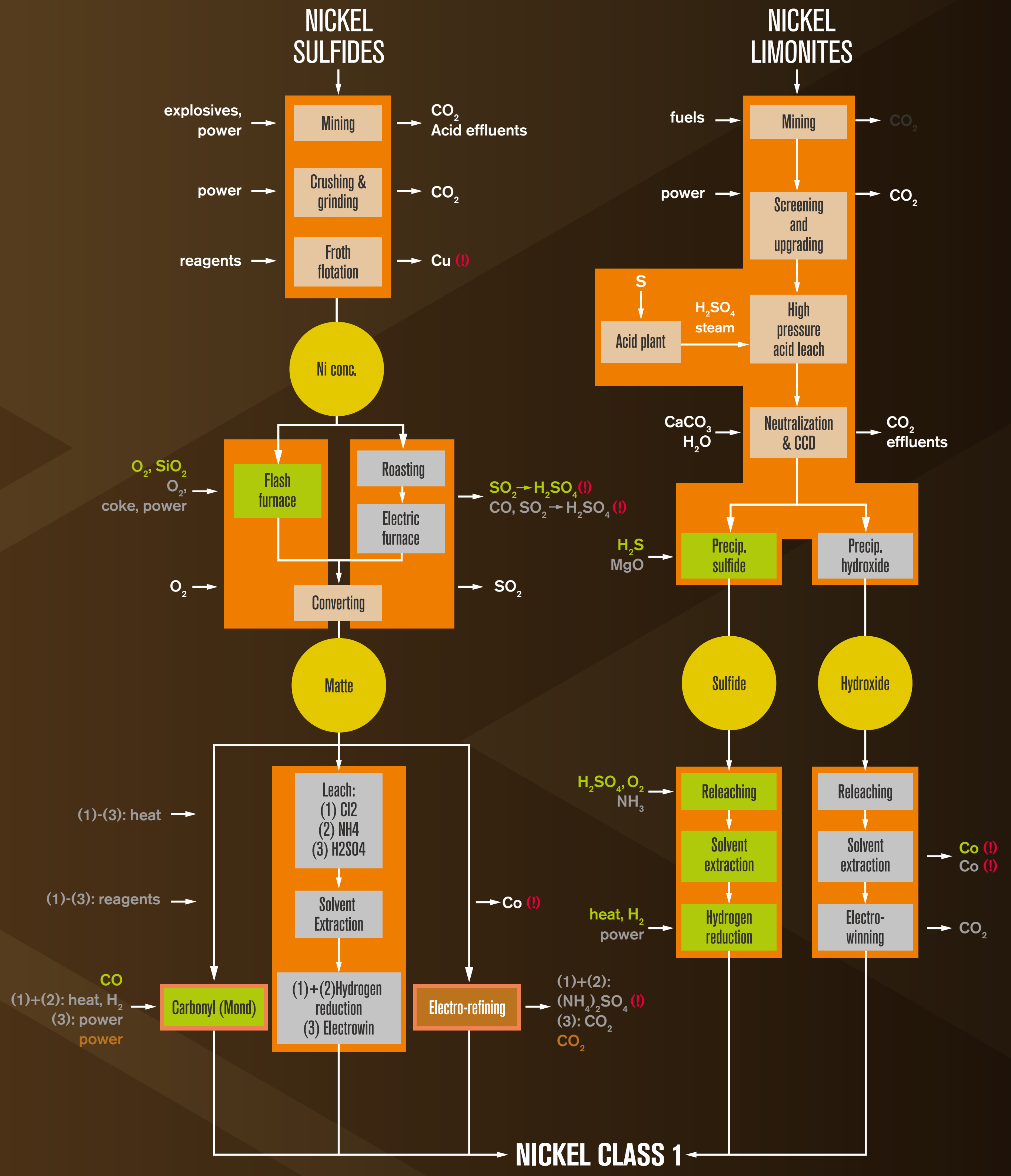


Figure 50: Process chain diagram for nickel class 1[90]

BOX OUT 009

Materials for lithium-ion batteries continued

Using nickel as an example (but the same largely holds for the other battery materials) these materials will need to be highly refined to get to the >99.9% purity for use in batteries. The process flow from nickel ore through to Class 1 nickel battery-grade materials consists of a number of steps, following a variety of routes. All of these are CapEx and OpEx intensive.

The refining capacity for these highly refined metals is in short supply (see figure 53), once projected additional demand for batteries is included. The nickel industry (see figure 52), however, is reluctant to build new capacity as the nickel price does not currently warrant the investment of around $70bn (see figure 51), according to one of the world's largest nickel miners and refiners (Vale), who summarised the issue like this:

"This points at a structural deficit of nickel supply for batteries from 2023 onwards which has been corroborated by a number of sources including McKinsey."

(see figure 48)

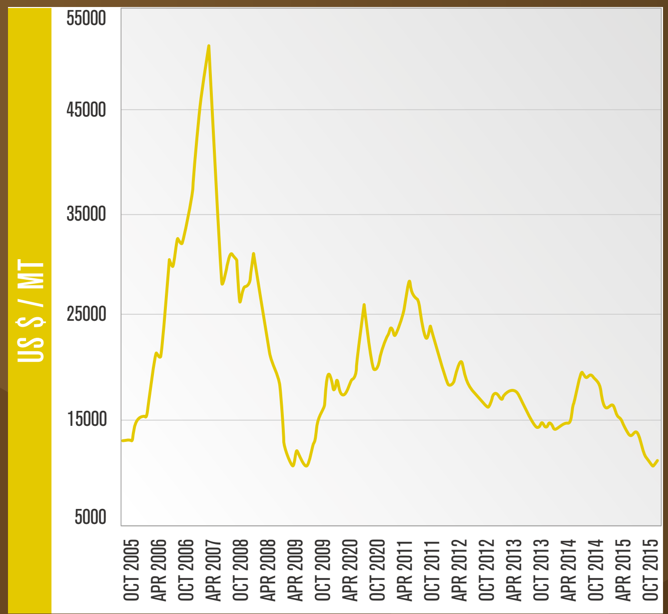


Figure 51: Nickel price history

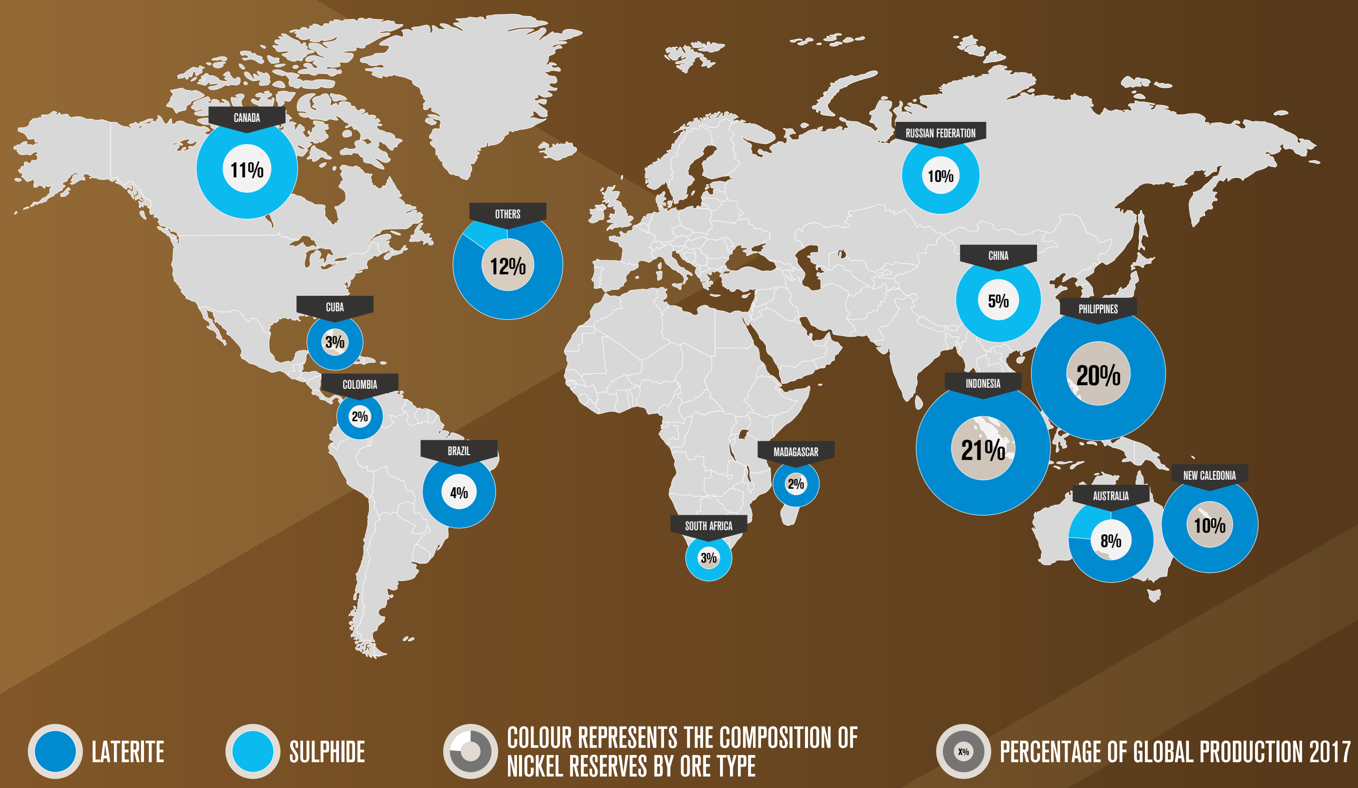


Figure 52: Percentage of global nickel production 2017[91]

Figure 53: A nickel refinery

Figure 54: Nickel mining

Mining (and recycling) of raw materials

Only some of the highest grades of nickel are good enough for batteries (Class 1).

Class 1 nickel can be made from limonite and sulphide ores. (Figure 52 shows the global distribution of these resources.) The latter is cheaper, less energy- (and often carbon-) intensive, as well as having less of an environmental impact. (Figures 53, 54 and 55 are illustrative of Nickel mining and refining operations).

Nickel is used primarily as a constituent (6-10%) in stainless steels, in superalloys and increasingly in the batteries for EVs.

Nickel is abundant and has been traded on the LME for many years. Prices are volatile as speculators can raise them much higher than normal supply/demand dynamics would dictate, see figure 51. Conversely, they can sometimes be driven below the nickel miners' break even price.

OEMs can manage price volatility by financially hedging nickel with various banks. This eliminates market volatility as prices are effectively pegged to the hedged price.

Nickel is an ingredient (typically ~50%) in all nickel-based superalloys for the aerospace sector.

Figure 55: Nickel Mining in New Caledonia

BOX OUT 010

Materials for lithium-ion batteries

6.94 3
[He]2s[1]
Li
Melting point: 180.5°C
Boiling point: 1342°C
LITHIUM

Lithium

Until recently, the main use for lithium was in ceramics. Its key role in lithium-ion batteries for electric vehicles and energy storage now sees it increasing in importance (see Fig 57) and becoming more vital to UK manufacturing as the automotive industry switches over from internal-combustion-engined vehicles to battery-powered cars and lorries. Lithium has recently been added to lists of critical raw materials (see the EU's graph of CRMs Figure 1). Previously, the range of sources in a number of countries kept it sub-critical but given the 'race to build gigafactories' and the consequential need for a rapidly increasing supply of raw materials, it is not surprising to see lithium now classed as critical. The main sources of lithium are: (1) shallow underground brines, salars, in the Lithium Triangle sourced, in South America (see figure 58,59,60), which are evaporated in large ponds in desert areas to produce lithium compounds: and (2) granite-related pegmatites, hard rocks, usually mined in open-cast quarries with associated processing to make a concentrate of the lithium ore minerals. The most famous pegmatite deposit is the Greenbushes mine in Western Australia. There are many other lithium pegmatites that are potential sources if they can be mined economically. There are also non-conventional sources of lithium, like seawater, but they are not economically viable at present.

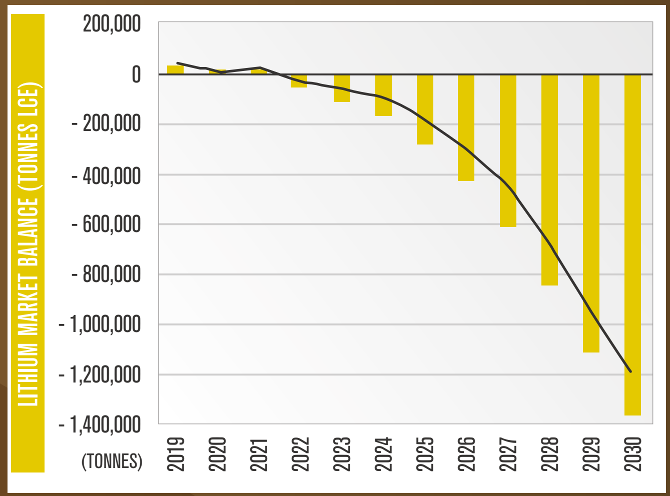


Figure 56: Lithium market balance
Source: Created from data from benchmark mineral intelligence

Lithium is also one of a few metals that could be sourced, to some extent, in the UK. There are projects looking at unconventional sources of lithium, such as underground brines circulating in fractures in South West England. Another approach is to extract the lithium from lithium-bearing mica, either in new quarries or from china-clay waste.

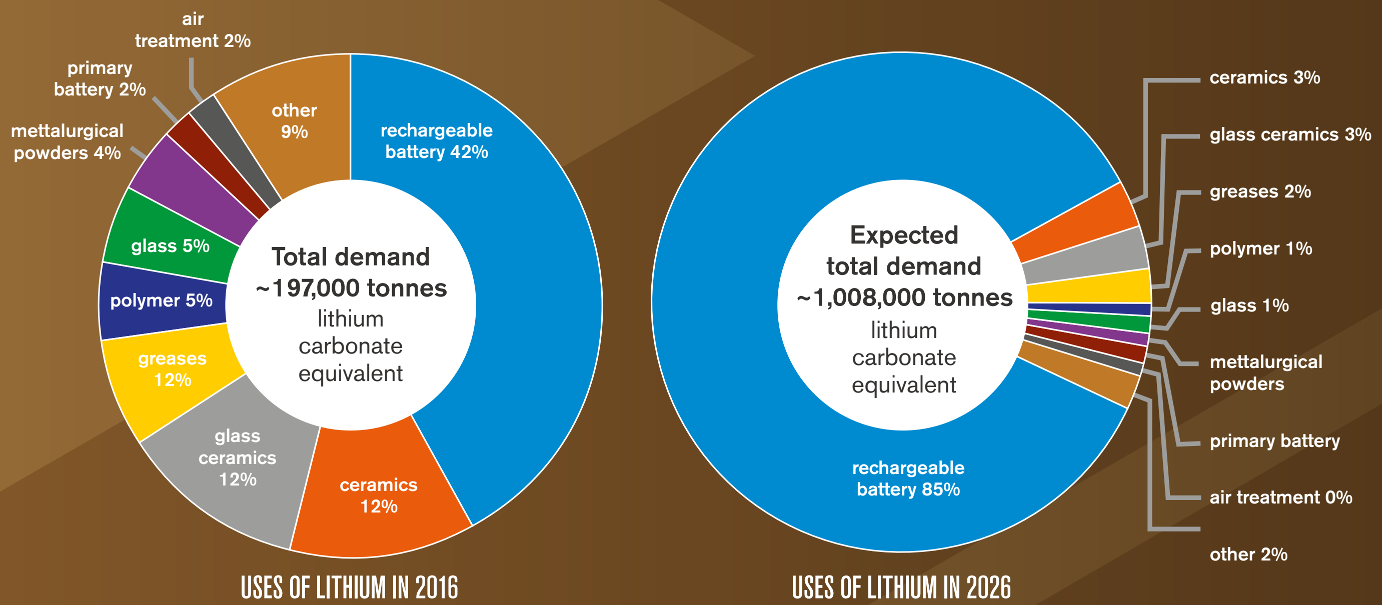


Figure 57: Uses of lithium

Figure 58: Salar de Uyuni, Potosi, Bolivia, South America. The world largest salt and lithium reserve at 3650 meters above sea level. Potosi, Bolivia, South America.

Figure 59: The Rockwood Lithium Mine

Figure 60: Evaporating ponds for lithium production. Image courtesy: Alexandra Sweeney.

BOX OUT 010

Materials for lithium-ion batteries continued

Lithium in the UK

There are active exploration projects for lithium in the UK, (see figure 61-64) providing the potential for domestic production of some battery raw material. British Lithium and Cornish Lithium are assessing the recovery of lithium from the mineral, mica, in Cornish granite. Cornish Lithium are developing lithium extraction from brines in conjunction with a deep geothermal energy project at United Downs in Cornwall.

Figure 61: Exploration for lithium mica

The ultimate source of lithium is the mica in granite, but natural, deep fluids have already done the hard work and leached the lithium into solution. Northern Lithium have recently announced a new project to test the Weardale Granite of County Durham for deep lithium-bearing brines. These are all highly innovative projects that require substantial research and development and have been successful in attracting investment as well as research grants. They have also been highlighted in regional development opportunities and plans.[92,93]

The exploration for battery raw materials is part of a renewal of interest in metals exploration in the UK. In the southwest, there are active projects for the critical metal, tungsten, the technology metal, tin, and also copper (Tungsten West, Cornwall Resources, Cornish Metals, Cornish Tin). Elsewhere, there are projects exploring for gold and base metals. These new projects have to navigate a complex mineral rights system, which some consider to be old-fashioned and hard to navigate. Mineral permitting is part of our overall land-use planning system and as such needs to balance competing interests (economic, social and environmental) in a relatively small, densely populated country. It has been subject to a regular review by the UK Government and Parliament.

Figure 62: Exploration for lithium mica

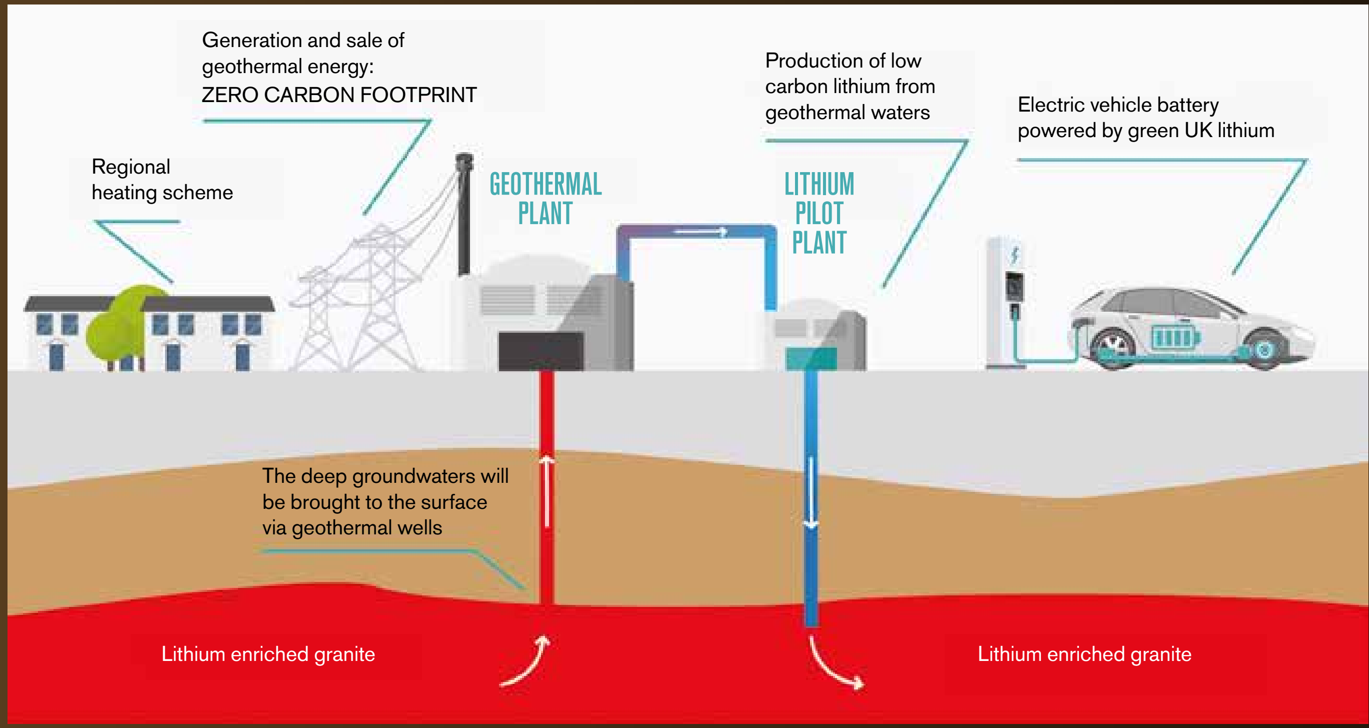


Figure 63: Pilot lithium extraction plant. Supplied by Cornish Lithium

Most of the permitting issues relevant to metals mining also apply to industrial minerals and the construction minerals industry, which is a major UK sector. In 2018, the CBI Minerals Group and Mineral Products Association published a UK Minerals Strategy[94] setting out proposed environmental planning and regulation principles for environmental protection, while delivering the economic benefits of domestic production. Consideration of these proposals alongside the development of new regulations for geothermal energy rights[95] (see figure 63), and extraction of metals from natural waters would be timely. (see the Governance and Regulations Section).

Figure 64: Cutting core for analysis

BOX OUT 011

Materials for lithium-ion batteries

12.011 14
[He]2s²2p²
C
Melting point: 3825°C
Boiling point: 3825°C
CARBON

Graphite

Graphite plays a crucial role in a number of key industries, including steelmaking, nuclear reactors and lithium-ion batteries. Spherical graphite, also known as battery-grade graphite, is processed into an ultra-high-purity form (>99.95 % carbon) for its use as the battery anode. Its spherical shape allows more graphite to fit into a smaller space, which improves the conductivity and the rate at which the battery can be charged and discharged. China is currently the only producer of battery-grade graphite in industrial quantities[96].

However, sustained high prices are encouraging developments outside of China[97]. The global market for graphite is expected to grow to $21.4 billion by 2024, with a compound annual growth rate of 5.6%. Demand is being driven by a 20% year-on-year growth of lithium-ion battery producers[98]. The expansion of the hydrogen economy, where hydrogen is used as an energy vector, will also drive the demand for graphite in some types of fuel cells.

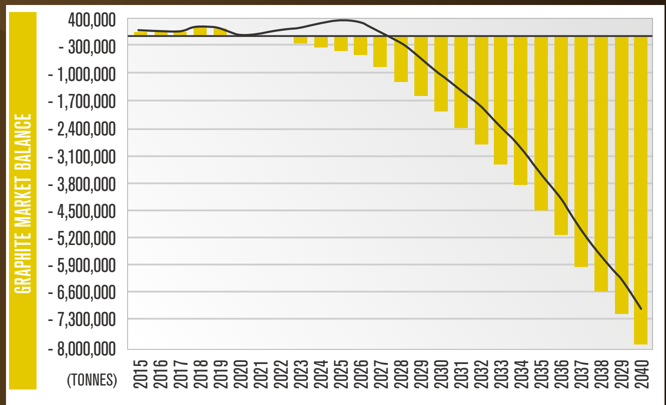


Figure 65: Graphite market balance.
Source: Created from data from benchmark mineral intelligence.

BATTERY MATERIALS: THE CHALLENGE

The figure below, based on estimates by the Faraday Institution in 2020, indicates the expected huge increase in raw-material demand from the UK over the next 15 years. Imports of cobalt are expected to exceed 10 ktonnes, while the amounts of lithium carbonate equivalent and nickel are likely to top 50 and 60 ktonnes, respectively, by 2035, driven largely by the requirements of batteries for electric vehicles.

The issue is not that there isn't enough nickel, cobalt, lithium and graphite in the ground, but rather that it is not economically viable to mine (or recycle) and refine it to the specification required for battery electric vehicles in the quantities required by 2030. Higher prices are inevitable and required to bring on more supply. This will directly lead to higher battery prices and therefore higher vehicle prices, which are likely to slow down the production and uptake of electric vehicles globally, leading to adverse climate impacts.

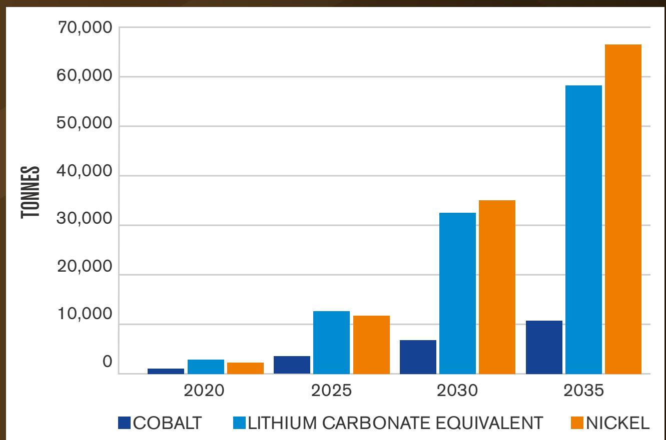


Figure 66: UK demand for raw materials to 2035.
Source - Faraday Institute estimates[4].

LOCATION OF BATTERY MATERIALS

The number of countries with the resources required for lithium-ion batteries is small (see the map below). In fact, the Democratic Republic of Congo and China dominate with their large reserves of cobalt and graphite, respectively. The UK and Europe have no significant resources of any of the materials required for lithium-ion batteries and will continue to remain reliant on imports. Ensuring access to these technology-critical metals and natural graphite must be central to any UK strategy for ensuring that high-technology industry and skilled jobs in manufacturing are retained.

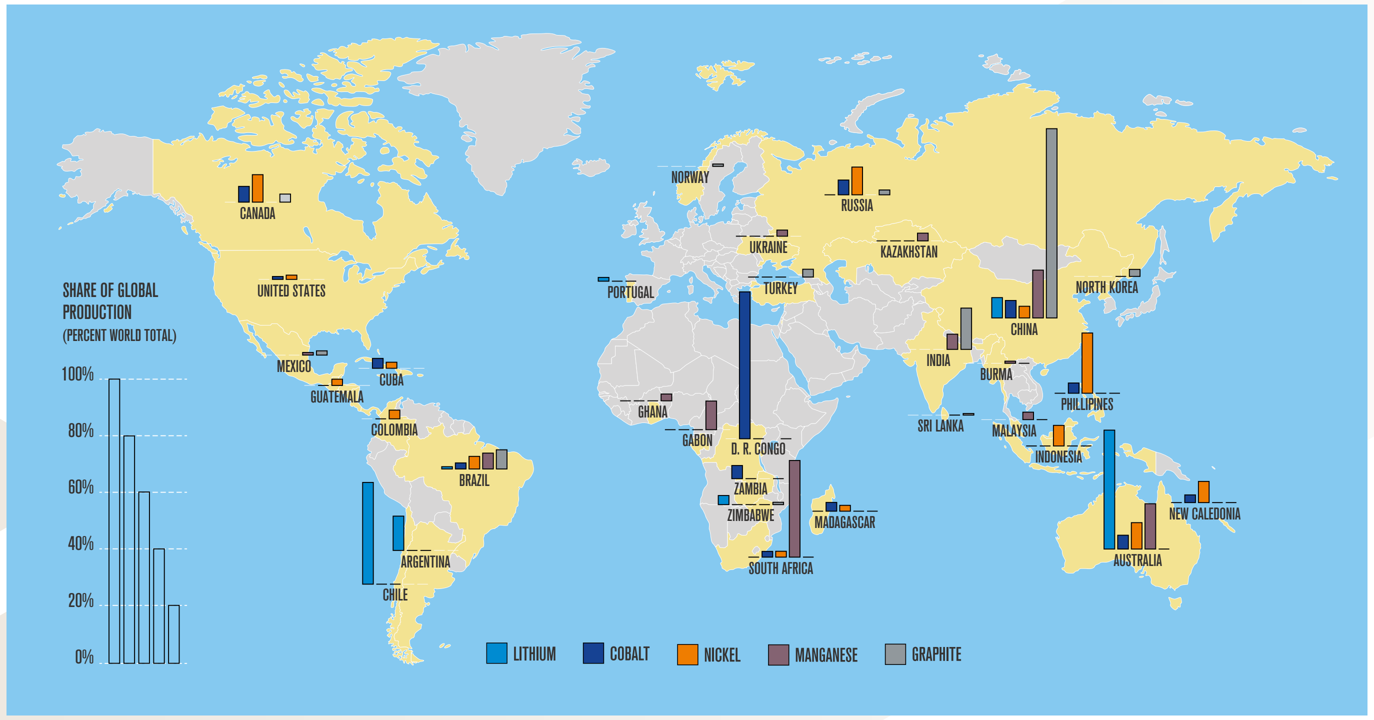


Figure 67: Primary resources for technology-critical metals[99].

As can be seen on the following page, while the mineral resources for lithium-ion batteries are far from uniformly distributed, there is even more of a concentration in terms of processing capability, much of which is currently associated with China, which has a large concentration of battery manufacturers with a highly vertically integrated supply chain.

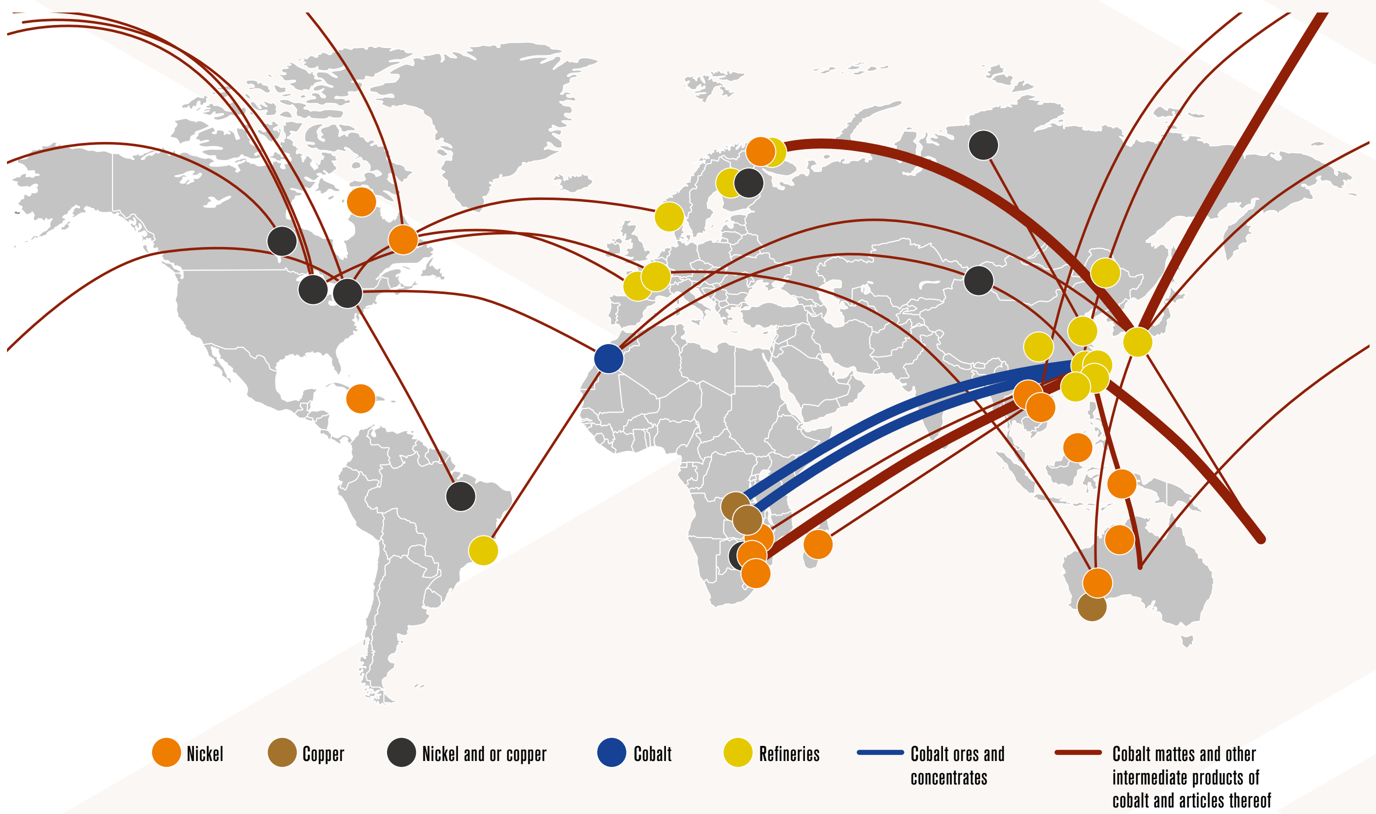


Figure 68: Flow of cobalt around the world[100]

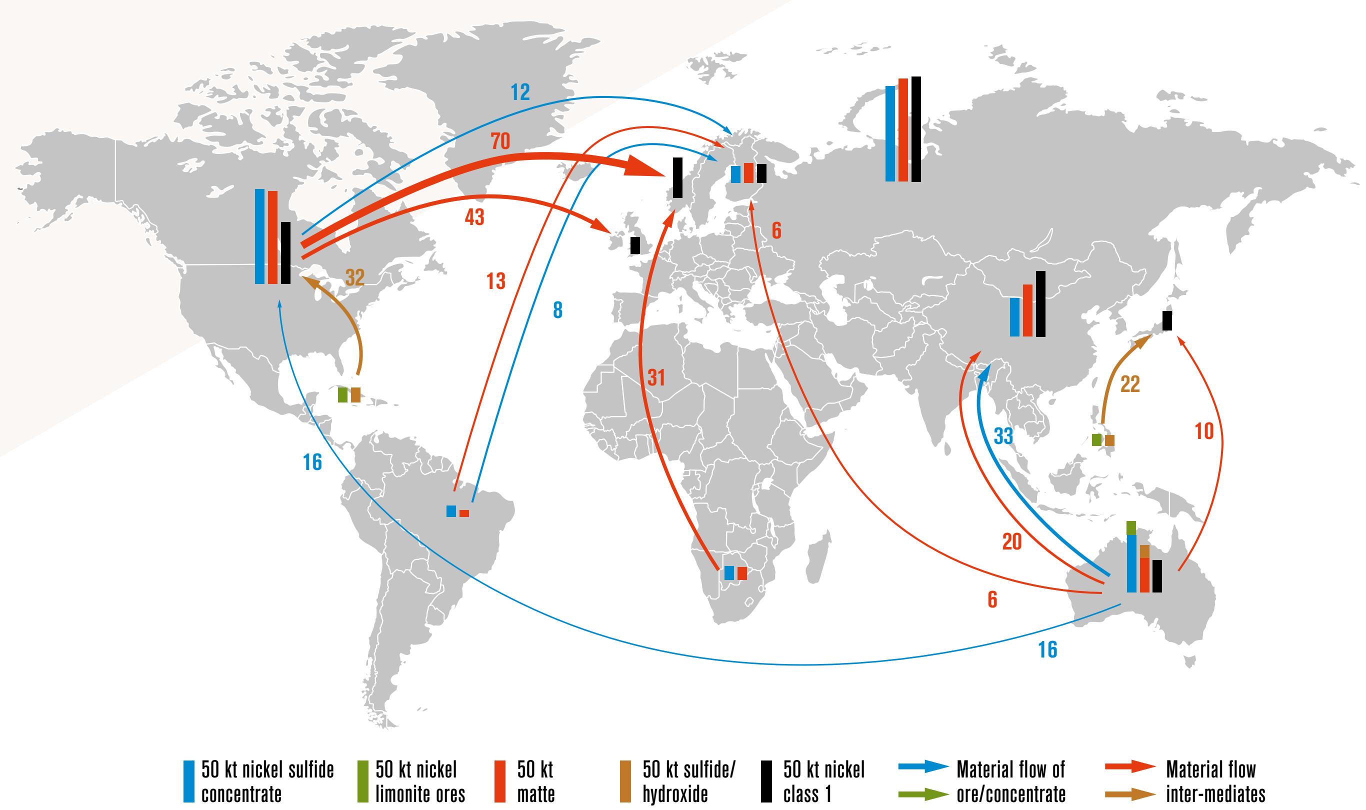


Figure 69: Flow of nickel around the world[90]

ELEMENTS OF A UK SUPPLY-CHAIN

There is no mining capacity for nickel or cobalt in the UK, but Vale has a nickel smelter at Clydach in South Wales, where it refines nickel materials that are rich in cobalt. Opened in 1902, Clydach refinery is one of the oldest in the world, producing refined nickel in the form of powder and pellets that are sold to more than 280 customers in over 30 countries across Europe, Asia and the US. The refinery is supplied with nickel oxide, an intermediate product, from Vale's smelters in the Sudbury region of Canada[101]. According to EU figures, $302 million of unwrought, unalloyed Ni was exported from the UK in 2017. However, existing data on cobalt and nickel are not detailed enough to allow commodity traceability across the UK supply chain.

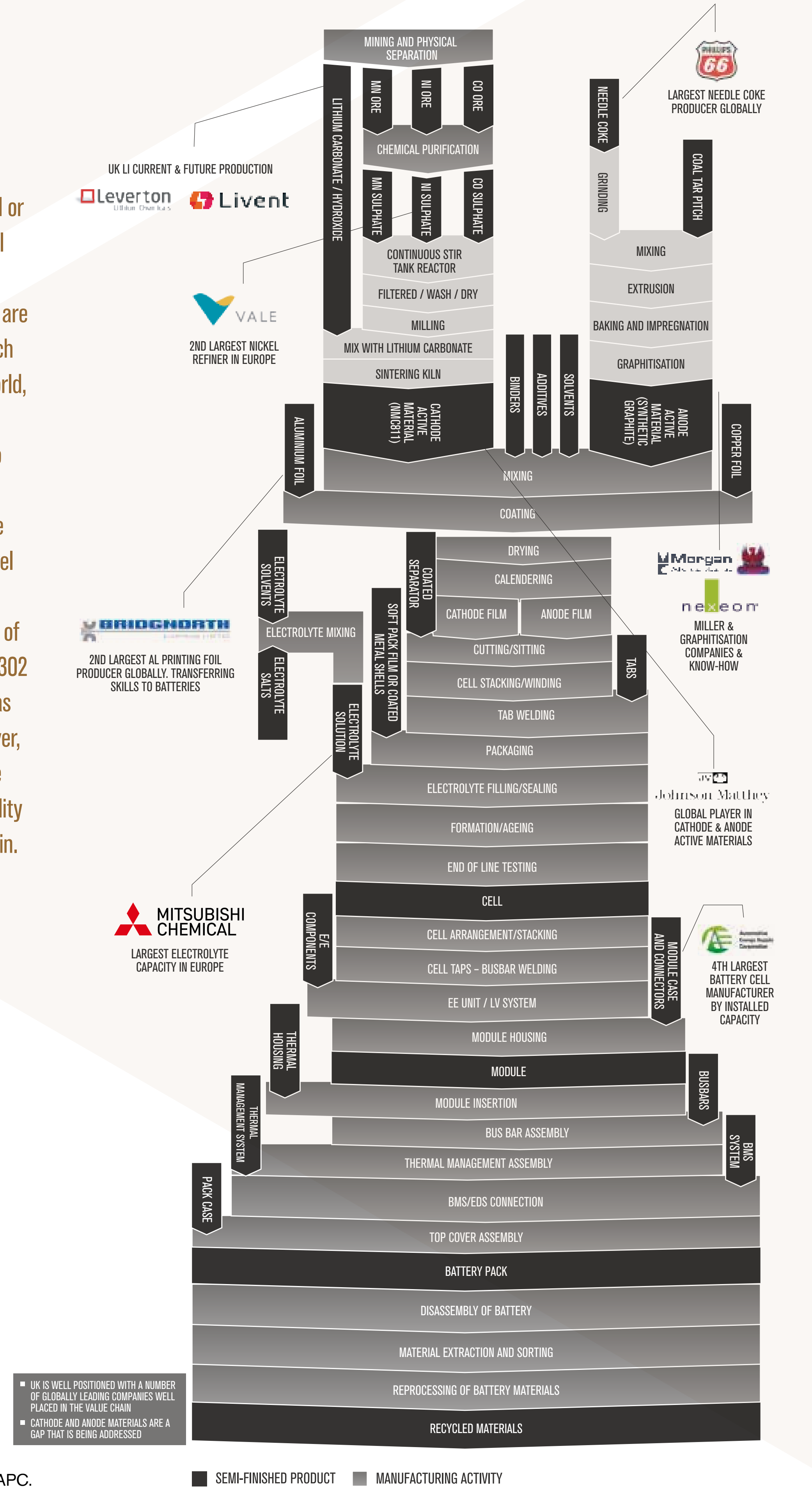


Figure 70: Battery value chain courtesy of APC.

ELEMENTS OF A **UK** SUPPLY-CHAIN CONTINUED

Potential Elements of a UK Supply-Chain

P66 is the only needle coke (a precursor to synthetic graphite) producer of note in Europe. Its Humber facility produces enough to satisfy Europe's demand for electric vehicles until 2030. With no major synthetic graphite producers in Europe and the process being energy intensive (and therefore potentially carbon intensive) this is a unique opportunity for the UK with large amounts of wind power coming on line.

Vale operates one of Europe's largest nickel refineries, in South Wales, currently supplying very-high-grade nickel into various high-value applications such as alloys for Rolls Royce's gas turbines.

The UK has two lithium carbonate and hydroxide specialists with the capability to scale up quickly.

Mitsubishi Chemicals (Teeside) operates one of three electrolyte production sites in Europe.

Johnson Matthey is a global leader in cathode active material manufacturing, covering both LFP and a high nickel eLNO materials. It has R&D and production sites around Europe.

Significant investments by these companies could create a snowball effect for the whole supply chain to develop very quickly. UK Government investment similar to what is being offered in Europe is required urgently, to ensure these investments are timely and with the scale necessary. The UK Battery Industrialisation Centre, which is currently the only one in Europe, offers a unique opportunity to assist this localisation effort.

◄— See previous page for a diagram of existing elements of a potential UK battery supply chain.

ETHICAL ISSUES
AROUND THE PRODUCTION OF BATTERY MATERIALS

UK steel producers, the chemical industry and makers of cemented carbides and other hard materials, together with battery manufacturers like Johnson Matthey, rely on imports of cobalt as there are no significant cobalt resources in the UK.

Unregulated mining in the Democratic Republic of Congo, sometimes referred to as artisanal mining, including the use of child labour, has been in the headlines as the price of cobalt has risen. However, most cobalt is still supplied by large mining companies like Glencore, which produced 46,300 tonnes of cobalt last year, up 10% from 2018, but expects to generate only about 29,000 tonnes this year after shutting down its Mutanda mine in the DRC, the world's largest cobalt operation, last year.

In recent years, cobalt has been subject to controversy due to reports of human-rights abuses, including the use of child labour, in artisanal and small-scale mines in the DRC. Between 15-30% of the DRC's output, comes from artisanal mines[102]. Ethically focused OEMs have taken measures to ensure their elemental cobalt supply is sourced to international ethical standards and in some instances from outside of the DRC.

Prices nearly quadrupled, (see page 64), in the 18 months to Q2 in 2018 as speculators warehoused thousands of tonnes of high-grade cobalt in anticipation of greatly increased prices due to the projected increase in demand from the EV/HEV sector. Prices started to slide back to normal as speculators left the market and real market supply/demand dynamics resumed.

Some argue that artisanal mining plays an important role in stabilising cobalt prices and meeting demand. They contribute as so-called "swing producers", who are able to act quickly when market prices are high, but then tail off in periods of low demand. Figures for artisanal production, are hard to track, as there is an understandable lack of transparency and supply-chain data around how it is traded, but it was estimated that in 2007, artisanal production from the DRC was the second biggest global producer after DRC's official sector. That said, the DRC does still recognise the sector and provides some assistance through the Service for Assistance and Supervision of Artisanal and Small-Scale Mining (SAEMAPE)

Ethical issues surrounding the mining of technology-critical metals first came to the world's attention in the 1990s. This resulted in a "conflict minerals" law in the US, and a European conflict minerals regulation that comes into force on 1 January 2021. Cobalt is not part of this regulation, however. The Cobalt Institute, based in London, has implemented its own responsible-sourcing scheme called CERAF, which requires its members to be compliant with recognised schemes. Multinational NGOs such as the Pact Mines-to-Market programme are working with the artisanal miners to improve their conditions. The ethical approach is generally not to stop the purchasing of minerals from problematic regions – the local population could then be even worse off – but to intervene to ensure supplies are coming from responsibly run mines. Large companies such as Google and Apple are reaching back through their supply chains to help artisanal miners.

Figure 71: Mwinilunga, Zambia - December 6th, 2012: Three young African miners work in an underground mine and dig for resources

Environmental issues around the production of battery materials

The environmental standards of mines producing cobalt, nickel and lithium are varied, ranging from the highest international standards to practices that do not safeguard the environment. With global production increasing sevenfold between 2008 and 2015, there are also increasing reports of health problems. Environmental problems have been reported in Australia (water quality), Cuba (pollution plumes) and Zambia (poisoned soil). Two years ago, 17 nickel mines were closed or suspended in the Philippines because of environmental concerns. In Chile's Salar de Atacama, a centre for lithium production, 65% of the region's water is consumed by mining activities: one tonne of lithium requires 1900 tonnes of water to extract the metal. This impacts on the farmers in the region, who are then forced to import their water from other parts of the country.

The UK must take a responsible position in the sourcing of materials as it transitions to a low-carbon economy.

BOX OUT 012

Lithium-ion Batteries & The Race To Build Gigafactories

All regions around the world are seeing industry move towards technologies that support decarbonisation; but some will get there faster than others. The scale of the investment required for sectoral transition is staggering and there will be winners and losers in the process. It is our recommendation that targeted investment in this sector needs to increase dramatically, if the UK is to catch up with international competition, let alone harbour any ambitions of being a world leader.

The International Energy Agency has called for global investment into battery supply chains in order to meet net-zero targets . The present trajectory has seen production capacity to double every three to four years. However, globally, they note that to meet our commitments, we will need to double capacity every two years[103]. Many other nations also have their eyes set on this prize and the rewards that will flow from building a successful EV industry. With ambitious net-zero goals and a plan to phase out ICE vehicle production, the UK must act decisively and ensure the attractiveness of the UK as a destination to build EV batteries, if it wants to avoid meeting these commitments primarily with imported products; however, this will require significant investment.

It was said that Tesla's first gigafactory would eventually cost $5 billion[104]. Tesla have said that they will invest[105] 4 billion euros ($4.41 billion) in their new European factory. The UK was scouted by Elon Musk as a potential location for Tesla's European factory. However, he cited Brexit as amongst the reasons he decided against the UK[106]. The German Government named Tesla as one of 11 companies to receive billions of euros in government subsidies, aimed at stimulating an EV industry in Germany[107]; it will receive €1 billion ($1.2 billion) from the German Government [108].

Britishvolt believes that it can deliver its first gigafactory for £2.6 billion ($3.5 billion)[109], however, it still has to raise a significant portion of the funds[110]. If all goes according to plan, it aims to start producing batteries by 2023. The Faraday Institution estimates that UK market demand would make a Gigafactory viable in 2022, with a second following in 2025[4]. In many other nations concrete foundations are being poured and factories constructed, while in others machines produce batteries by the million. In the UK, this remains, for now, an ambition.

Figure 72: Tesla's new Berlin Brandenberg Gigafactory Under Construction In Berlin

Figure 73: The Tesla Gigafactory in Sparks, NV

It is estimated that we will need 8 gigafactories in the UK by 2040[111]. The Faraday Institution has said that in the absence of battery manufacturing, 114,000 jobs could be lost . Without battery manufacturing capacity, the future for UK EV and automotive production has been described as bleak[112]. To turbocharge the transformation, the UK Government will need to match the ambition of other countries that are fully committed to this race. Despite the existing dominance of Asian suppliers, and the significant progress made by European and US battery manufacturing to match this, as we are still in a period of rapid growth, there is still every opportunity to catch up. It has been estimated in a recent German report that this will take at least five to eight years and cost in the region of €10 billion, in addition to EU funding in this area.

Focusing on the UK, some commentators have questioned whether the present scale of investment in this area is commensurate with the scale of the challenge, and whether it begins to approach the levels of investment that are being leveraged by others globally[113].

And yet, whilst globally, and in the UK, there is an intense focus on battery manufacturing, arguably the other key component of EVs, electric motors, receive far less attention. The comparative investment in the development of the UK supply chain for EV motors is more modest. There is the risk that without significant investment, the UK could also lose capability in this area. This should be a cause for concern, given China's dominance of the rare earth supply chain.

Medium term

As stated in the Electrical Energy Storage roadmap,[77] there are a number of technologies that enable low-cost batteries with much lower technology-critical metals requirements. Some of these technologies are actively being developed in the UK, ranging from silicon anode technologies to Na-ion and Li-sulfur batteries. A real focus on getting these scaled up and to market, for example, through the UK BIC, is a key priority. Significant government and private investment is required to do this at the speed and scale required.

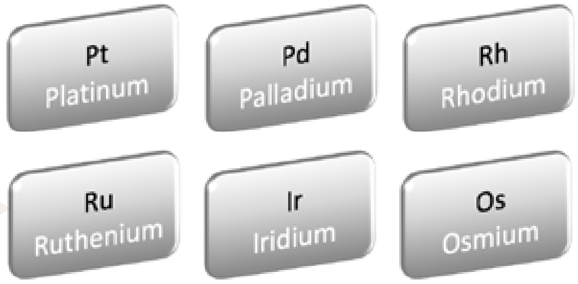
In parallel,l the recycling of technology-critical metals such as cobalt, nickel and lithium is urgently required. This would enable the UK refining and automotive supply chain to prosper in the longer term, and will become even more important as regulation requires ever increasing amounts of recycled content.

PLATINUM GROUP METALS AS CRITICAL MATERIALS

What are the Platinum Group Metals?

There are six platinum group metals (PGMs), of which the best known are platinum and palladium. The remaining four PGMs are available in smaller quantities and always as a by-product.

All six PGMs have unique properties, which make them difficult to substitute, and their usefulness, combined with their rarity, makes them very expensive.



What are they useful for?

CATALYTIC CONVERTERS – TECHNOLOGY FOR CLEANER AIR

Catalytic converters process the fumes that come out of petrol and diesel engines, converting harmful gases including carbon monoxide and nitrogen oxides (NOx) into gases which are already present in the air (see figure 74). In petrol cars, most catalytic converters contain palladium and rhodium. The major component of this is 2-5g of palladium, with small amounts of rhodium included to catalyse NOx reduction. In diesel cars, catalytic converters typically contain less palladium but 3-6g of platinum[114,115], which is close to the amount in a traditional wedding ring. However, the amount of all the metals loaded onto a catalyst changes over time: in 2019, the global average palladium loading on a petrol car went up 14% and rhodium loading increased by 20%. This was the result of tightening emissions legislation in several regions of the world.

Figure 74: Cutaway catalytic converter

CATALYSTS FOR MAKING CHEMICALS – SUSTAINABLE MANUFACTURING

In large-scale industrial processes, catalysts are used to decrease the amount of energy, and hence environmental impact and cost, associated with the manufacture of bulk and speciality chemicals. Catalysts containing rhodium, iridium and ruthenium are used to produce acetic acid, which is a component of products including paints, adhesives and artificial fibres. Hull is home to Europe's largest acetic acid production facility, which uses a ruthenium based catalyst. In Edinburgh, palladium catalysts are used in the manufacture of oxycodone, which is widely used for management of pain (see figure 75).

HIGH-PERFORMANCE GLASS – DATA AND DISPLAY PRODUCTS

A less well known application of platinum and rhodium is in alloys which are used in the manufacture of fibreglass used in the electronics, construction, renewable energy and automotive industries. These alloys are also used to produce next-generation LCD glass panels for large-screen televisions measuring over 60 inches.

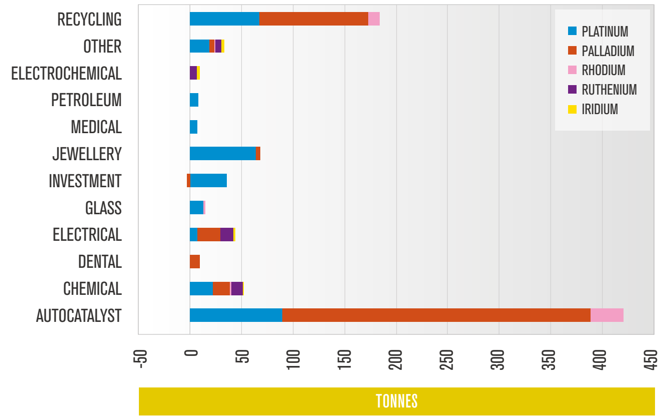


Figure 75: Proportion of PGMs used in the various sectors and recycling in 2019; note that "Investment" can be positive or negative in any given year[116]

ELECTROLYSERS AND FUEL CELLS – CLEAN ELECTRICITY

Electrolysers make hydrogen out of water; fuel cells take the hydrogen and make electricity. At present, fuel cells are used in electricity generators and to power vehicles ranging from forklift trucks and passenger cars to boats and submarines. Since 2011, Londoners have been able to travel on zero-emission fuel cell buses and low-emission diesel/fuel cell hybrid buses make up 30% of the fleet (see figure 76).[117]

While not a huge market at the moment, the UK has a leading technology position and an expanding manufacturing base in fuel cell technologies. Hence, electrolysers and fuel cells offer an opportunity for the UK to move away from coal, gas, and hydrocarbon-powered vehicles, and to take a market lead in clean technologies including hybrid fuel cell/lithium-ion battery drivetrains.

The PGMs used in fuel cells and electrolysers are platinum, ruthenium and iridium. Of these, iridium is the scarcest as there is not very much available and relatively large amounts are required in each electrolyser. Fuel cells and electrolysers are not sustainably recycled in the UK at present, although there are a number of funded programmes investigating the value chain and technology options.

Figure 76: London fuel cell bus

JEWELLERY AND INVESTMENT

A significant amount of platinum is locked up as metal, in jewellery or in metal bars held by banks and physical exchange-traded funds (ETFs) (see figure 77). The amount held or sold depends on market sentiment. During 2019, for example, investors added over one million ounces of platinum to their ETF holdings, taking the total volume of platinum under investment to a record 3.4 million troy ounces (>100 tonnes). This quantity is equivalent to 57% of the 2019 primary Pt supply. In contrast, physical investment in palladium ETFs reached a peak in 2015 but holdings have declined sharply since then, as record prices have prompted profit-taking and the amount dropped to around 590,000 ounces at the by August 2019.

Figure 77: Platinum bars

PGM Metal Prices

The value of each PGM fluctuates. For example, 31 g rhodium (1 troy ounce) was worth $13,800 on 13th March 2020, but only $7,000 on 7th May. From a financial perspective, PGM metal prices drive investment and the economic feasibility of mining and recycling. From a manufacturing perspective, in some applications PGM metal prices can influence how much metal is used.

For example, between 2002 and 2017, platinum has consistently been more expensive than palladium (see figure 78), so it was cheaper to minimise the amount of platinum in a catalyst or product by adding more palladium. The price crossover in September 2017 has changed that. For automotive manufacturers, one way to mitigate rising costs is to exchange some of the palladium in catalytic converters for platinum. Due to the different metal chemistries this is not straightforward: it requires technical development of the catalyst and in some cases reoptimisation of the way the engine is calibrated.

There was an unforeseen consequence of this rise in the palladium price. In the first six months of 2019, more than 2000 catalytic converters were stolen from cars in the UK [118]. This is more than double the number stolen in the whole of 2018 and a direct result of high rhodium values and the value of palladium reaching unprecedented highs.

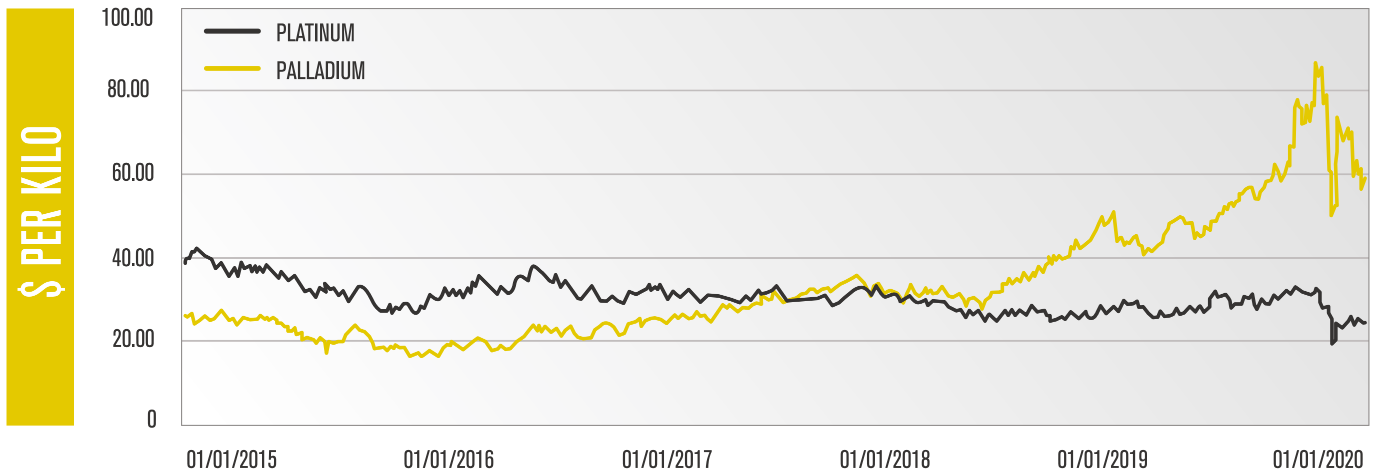


Figure 78: Fluctuation in platinum and palladium prices since 2015

PGM supply and demand

Unlike other strategic elements such as cobalt and the REEs, there have historically been reserves of refined platinum and palladium which can buffer fluctuations in metal price and supply. It is challenging to estimate what quantity of metal is held in above ground stocks at any given time, but there has been considerable drawdown in recent years: around 7m ozT platinum and 12 m ozT palladium have been exported via major trading centres in London and Zurich since 2007.

Why are the PGMs critical?

South Africa has a large proportion of the world's platinum ore, while considerable amounts of palladium ore can be found in Russia (see figure 79). The supply of mined metals therefore depends on the political and economic conditions in these countries: wage negotiations, strikes, shaft closures, electricity shortages all contribute to fluctuations in supply. Added to that, PGMs come out of the ground in very small amounts - four kilos of ore produces about enough PGM to cover a little fingernail. How can it be economic to mine and recycle them?

The reason is that it is difficult to find cheaper metals that will do the same things as PGMs. While "thrifting" – using less - PGM can usually be achieved, the PGMs have unique chemical and physical properties that to date it has proved impossible to replicate. Without these metals, technology would never have advanced as far as it has. And demand continues to increase.

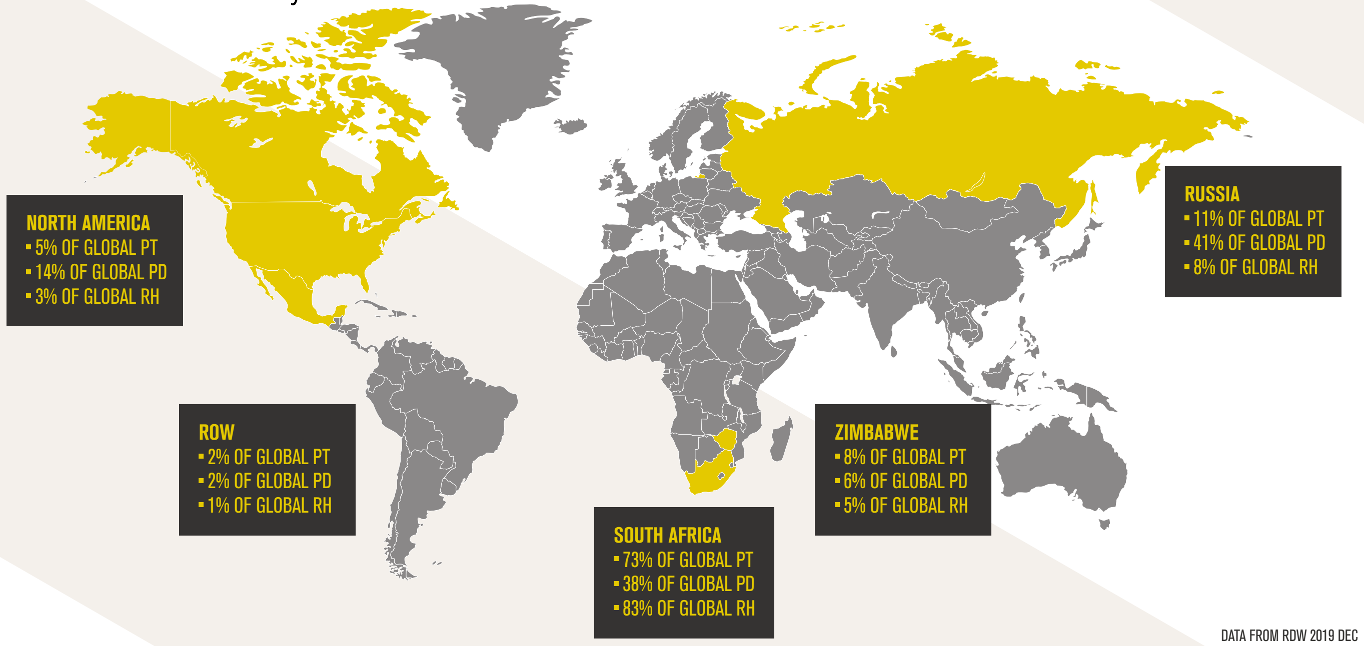


Figure 79: Global PGM primary supply - 2019

Primary and secondary refining of PGMs

Mining (primary refining) of PGMs supplies around two thirds of global PGM demand, and the remaining third depends on recycling (secondary refining). Europe is home to a number of secondary refiners in France, Belgium, Norway, Germany, Switzerland and the UK boasts the world's largest secondary refiner of PGMs, Johnson Matthey. Secondary refining offers technologically advanced companies the security of PGM supply on which they depend to remain competitive.

AEROENGINE MATERIALS

Since its earliest development the performance of the aero gas turbine has always been limited by the capability of available materials. This is particularly true in the high-temperature sections of the engine: the high pressure (HP) compressor, combustor and turbine (see figure 80). Here the peak temperature and pressure attainable and hence the thermo-dynamic efficiency of the cycle is limited by the temperature capability of the alloys used. Improvements in performance, fuel efficiency and emissions are therefore only possible through the use of advanced high-temperature materials systems. The materials used must combine temperature capability with the highest levels of mechanical integrity and resistance to corrosion and oxidation.

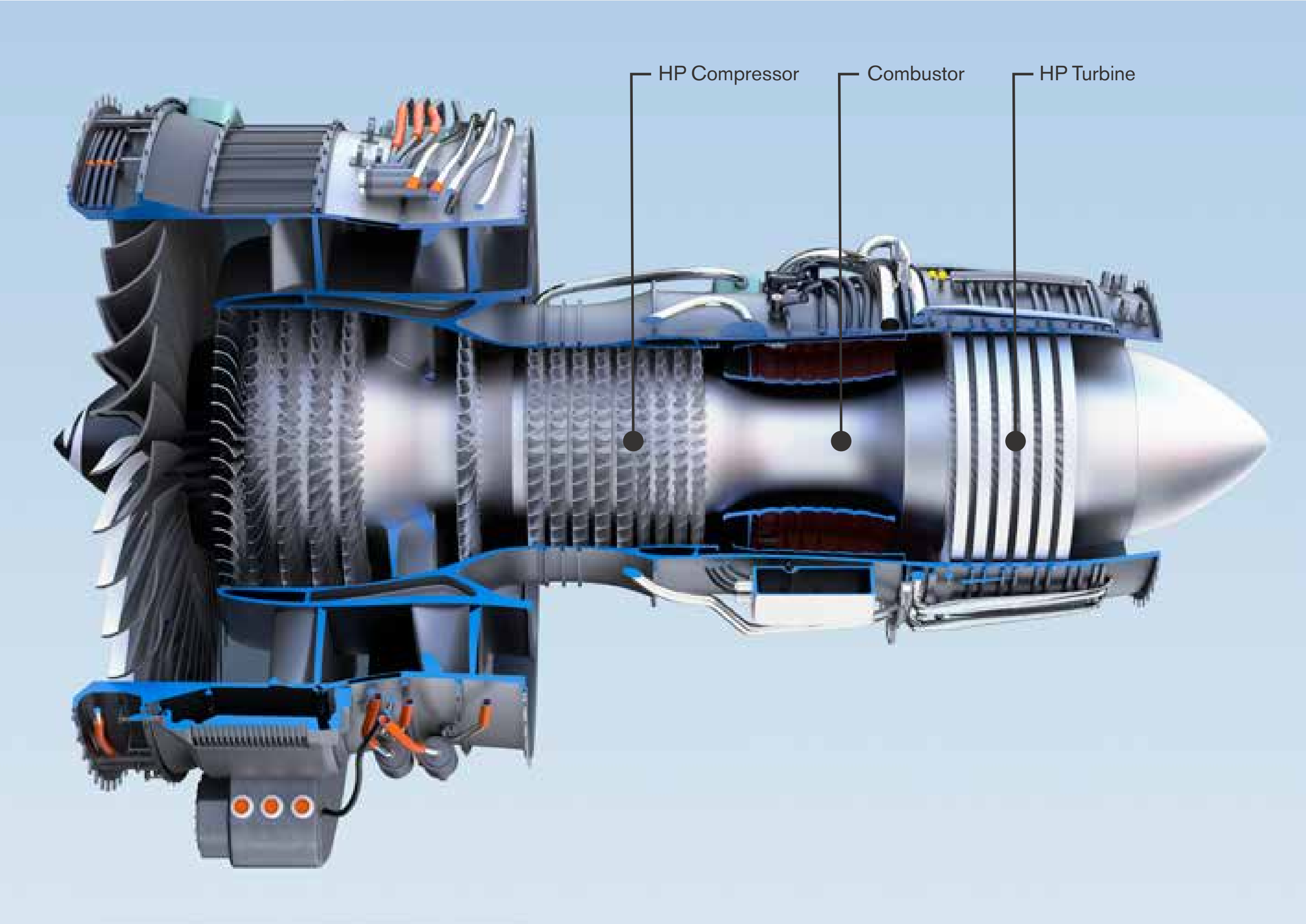


Figure 80: A cross-section of a modern gas-turbine engine indicating key engine components of relevance to this section.

ALLOY	Ni	Cr	Co	Mo	W	Re	Al	Ti	Ta	Nb	Hf	Fe	C	B	Zr
U720	Bal.	18	15	3	1.3		2.5	5.0					0.035	0.033	0.03
IN718	Bal.	19		3			0.5	0.9		5.1		18.5	0.04		
CMSX-4	Bal.	6.5	9	0.6	6	3	5.6	1	6.5		0.1				

Figure 81: Table shows the typical composition of the commonly used disc alloys IN718 and U720, and blade alloy CMSX4 (in wt%).

The high-temperature components in the engine, i.e., static casings and rotating discs and blades, are all manufactured from nickel-based superalloys. These materials have complex compositions, based on nickel, but containing numerous alloying additions (see figure 81). Each of these yields specific benefits while interacting in multiple ways with the other elements present. The overall composition is carefully balanced and optimised to meet a wide range of performance requirements, including high-temperature strength, fatigue and creep resistance, environmental resistance and density.

In addition to chemistry, the performance of an alloy in an application is determined to a large degree by its processing route and subsequent structure. Processing routes are component specific and tailored to provide the necessary properties. Raw-materials sources and manufacturing methods are rigorously controlled to ensure consistent product quality.

High-performance disc components are manufactured through powder metallurgy to achieve the highest levels of mechanical integrity, whereas HP turbine blades are manufactured via single-crystal casting to achieve extremely high-temperature capability (see figure 82).

Figure 82: A high-pressure turbine blade

This component is required to operate directly behind the combustor in a gas stream in excess of 1750K while rotating at more than 10,000rpm, extracting the energy necessary to drive the compressor. To survive in this environment the blades are cast as a single crystal with complex internal cooling passages and are subsequently protected by environmental and thermal barrier coatings.

The composition, as shown in table 1 for the alloy CMSX-4, contains multiple elements, some of which may be classified as strategic or scarce according to the terms of this report.

Nickel (Ni) is present as the majority element. It provides a strong, ductile matrix with good environmental stability and alloying potential. Cobalt (Co) is also present to strengthen this matrix.

Chromium (Cr) additions are made predominantly to provide environmental protection together with aluminium through the formation of stable oxide films.

Molybdenum (Mo) and tungsten (W) are added for resistance to high-temperature deformation. Rhenium (Re) is also a very powerful element for providing strength at the highest temperatures for extended time periods. In more recent alloy developments, ruthenium (Ru) additions were also introduced, working together with Re to provide the very highest levels of high-temperature performance, but with significant cost implications.

Aluminium (Al), titanium (Ti) and tantalum (Ta) all provide very significant strengthening through the formation of a high volume fraction of fine-scale particles within the matrix and their levels are optimised to control the amount and properties of these precipitates. Hafnium (Hf) is also present at a low level for a range of reasons, including the 'gettering' of oxygen and sulphur.

In addition to those elements present in the alloy itself, coating systems for oxidation and corrosion protection can contain platinum (Pt), typically in conjunction with Al or Cr. Ceramic coatings for thermal protection contain low levels of yttrium (Y) in the form of yttria-stabilised zirconia. These coatings are essential to protect the underlying metal from the aggressive engine environment and achieve desirable levels of performance and component life. Some of these elements can also be used in the manufacturing processes, for instance in foundry ceramics, but this is beyond the scope of this report.

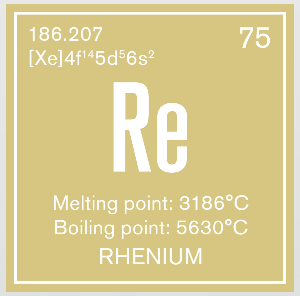
In general, the substitution of elements is extremely difficult since, as outlined above, each addition is present for a specific reason and contributes to the performance of the alloy and hence the system as a whole. Careful alloy design and processing control ensures that maximum benefit is gained from each percentage addition employed. Revert and recycling are used throughout the manufacturing and product life cycle to maximize material recovery. One exception is Ru, where in general manufacturers have sought to remove alloys containing this element from their products as a result of unacceptable price instability.

Future technology developments may bring additional materials into consideration for aerospace propulsion systems. The development of hybrid electrical propulsion will require high-performance magnetic materials using rare earth elements such as samarium (Sm) and again Co.

Energy-storage systems are also likely to require Co and Ni within high-performance electrodes.

Aspects of sourcing and control of the alloying elements of major interest for this report, i.e., Re, Ta, Co and Ni. Co and Ni have already been discussed earlier in the report. In each case secure and sustainable supplies must be assured at acceptable cost to support the production demands for engine components. Ethically focused OEMs, such as Rolls-Royce, take robust measures to ensure elemental materials are sourced to recognized international standards with regard to conflict and wider human-rights issues, such as OECD 'Due diligence guidance for responsible supply chains of minerals from conflict affected and high risk areas'.

Rhenium



Rhenium is a by-product of molybdenum production, which itself is a by-product of copper production. Rhenium sources are primarily found in Chile, USA and Poland. Rhenium is not mined or produced in any regions classed as "conflict" or associated with any human-rights abuses.

Some 80% of rhenium demand is for aerospace superalloys, with the balance being used in catalysts in the petro-chemical industry. Increasing aerospace demand and the threat of an additional use in liquid-to-gas distillation created a tight market during the mid-2000s and the price leaped six-fold in two years to nearly $12,000/kg, (see figure 8).

Tight primary supply and accompanying high prices in 2006/07 triggered the creation of the rhenium recycling industry. This captured rhenium units previously lost in producing other nickel superalloys.

At the same time OEMs applied pressure on melters to utilise more of their closed-loop solid revert. This consisted of cleaned up casting foundry solids, scrapped blades and eventually EoL blades. Increased revert reduced the virgin rhenium units required and reduced costs. Nowadays, common rhenium-containing superalloy melts use ~40% revert in the melt composition.

Over the years increased primary supply, various OEM rhenium reduction programmes, increased revert usage and the generation of rhenium units via the rhenium recycling of grinding wastes have caused the rhenium price to plummet to pre-crisis lows, see figure 83.

It is believed that aerospace OEMs place long-term agreements (LTA's) for rhenium directly with rhenium suppliers to cover their requirements as rhenium is not traded on any exchange.

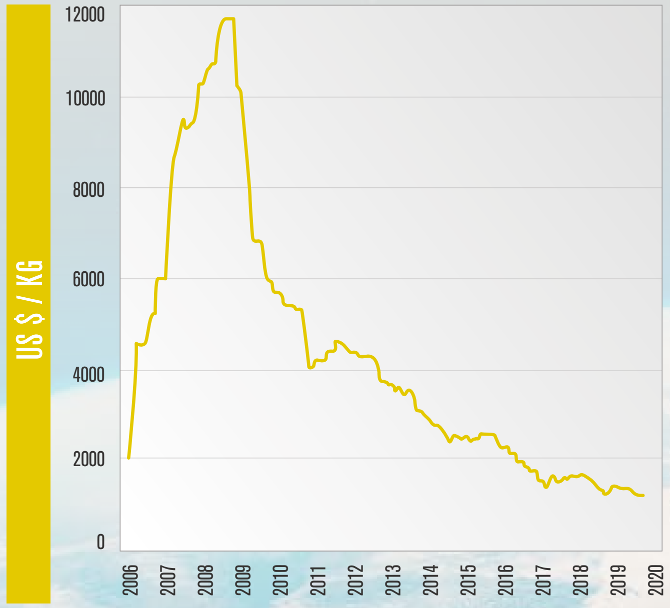
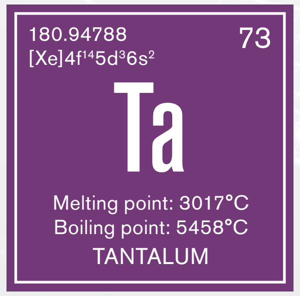


Figure 83: Rhenium price history

Tantalum



Tantalum is supplied from two sources; the mining of Tantalite ore and the revert of various scrap and recycling of wastes. Tantalite ore is supplied via both conventional mining in heavily mechanised open pit/underground mines and produced via artisanal, labour intensive methods, in typically central African countries. Tantalite ores are found primarily in central Africa (Democratic Republic of Congo (DRC) and bordering countries), Australia and Brazil.

Tantalum is one of the four "conflict minerals" along with tin, tungsten and gold which are produced in central African countries. Ethically focussed companies, such as Rolls-Royce (RR), have, since 2010, only purchased and contracted tantalum supply from ethically approved sources, i.e. approved by the Responsible Mining Initiative, formerly EICC.

The tantalum capacitor industry consumes approx. 50% of World supply with other industries, such as superalloys, sputter targets, carbides and chemicals making up the remaining demand.

Starting in 2008 some large tantalum mines were closed, central African supply was classed as conflict minerals and the remaining primary supply (Brazil) was removed from the market via a long-term contract. In tandem with dwindling ore supply, the recovery, starting ~2010, of the consumer electronics (capacitors) and aerospace industries saw prices near triple, (see figure 84).

In 2013 prices started to trend downwards, due to two main factors. First the creation of ethically produced, certified and auditable ores out of central Africa, driven by the capacitor makers. Second was the increased quantities of tantalum in closed loop revert, at similar percentages as rhenium containing alloys, and the increased recycling of tantalum containing scraps and wastes. Both reduced the virgin units required.

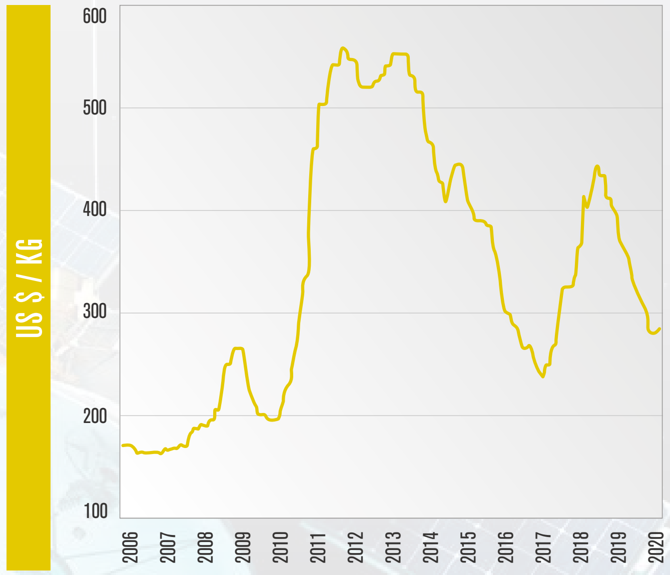


Figure 84: Tantalum price history

Prices started an upward trend at the end of 2016 this time due to the Chinese Government shutting polluting tantalum smelters and processors on environmental grounds. As processors cleaned up their factories licences were granted and supply (and prices) returned to normal levels.

Since tantalum is not traded on any exchange it is usually contracted by OEM's over a one to three-year timeframe in order to secure prices and protect supply.

SUMMARY FOR PRIMARY MATERIALS

The technology-critical metals metal market often operates in a different way to the market for major metals, resulting in specific challenges for access. Several of these metals are not traded on the London Metals Exchange, the mining and refining is often state controlled and this has resulted in near-monopoly situations in these supply chains for some technology-critical metals.

The true cost of the environmental and ethical impact of technology-critical metals is not currently factored in to the price of the metals. There are international measures being proposed, however, to resolve this which would have an impact on the viability of mining and refining operations globally.

Ultimately the UK will need access to raw materials around the globe and resource diplomacy should form a key part of any UK technology-critical metals strategy. The City of London is an epicentre for global mining operations, consultancy and finance and this should be leveraged in developing strategic plans around these technology-critical metals.

The UK has a few indigenous reserves of these technology-critical metals (e.g. - lithium, tungsten) and we should accelerate the development of these sites by updating the regulatory environment.

Without the refining capacity to convert the extracted ores into metals, alloys and materials there is no point in gaining access and the UK will miss out on some of the highly valuable parts of the supply chains (e.g.- motors and batteries). The UK has key companies in the supply chains for technology-critical metals, as outlined in the report, but also supply-chain gaps that need to be filled in order to capitalise on the large economic opportunity for the downstream markets. Any refining capacity should support both primary and secondary markets, with secondary materials covered in detail in the next section.

The supply issues around different technology-critical metals are complex and often targeted measures are required for each subset of material, as outlined in the recommendations.

Large multinational companies can put measures in place to protect themselves from the price volatility of technology-critical metals, by, for example, hedging on metals and putting in place long term agreements. Around the world we are seeing companies vertically integrating down the supply chains to secure access. It was clear however that SMEs are particularly vulnerable to price volatility in the technology-critical metals markets and examples were presented at the commission where companies had moved to other regions of the globe where technology-critical metals access could be guaranteed at controlled prices.

SECONDARY MATERIALS

CURRENT **RECYCLING RATES**

A secondary market for technology-critical metals would provide a strategic resource for the UK and diversify the supply where risks exist. However, there are technological, economic and societal challenges that must be addressed to make this happen. Current re-use and recycling rates for many of these technology-critical metals are low (see figure 85)[1], although there are examples of successful circular economies. For example, while only 1% of rare earths are recycled, rates of 25% for platinum and over 50%[119] for rhenium (which provides the majority of supply to the aerospace industry) are being achieved.

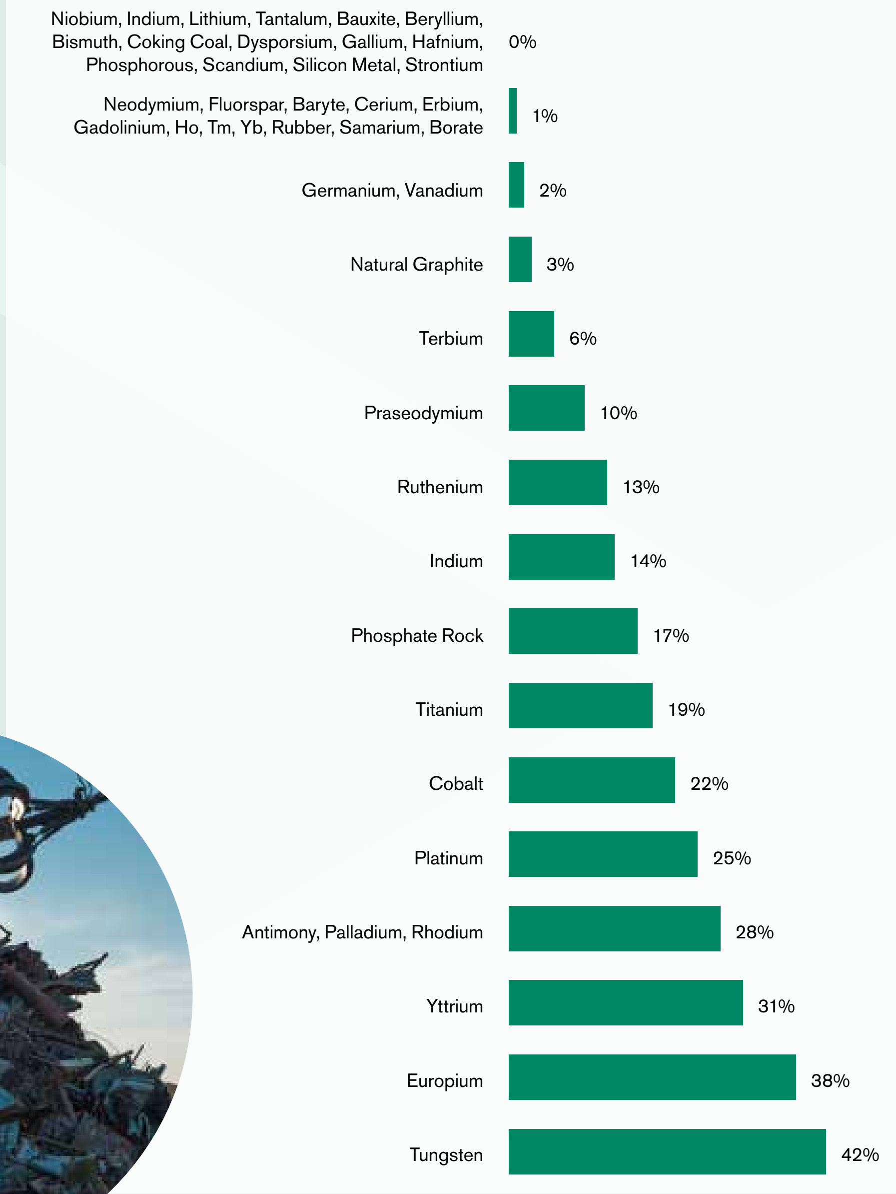


Figure 85: European Commission report on critical materials 2020.[1]

The Advantages of Recycling

Developing secondary markets for materials and products can shrink the environmental footprints for manufacturing, lower the costs for production and reduce greenhouse-gas emissions (see figure 86).

Recycling can also avoid the social and health impacts outlined in the primary section, but only if high-quality recycling processes are applied.

Primary	kt CO_2/t Primary	kt CO_2/t Secondary	% reduction
Aluminium	383	29	92%
Copper	125	44	65%
Ferrous metals	67	70	58%
Lead	163	2	99%
Nickel	212	22	90%
Tin	218	3	99%
Zinc	236	56	76%

Figure 86: CO_2 footprint of secondary production of metals compared to primary[120].

Carbon Footprint of Metals From Primary and Secondary Production

Recycling aluminium is around 92% more energy efficient than primary production[120]. The Waste and Resources Action Programme (WRAP[121])has estimated that the adoption of resource-efficient business models, such as remanufacturing, repair, leasing and recycling, could deliver a net GVA gain of £86bn for the UK by 2030, with 21million tonnes of materials avoided and 37million tonnes of materials diverted. A recent OECD report on global material resources concluded that recycling will become more competitive than the mining of minerals due to projected technological developments and changes in the relative prices of production inputs. This will mean the recycling sector could grow faster than that of mining. The report also notes that the high labour costs for secondary production often hinder the expansion of the market for secondary non-ferrous metals[122].

UK Government Strategy

The UK Government published its strategy for waste in December 2018 entitled “Our waste, our resources: A strategy for England”[123]. The report covers plastics, Waste Electrical and Electronic Equipment (WEEE), batteries, automotive and food waste, but there is little reference to technology-critical metals. It is important to note that although technology-critical metals are present in these waste streams, their use is far broader than these sectors and a comprehensive policy on the circular economy should include all markets.

Technology-critical metals have unique challenges for the waste industry. As they are often only present in small quantities, they cannot be processed using conventional technologies, and in some cases the supply-chains do not exist.

Ultimately, as set out in the UK Strategy for Waste, any circular-economy policy should maximise the value of a resource while minimising waste and its impact on the environment.

In the UK Government waste and resources action plan and the recently published DEFRA[124] report on waste management there is a clear drive to develop a waste hierarchy (see figure 87). The first step should be to avoid products entering the waste stream and to minimise the production of waste materials during manufacture. Next, materials should be re-used where possible, and recycled if this is not realistic. Finally, for materials that cannot be recycled, for some there is a possibility of energy recovery through thermal processes. If none of these approaches are possible then waste should be treated to make it inert or safe with disposal as a last resort.

It should be noted that recycling covers a range of processes. Bulk-materials recycling processes are not necessarily suited to the recovery of critical materials. Many of the materials-separation techniques designed for bulk materials produce poor returns when recovering critical materials.

Furthermore, while we are familiar with the recycling of consumer products, there is significant potential to recycle scrap materials within manufacturing processes. There are significant gains to be made in new manufacturing techniques for many of these materials, for example, for rare earth magnets where the losses during manufacture can be from 20 to 60%. When these materials enter the waste market we should be reusing the products or components, or keeping the material in a processed form by re-using them in a “short-loop” recycling process to minimise costs. Some specific examples are described later in this report. As the materials cascade down the waste hierarchy, the ability to keep these materials in the UK supply chain diminishes as the value decreases and the processing will have to compete with cheaper competitors around the globe. This is one of the reasons why 80% of the metals we extract in the UK in the recycling industry are shipped offshore for processing[125]. In fact the largest tonnage of waste exported from the UK is for metals compared to all other waste streams

The waste and resources action plan (WRAP) provides good-practice guides for the re-use and recycling of WEEE, but there are specific challenges that exist for technology-critical metals, which are outlined in this report.

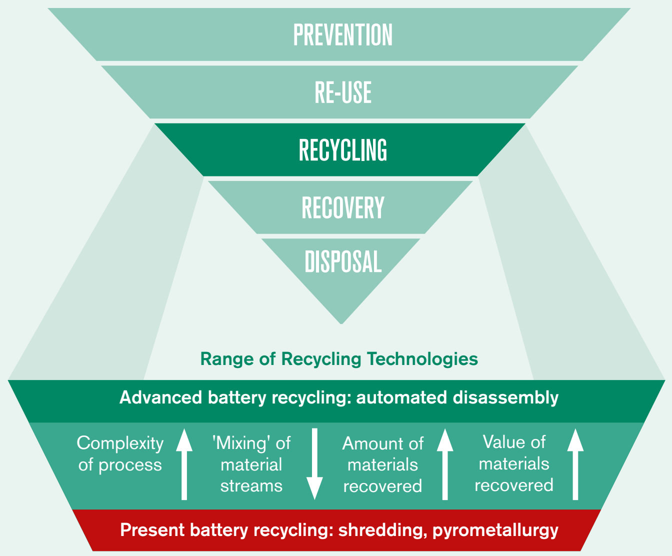


Fig 87: The Waste Management Hierarchy & Range of Recycling Options for lithium-ion batteries[126]

CHALLENGES FOR THE RECYCLING OF TECHNOLOGY-CRITICAL METALS

Technology-critical metals are particularly challenging to recycle, in part, due to the small quantities of these materials in many applications, but also due to the design of the components where they are used.

Society is rapidly shifting from a fossil fuel based economy towards clean growth, where electrically driven products will dominate. This is resulting in the rapid expansion of wind-turbine technologies, photovoltaics, robotics and electric motors and batteries for EVs[127]. These technologies are still being optimised for performance and therefore there is often a lack of design standards, which presents challenges to the recycling/re-use industries. It is clear that at present design-for-recycle/re-use is not one of the major drivers for many of these applications. Often the technologies and supply chains to recycle some of the technology-critical metals are not mature or do not exist, so the machine designers sometimes have a lack of information from the downstream market. There is also a risk that by standardising a design this limits innovation and therefore the efficiency of electrical equipment.

Although a large proportion of technology-critical metals are contained in waste electrical equipment (WEEE) and the automotive sector, their use is far broader than this. However due to the life cycle of WEEE, in the short term, this sector is likely to provide a large proportion of technology-critical metals. As an example a mobile phone contains rare earth magnets in the speakers, vibrator and optics; they contain cobalt and nickel in the battery and tantalum in the micro capacitors (see figure 88). Over 61% of the world's population owns a mobile phone. The number of mobile devices is growing at a rate five times faster than the number of people. Only around 12%[128] of them are appropriately recycled. 350,000 mobile phones a year were dumped every day in 2010 – about 15 million phones.

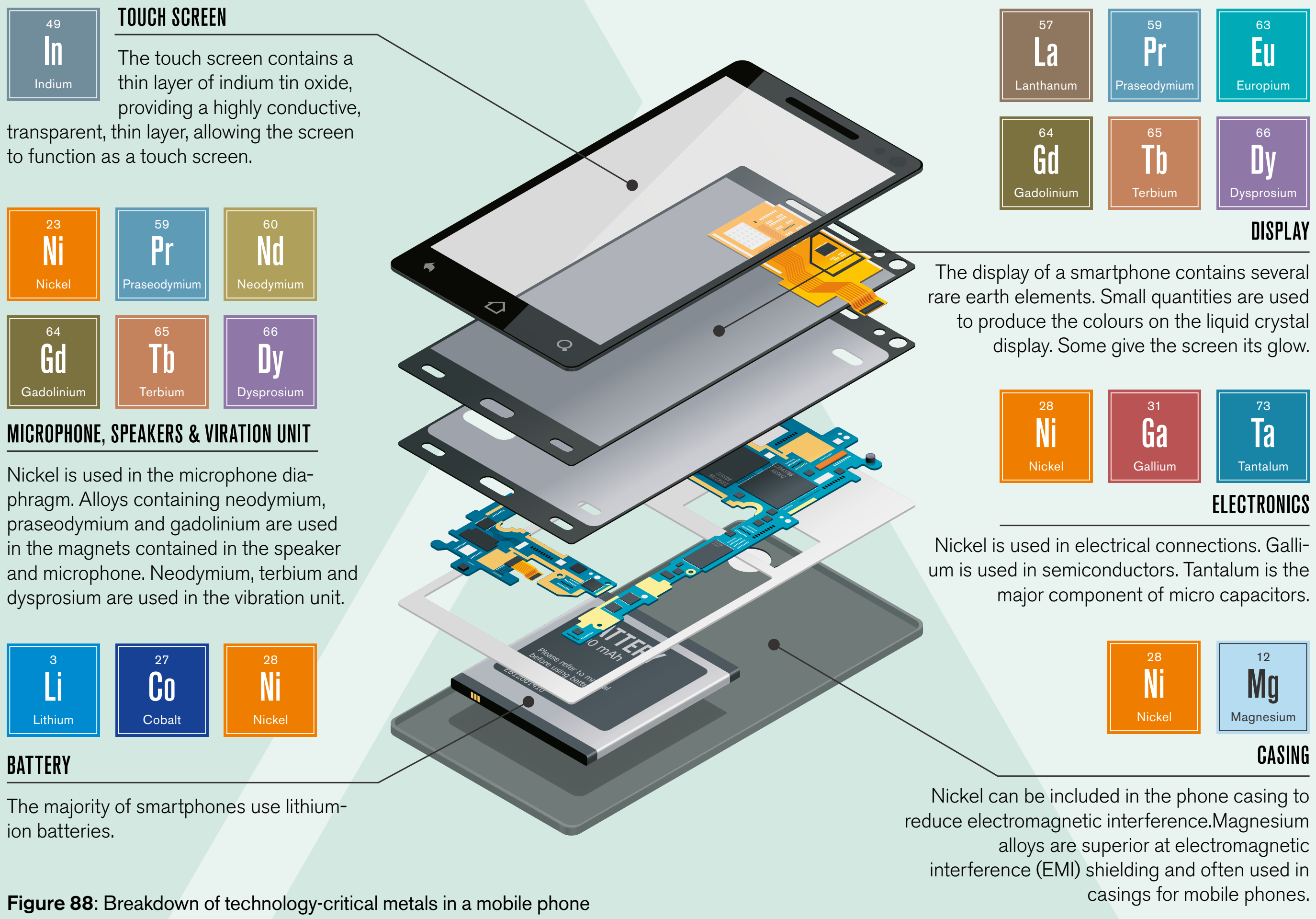


Figure 88: Breakdown of technology-critical metals in a mobile phone

CURRENT RECYCLING INDUSTRY

WEEE and end-of-life vehicles(EoL) tend to be treated as waste rather than as assets to be kept in the supply chain at the highest levels of function and value. They are often treated by coarse shredding and separation with a focus on the main materials by weight.

The UK has around 1600 firms[129] that process EoL vehicles. This ranges from very small companies that manually strip cars to large, multinational businesses that shred EoL waste and physically sort the materials prior to the metals being shipped on for further processing. The average car arriving at a recycling plant today is around 14 years old and based on an internal combustion engine (ICE). Approximately 70% of the car consists of ferrous metal, 9% plastics, 8% non-ferrous metals, 3% tyres and 3% glass by weight (see figure 89). Such a vehicle is relatively simple in terms of materials compared to the EoL vehicles that will come online in 10 years, when larger volumes of hybrid and electric vehicles will reach the end of their useful lives.

The current target for re-use and recycling of an ICE car is 95%[130], but this is a weight-based figure and does not distinguish between materials. Given the relatively small amounts of critical materials in ICE cars, they tend to fall foul of this target as they do not represent a significant proportion of the weight, despite being important to the functionality of the vehicle. The importance of these materials will only increase in the coming years. It should be noted that there is legislation in place for vehicle batteries (both lead acid and lithium-ion)[131], which will be discussed in the governance section of the report.

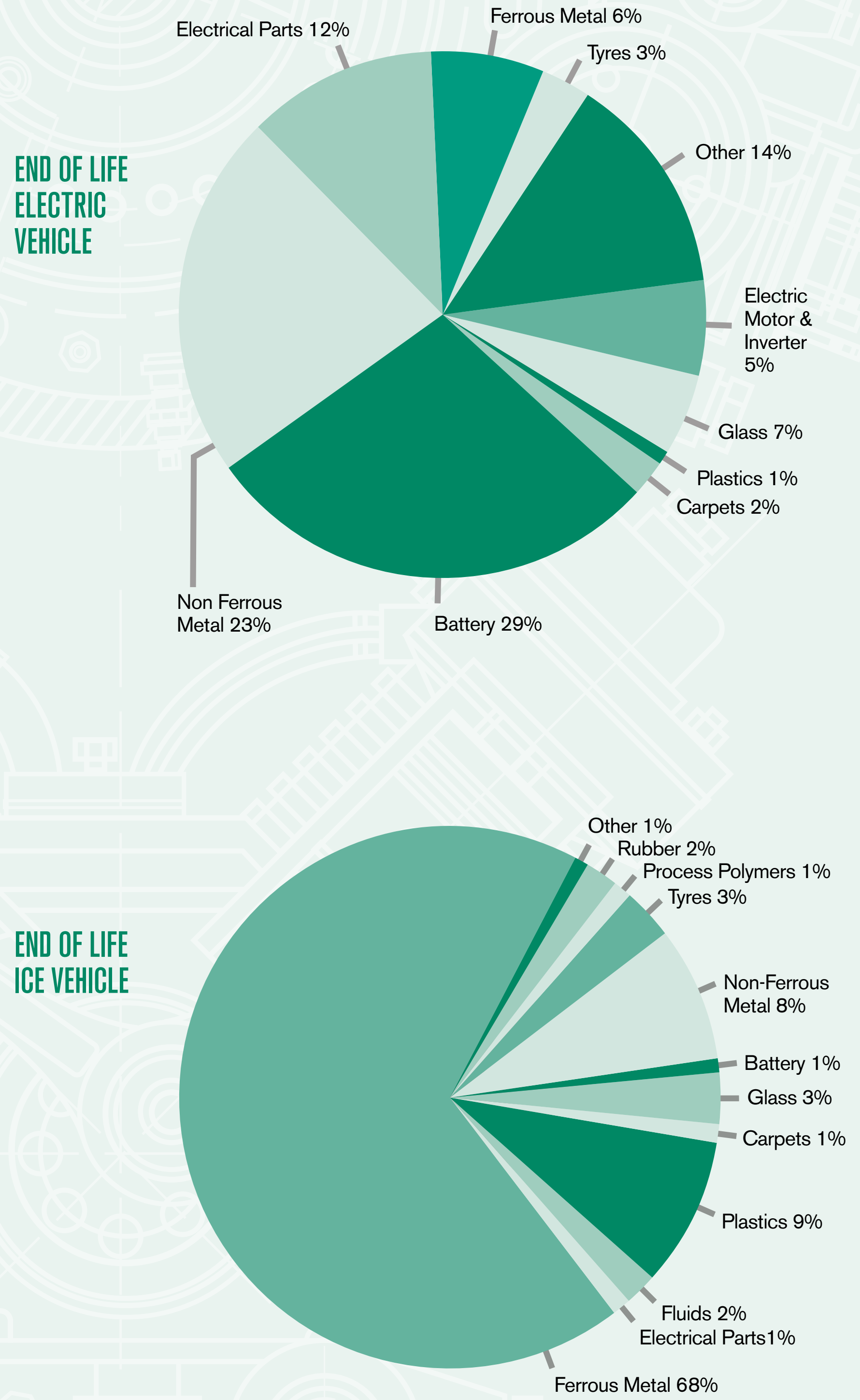


Figure 89: Composition by weight of a typical end of life electric vehicle and an ICE vehicle.

CURRENT **RECYCLING PROCESSES** FOR ELECTRONICS AND AUTOMOTIVE APPLICATIONS

When a car reaches its end-of-life (EoL) in the UK, it passes through multiple processes to liberate components from the vehicle or to separate materials. Initially, the car will pass through a depollution facility where the oils, gases and fluids are drained from the car. The tyres, battery, catalytic converter will then be separated from the vehicle. This is performed either because there is legislation driving the recycling (eg., - the battery) or because there is an economic value that is more than the manual labour costs for separation. The engine block is pulled from the vehicle; the shell of the vehicle is then crushed and shredded. The shredded material, which is typically below 10 cm is then processed in an auto-shredder-residue (ASR) plant (see figure 91).

Figure 90: Depollution facility (EMR)

At an ASR plant the shredded feed is separated into different materials, including ferrous metals, plastics, non-ferrous metals, combustible materials and brittle materials (e.g., glass). This is performed using physical sorting techniques including magnetic separation, eddy-current separation and density/size separation. All of these use some physical, electrical or magnetic property of the material to distinguish it from the other components/ materials (see figure 93). Electronic goods are also often shredded and passed through similar physical processes to liberate different materials.

The metals that are extracted from these processes are passed onto downstream processing facilities, which are either based on chemical techniques (e.g., hydrometallurgy) or pyrometallurgical processes where the metals are melted down and the impurities removed. At present, around 80% of the metals that are extracted in the UK are exported to different regions of the world. This is partly due to a lack of investment and support in the UK's materials-processing industries.

Figure 91: Auto shredder residue (ASR) plant

Figure 92: Shredded electronics

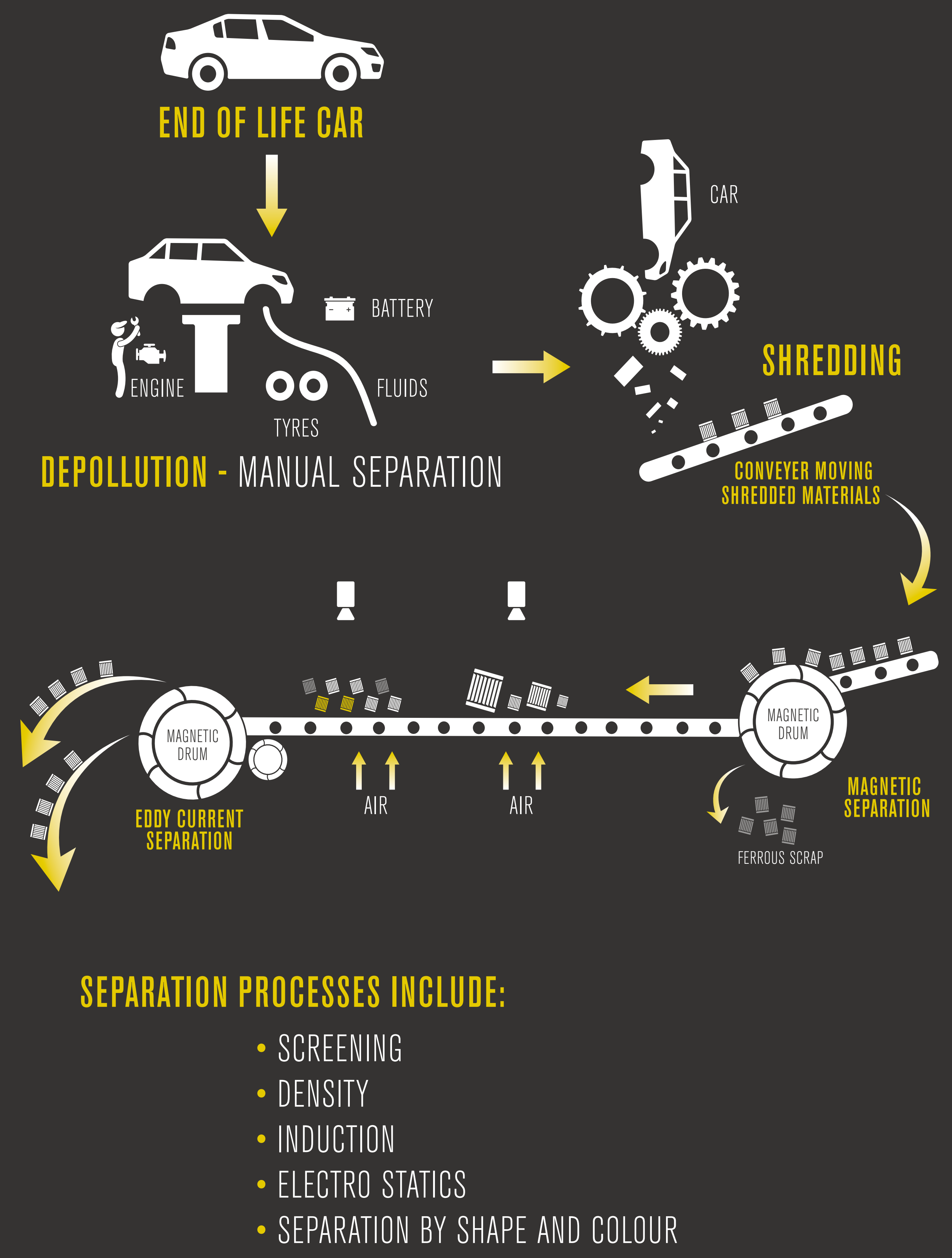


Figure 93: Examples of processes uses at an ASR plant.

BARRIERS TO THE RECYCLING OF TECHNOLOGY-CRITICAL METALS

There are technical, economic, legislative and societal barriers that have so far prevented a circular economy from developing for many of the technology-critical materials and components outlined in this report.

In a hybrid or fully electric car the range of materials is much wider than in internal combustion engine vehicles (ICE), while the components are often more complex. For example, the drive train will contain a large lithium-ion battery pack (see figure 94) and power electronics that deliver the electrical power to a drive motor. This is supplemented by regenerative braking systems, cooling fans, screens, electrical sub-components, which all contain technology critical metals. Many of these components contain a complex range of multicomponent materials (see figure 95), rather than single materials, such as a ferrous engine block, which are present in ICE vehicles. Therefore, the recycling challenge will become more complicated in the future and many of the current recycling processes that are applied to products containing critical materials either cannot be applied or result in a lower grade of material that is challenging to recycle in the UK.

One of the other major challenges is related to collection of products containing technology-critical metals. There are good collection systems for EoL vehicles but much lower collection rates for WEEE. Although it is extremely important, this topic is well covered in other publications and is not a focus here [44].

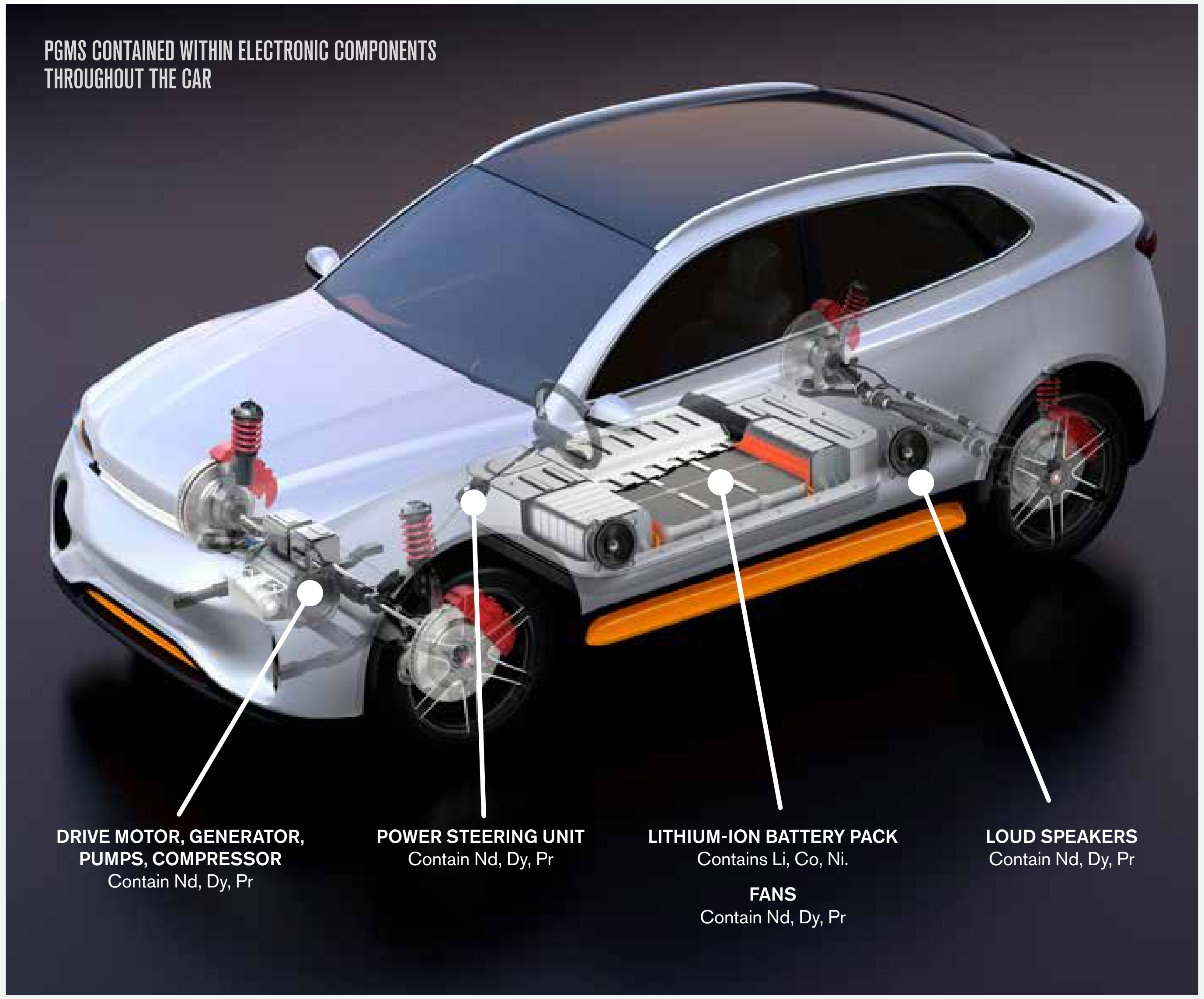


Figure 94: Examples of components that contain technology-critical metals in an electric vehicle.

THE SPECIFIC CHALLENGES AROUND RECYCLING LITHIUM-ION BATTERIES ARE EXPLORED IN MORE DETAIL ON PAGE 113

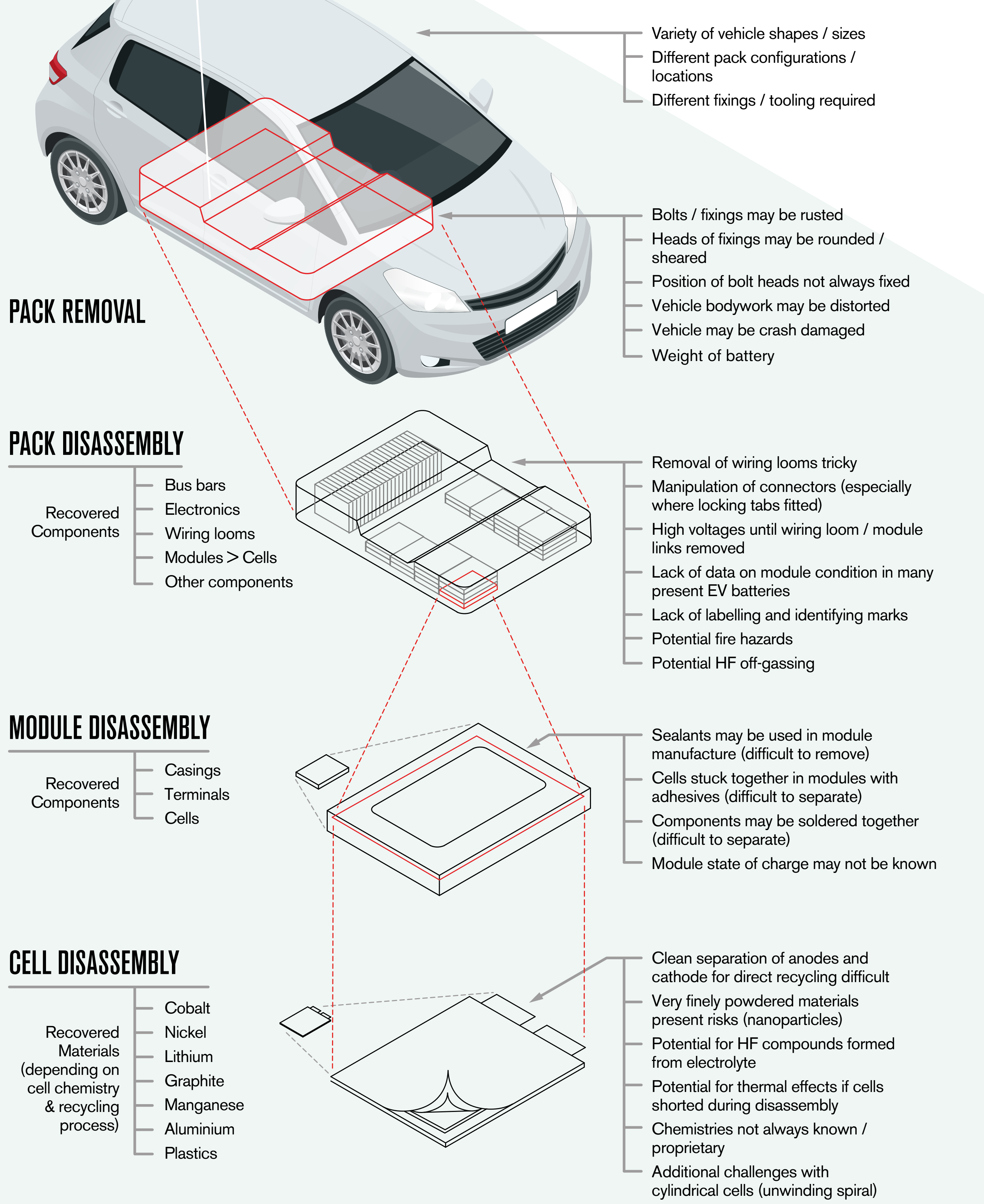


Figure 95: The challenges of disassembling lithium-ion batteries at different levels of scale[126].

BOX OUT
013

Rare earth magnets

What is the recycling opportunity ?

As outlined in the primary materials section of this report, the rare earth market is dominated by the permanent-magnet sector (Nd-Fe-B and Sm-Co magnets). This is split between many different applications[54], which means collecting these waste streams can be difficult. The EU ERECON report (2015) attempted to identify the “low hanging fruit” for the recycling of rare earth magnets based on Nd-Fe-B (see figure 96). The ranking list took into account the availability of the scrap, the ease of identifying the products, the collection rates, the amount of material in the application, the rare earth fraction in the material, the ease of removing the rare earth from the application and the extent to which particularly scarce REEs like dysprosium are used in those applications. It should be noted that there are other markets that should be taken into account, for example, pumps, and the UK should have its own priority list.

1. Hard disk drives, DVD and CD players
2. Automotive applications
3. Motors in industrial applications
4. Loudspeakers
5. Air-conditioning compressors
6. Magnetic separators
7. Mixed electronics
8. Electric bicycles
9. Wind turbines

Figure 96: ERECON prioritisation list for the recycling of rare earth magnets[54].

There have been multiple top-down studies investigating the potential waste flows and recycling potential for rare earth magnets in the EU and worldwide, but at present none for the UK [132,53]. The results show significant variations, partly because they make assumptions about the possible recycling rates prior to industrial-scale recycling being put in place. It should be noted that there is a lack of good quality data about where magnets are located in waste streams, which makes identifying and separating these components difficult.

Shultz et al [132]. proposed that 18–22% of light-rare earth demand and 20–23% of heavy-rare earth demand could be met between 2020 and 2030 worldwide. This equates to around 15,000 tonnes per annum (tpa) globally, in their pessimistic scenario, and 25,000 tpa in their optimistic scenario. Reimer et al [53]. attempted to predict when substantial Nd-Fe-B extraction could be expected in the EU from recycled sources. The paper highlighted that by 2025, 18,000 tonnes of potential return flows of Nd-Fe-B will become available, but predicted a very low recycling rate of around 600 tonnes in the same year. Part of the problem with these studies is in the technological assumptions that are made for the rate of extraction and reprocessing compared to the state of the art in this field, because the market is immature.

It should be noted that the mix of applications coming to end of life will change over the next 10-25 years, with large volumes of automotive waste and wind-turbine assemblies. The UK could use this as a strategic resource and manage this to the benefit of the UK.

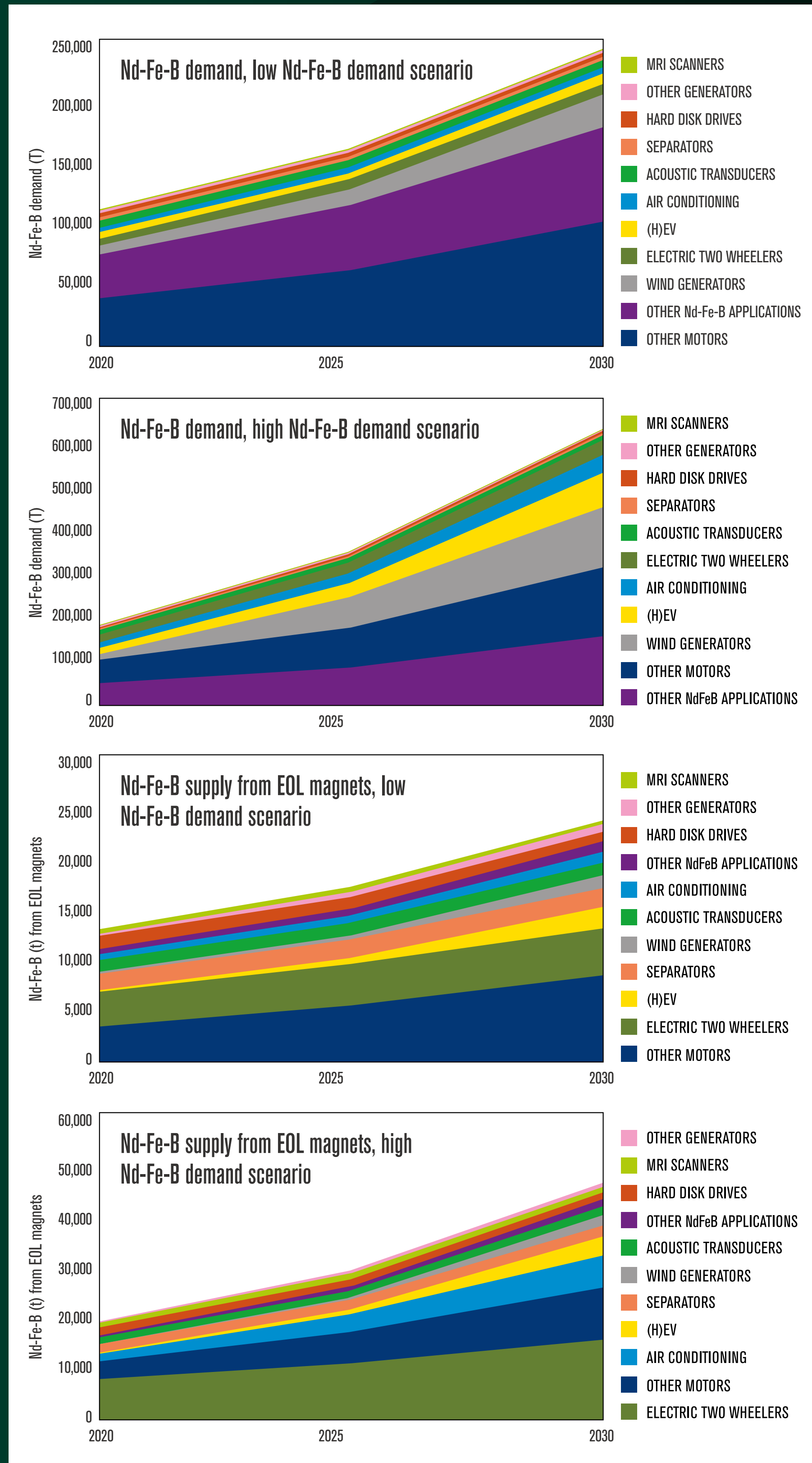


Figure 97: Nd-Fe-B demand and net supply from EOL magnets (losses during collection & disassembly have been subtracted), low and high Nd-Fe-B demand scenario, years 2020-30, tonnes Nd-Fe-B. [ref:Shultz et al.][132]

WHY IS THE RECYCLING RATE **LOW?**

Rare earth magnets are found in a wide range of applications. In an electric vehicle the magnets can be located in over 50 different applications, including drive motors, power steering motors, loudspeakers and seat motors. Most of these applications use soft magnetic laminations (Fe-Si), with the magnets very often glued or potted in epoxy resin (see figure 99). If the applications are left in the car during shredding the rare earth magnet material will be lost.

Figure 98: Toyota Prius generator and motor.

Figure 99: Rotor from an electric motor with glued Nd-Fe-B magnets.

This is due to the fact that if a permanent-magnet motor containing rare earth magnets is passed through a conventional shredder plant, the soft-magnetic laminations distort (see Figure 100) and can blunt the shredder's tooling, leaving the extremely brittle rare earth magnets to be crushed into a powder. This powder is permanently magnetic and sticks to the shredder and to the other ferrous scrap (see Figure 101). At an ASR plant it is possible to

Figure 100: Rotor from an electric motor after shredding

Figure 101: Shredded hard disk drives

see permanent-magnet powder cascading down the side of the shredder plant (Figure 102). The powder is very air sensitive, so it oxidises, breaks apart and becomes an increasingly fine powder. A study by Rowson et al. showed that the technology-critical rare earths are to be found in the finest fraction of the shredder plant, in the metallic dust, or they are stuck to the shredder itself[133]. At this stage the Nd-Fe-B is contaminated with other materials and has little economic value due to the high costs of separation. The downstream re-processing routes are also very limited at this point due to the oxygen contamination and impurity levels coming from the other waste. This is one of the reasons why less than 1% of the rare earths are recycled today. It should be noted that WEEE is often shredded and processed in the same processing plants. Exactly the same problem exists for Nd-Fe-B magnets in these waste streams (see figure 101).

Figure 102: Permanent-magnet powder cascading down the side of the shredder plant

DESIGN FOR RECYCLE

If the various components of the car cannot be shredded and then separated to remove the technology-critical metals, then some level of dismantling is required prior to shredding (see figure 103). Unfortunately, many of these technology-critical metal containing products are very complex, making them time consuming to dismantle manually. In many cases the associated costs can exceed the value of the extracted materials. However, only a few studies have been performed to ascertain the economic case for the extraction of many of these components pre-shredding and therefore feasibility studies are required to determine this. This needs to be performed across a wide range of applications.

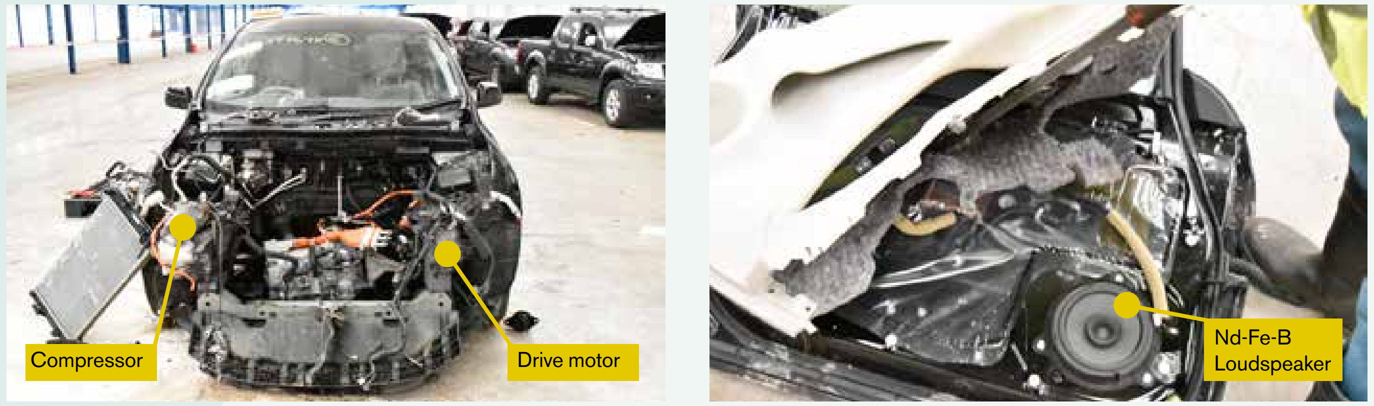


Figure 103: Dismantling of a Nissan Leaf to expose Nd-Fe-B magnet containing components

Although shredding is a quick way of separating bulk materials it can also produce large quantities of impurities in technology-critical-metal waste streams and therefore destroy value and increase the complexity and environmental footprint of the downstream reprocessing technologies. Disassembly as a precursor to recycling could retain more value; however, it is fraught with challenges and is labour intensive if done manually. By way of example, (see figure 104) shows the process of disassembly for an electric vehicle motor from a vehicle

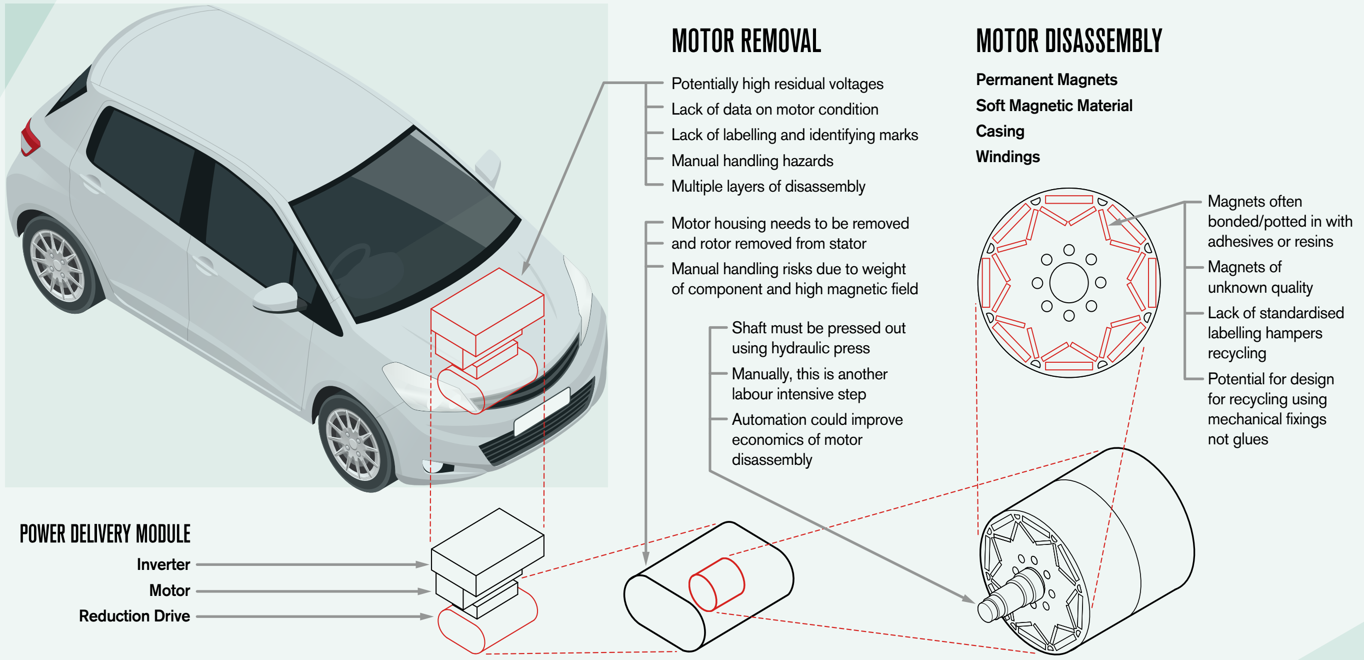


Figure 104: Challenges of EV motor disassembly at different scales.
Reference: Harper, G., Degri, M., Awais, M., Walton, A., (2021) Image of Electric Vehicle Motor Disassembly Challenges, UBIRA eData, University of Birmingham https://doi.org/10.25500/EDATA.BHAM.00000605 [Website] [Accessed: 16/03/21]

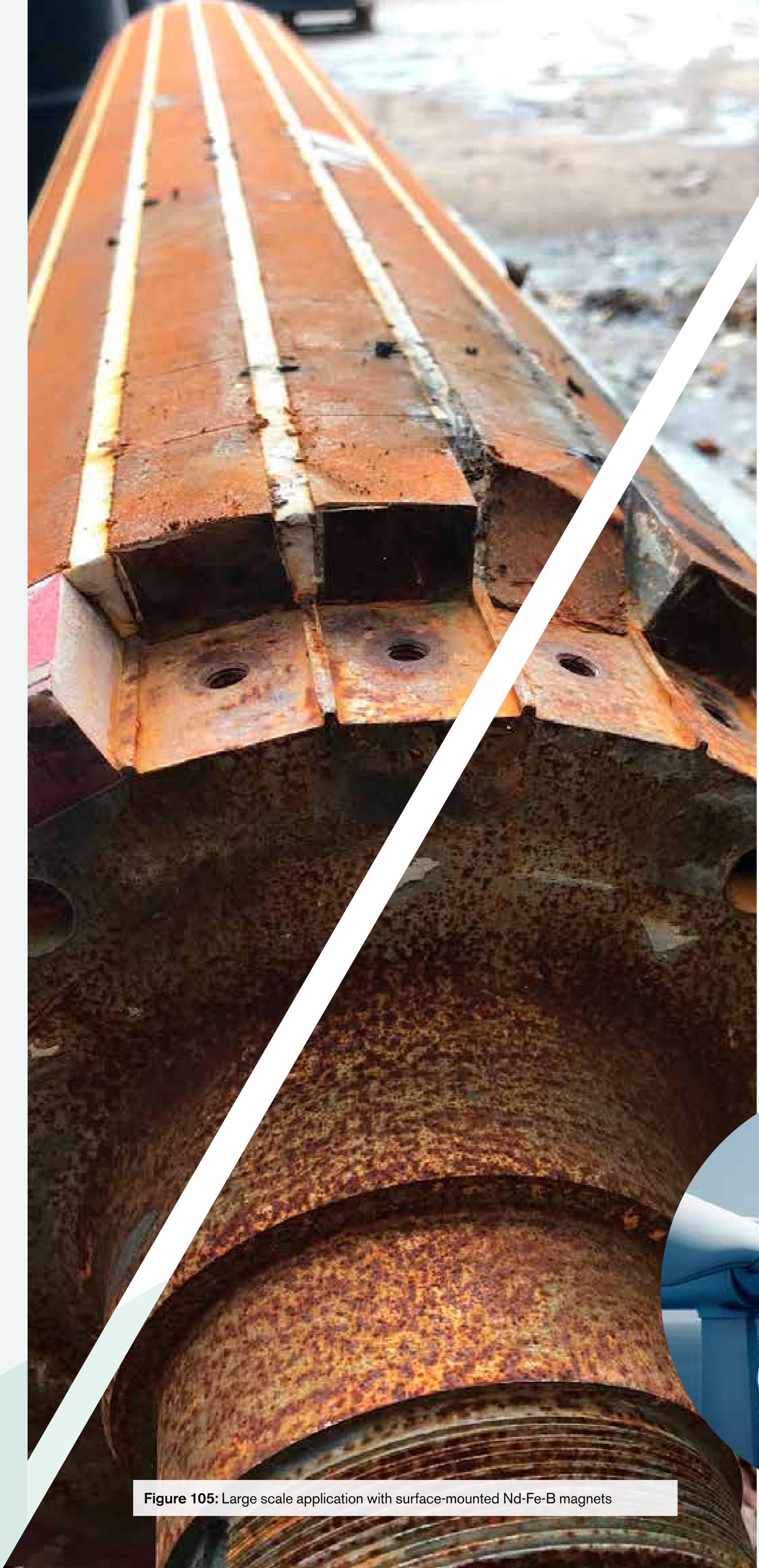


Figure 105: Large scale application with surface-mounted Nd-Fe-B magnets

It is also important to note that not all of the rare earth application sectors will suffer from the same complexity of design. For example, wind turbines, MRI scanners and separators at recycling plants will contain large magnets, which contain anywhere from 150 kg up to 4 tonnes of Nd-Fe-B (see figure 105). Although these markets are long term, given the lifetime of these products (10-25 years), there is an argument that this should be secured as a national resource and viewed as a possible strategic supply for the future.

Design for recycle and re-use will be a key component in driving up the recycling rates for rare earths, but also many of the other technology critical metals. This is particularly important if the product / material is to be kept in its highest form in the waste hierarchy for re-use or recycling. Ultimately, the design will affect the quality of material that can be extracted for downstream re-processing. For magnets those design decisions need to be made with the downstream processors and should factor in the glues, binding structures and coatings, all of which affect the quality of recycled magnet that can be made from the material. There are already a few electrical machines that factor in some of these design choices but, they are few and far between.

BOX OUT 014

Sensing and Automated Sorting of TCM Containing Waste

In order to recycle rare earth magnets the magnet containing components require removal prior to shredding. For some components the costs of manual disassembly are likely to be too high in the UK. For this reason researchers and companies have started to develop automated systems for sensing and sorting waste. For example, in the EU FP7 Remanence[134] project an automated system was developed for sensing the magnetic flux from magnets in hard disk drives then removing this part of the drive automatically (see figure 106/107). This is being extended for different magnets containing waste streams in the EU SUSMAGPRO project. In another example, Apple have developed an automated system for disassembling particularly types of i-phones[135].

Waste handling presents significant challenges for robotics as most end-of-life products are not set sizes and shapes. However it is clear that these technologies will have a role to play in the future. If they can be implemented at industrial scale they would allow for re-use of components, improve the range of materials that could be recovered, potentially reduce costs and reduce the environmental footprint of the downstream processes. Similar automated processes are now being investigated for lithium-ion batteries, not just for these reasons, but also because of the safety concerns associated with the disassembly of these products[136] this is one of the activities of the ReLiB project funded by the Farraday Institution.

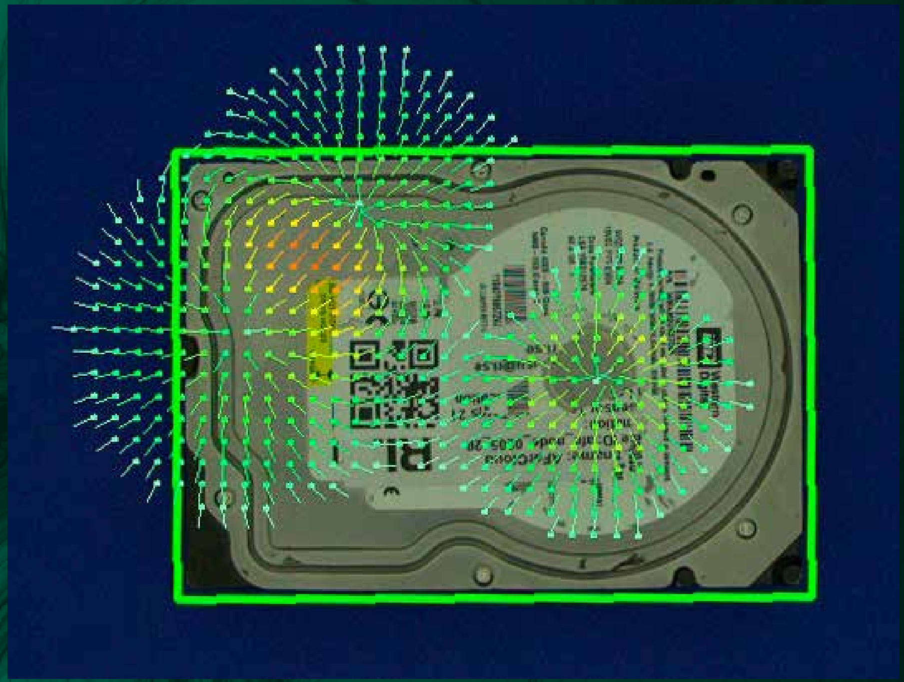


Figure 106: Sensing of magnetic flux above a hard disk drive. Developed by RISE Sensor Systems as part of the REMANENCE project.

Figure 107: Automated handling and separation of voice coil motor from hard disk drives. Developed as part of the REMANENCE project.

SEPARATION AND RE-PROCESSING

One of the major problems with the recycling of rare earth magnets is how to separate the material from the component's binding structures and coatings. This is partly because of the very high magnetic fields that can be generated as well as problems with glues. Several methods have been proposed to demagnetise and separate magnets from waste streams, including thermal (>330°C), magnetic and a process which uses hydrogen called HPMS (Hydrogen Processing of Magnet Scrap[137].

Hydrogen is already used in the primary production of Nd-Fe-B magnets to break up the cast alloys into a powder for sintered magnet production[138]. This was developed by Harris et al in the Magnetic Materials Group at the University of Birmingham (UK) and is now used to process all the Nd-Fe-B magnets worldwide. Using hydrogen reduces the production costs for rare earth magnets by approximately 25%[138]. The same research group is now using hydrogen to separate and to recycle rare earth sintered magnets in the HPMS process (Hydrogen Processing of Magnet Scrap)[139]. During the HPMS process the hydrogen preferentially reacts with the Nd-Fe-B magnets in the waste stream. The Nd-Fe-B material expands and breaks apart into a demagnetised powder, which can be separated from the glues, coatings and housings where the magnet is contained (see figures 108,109,110). The extracted alloy powder is of a quality that can be reprocessed directly back into Nd-Fe-B magnets[137]. The patented HPMS process has been licensed to Hypromag Ltd, who aim to produce a range of magnet products at the Tyseley Energy Park in Birmingham (UK)[140] It is interesting to note that the invester in Hypromag Ltd[71] is a junior mining company, Mkango Resources Ltd[141], who are developing primary rare earth resources in Malawi[142].

Figure 108: Voice coil motors from hard disk drives

Figure 109: Voice coil magnets after HPMS processing

Figure 110: HPMS Pilot plant at the University of Birmingham

Re-processing

Once a magnet is separated from the waste stream it can be re-processed in several different ways by putting the material back into the primary supply chain (see figure 111)[143].

Ultimately the further the material is put back into the early parts of the supply chain the higher the cost and the larger the environmental penalty[144]. This also increases the capital costs for building a plant. It is very likely that multiple recycling routes will be required as not all of the magnets will be separated to a quality where the powder can be directly re-used to form magnets.

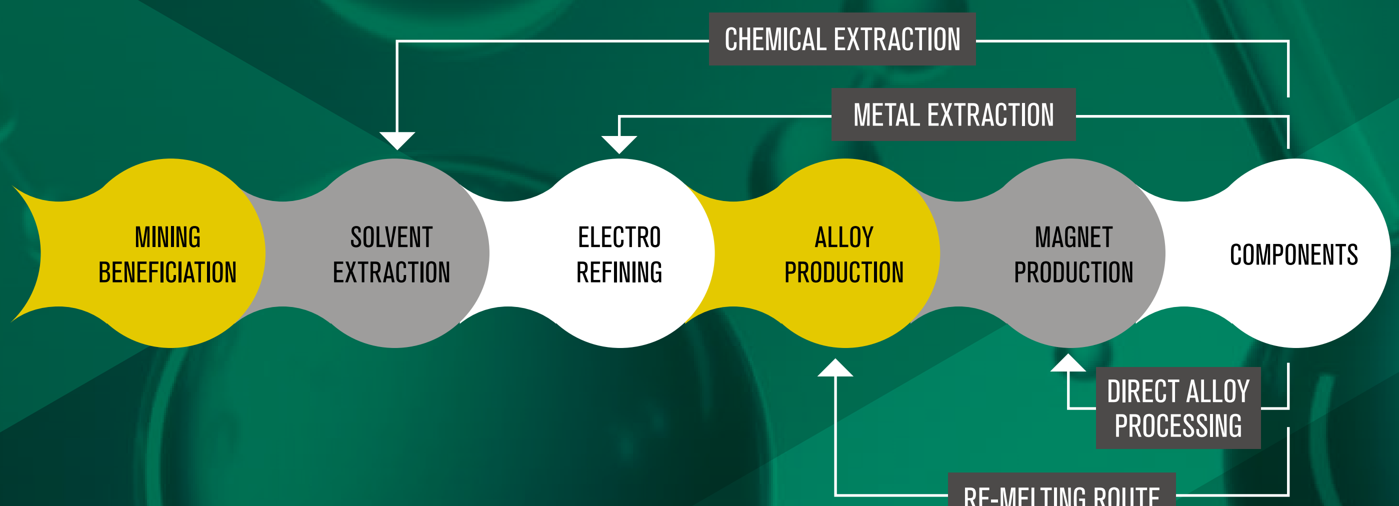


Figure 111: Simplified representation of the re-processing options for extracted Nd-Fe-B magnets compared to primary production.

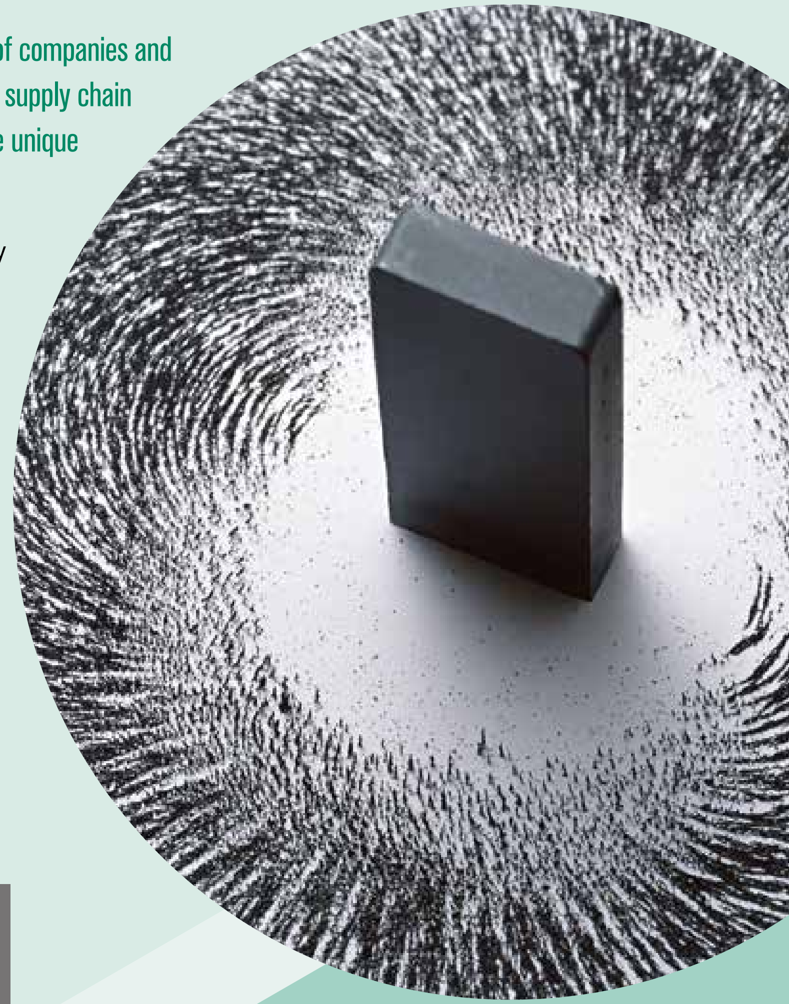
During the separation processes either a separated rare earth metal is created or an alloy that can be re-used to form new magnets. The Magnetic Materials Group (MMG) at the University of Birmingham have led international efforts to recycle rare earth magnets. Working with Less Common Metals Ltd., they have shown that it is possible to re-melt new alloys with comparable properties to the primary material. The MMG has also demonstrated that it is possible to produce sintered and injection moulded magnets from HPMS powders as part of several EU programmes (Remanence, Neohire and SUSMAGPRO)[145,146]. By directly re-sintering, the HPMS alloy powders can be converted back into magnets using 88% less energy and scoring 98% lower on Human Toxicity[144].

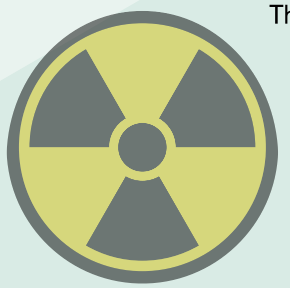
Less Common Metals based in Elsemere Port are also developing technologies to extract rare earth metals from production swarf in the EU[147]. However, if the material is to be placed further back in the supply chain to chemically extract the rare earth metals from the alloys then this part of the supply chain does not exist in the UK at present. There are a number of potential projects to build up this capability in the UK, including Seren and Peak Resources in Teeside and Pensana in Humberside[72,73,74]. All of the above processes will be required for both primary and secondary materials and as such there needs to be coordination with both ends of the supply chain.

ADVANTAGES OF A SECONDARY ECONOMY

If and when a secondary economy for magnets is created, it would significantly reduce the environmental burden compared to the primary production of these materials. If "short-loop" recycling can be initiated, then many of the expensive and capital-intensive processes can be avoided.

Secondary materials can be sourced from a much wider array of companies and countries, which reduces the risk of supply shortages when the supply chain is narrow. We already have this material in the UK, and we have unique technologies to extract these materials at low cost.





The material that is extracted will only contain the rare earths that are in demand, unlike a primary ore, where all 17 rare earth elements are mixed together and need separating. A recycled source of materials will also not contain any radioactivity, a problem with some primary resources[143].

It would be quicker to build up the secondary supply chain, particularly the direct re-processing options, and this would provide capital equipment and expertise that could be multipurposed for primary production. Secondary materials are not a competitor to primary production and should not be viewed as such. Both will be required as a recycled source of material will only meet a proportion of demand. Initial estimates suggest up to 20%.

There are now international efforts to recycle rare earth magnets, but the very limited flow of material tends to be exported for chemical extraction of the rare earth elements. This only exacerbates the problem of supply security and it increases the environmental footprint. The EU and US are now providing co-investment to scale up recycling processes into commercial activities. Without rapid intervention in the UK we will miss out on this important market, despite being at the forefront of research in this area.

RECYCLING AND RE-USE OF LITHIUM-ION BATTERIES

Regardless of where lithium-ion batteries are manufactured, the UK will have to consider how to deal with the problem of battery waste when they eventually reach their end-of-life. It is estimated that in the near term, without a facility to process lithium-ion batteries, the total number of EV batteries reaching end-of-life for battery recycling, could be between 70,000 and 106,000 battery packs by 2025[148].

Not all of these batteries will need to be recycled immediately. As has been shown, the bulk of the battery market will comprise large automotive batteries. At some point, their state of health drops below the point where they can provide an acceptable range in an automotive application (often taken to be 80% State of Health)[149], however, they still have the ability to store energy. Many of these batteries will be suitable for use in second-life applications that are less demanding, for example, stationary energy storage. To quantify this residual value, it has been estimated that EV batteries could achieve a second-life value of £83.00/kWh[150].

Some of these batteries will leave the country, exported in products destined to be refurbished and resold into markets in developing countries. Mobile devices are often collected, exported, and repaired or refurbished in countries with lower labour costs[151,152]. For electric vehicles, however, this situation is less acute for the UK, as being in the minority of countries with right-hand-drive vehicles, the export market for these vehicles is more limited. That said, battery packs may be exported for second-life applications. When batteries leave the UK, the value of the materials and the opportunity to recycle them is lost. Given the importance of these materials, there are risks to losing this strategic resource to other countries.

Some predictions see the growth in demand for batteries outstripping the availability of technology-critical metals. This could occur as soon as the 2020s[153]. From a battery owner's point of view, if an end-of-life battery can be sold into a second-life application, rather than paying to dispose of waste, it becomes an asset rather than a liability, so this is the economically prudent course of action. However, taking a broader resources perspective, second-life use of lithium-ion batteries, while better exploiting the lifetime storage capacity of lithium-ion batteries, delays the return of technology-critical metals back into the economy[154]. It is not clear whether the optimum strategy is to have used lithium-ion batteries performing poorly in a second-life application, or whether it is better to recycle the materials in these batteries, turning them into new, high-performing batteries.

Globally, Asian countries lead in the development of volume recycling of lithium-ion batteries[155]. Many of these operations are vertically integrated with the large Asian battery manufacturers. The recycling market for lithium-ion batteries is better developed, compared to some other technology-critical metals, with commercial activities in the EU. Presently, there are no operational, commercial lithium-ion battery recyclers in the UK, although there are a number of planned initiatives and pilot plants.

The recycling processes employed by various firms vary in their techniques, impacts and efficiency[156]. As noted in the previous section on rare earths, there are a range of recycling technologies and our approaches to battery recycling are evolving rapidly.

Some recycling initiatives do not have the capability to take an end-of-life battery and transform it into a form where materials can be re-used in new battery manufacturing. They are effectively 'pre-processing' operations that reduce the battery into what is known as a "black mass". Through the process of mixing the materials in the battery, value is destroyed and the scope of subsequent recycling processes is limited[157].

There are also challenges with the transportation of end-of-life batteries and battery waste. If the supply chain is not developed to utilise this material from recycling, it could potentially be exported to large recyclers overseas. However, this represents a lost opportunity for the UK to capture the value in these materials. The international breakdown of the lithium-ion battery recycling industry is shown in figure 112.

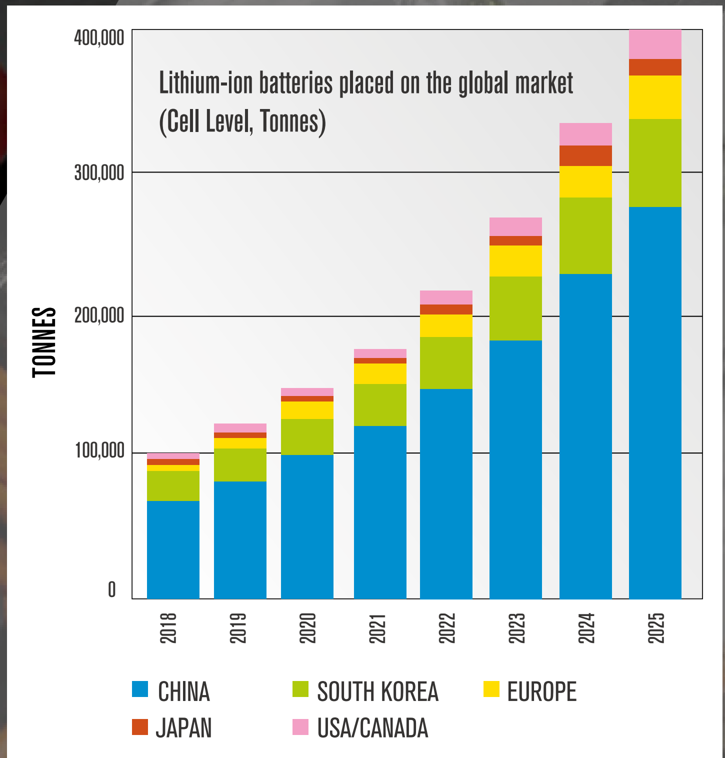


Figure 112: Melin, H.E. (2018) The lithium-ion battery end-of-life market – A baseline study, Circular Energy Storage, London [158]

CHALLENGES IN THE RECYCLING OF LITHIUM-ION BATTERIES

There are six main metals used in the production of cathodes for lithium-ion batteries: aluminium, cobalt, iron, lithium, manganese and nickel. The technology-critical metals, nickel and cobalt, are part of the most common battery cathode materials, which are oxides deposited onto an aluminium foil. This cathode foil is positioned between a separator and the anode, (see figure 113). The separator, cathode and anode are then packaged into different containers, with each vehicle manufacturer having its own layout, for example: cylindrical (Tesla), prismatic (BMW) or pouch (Nissan) cells.

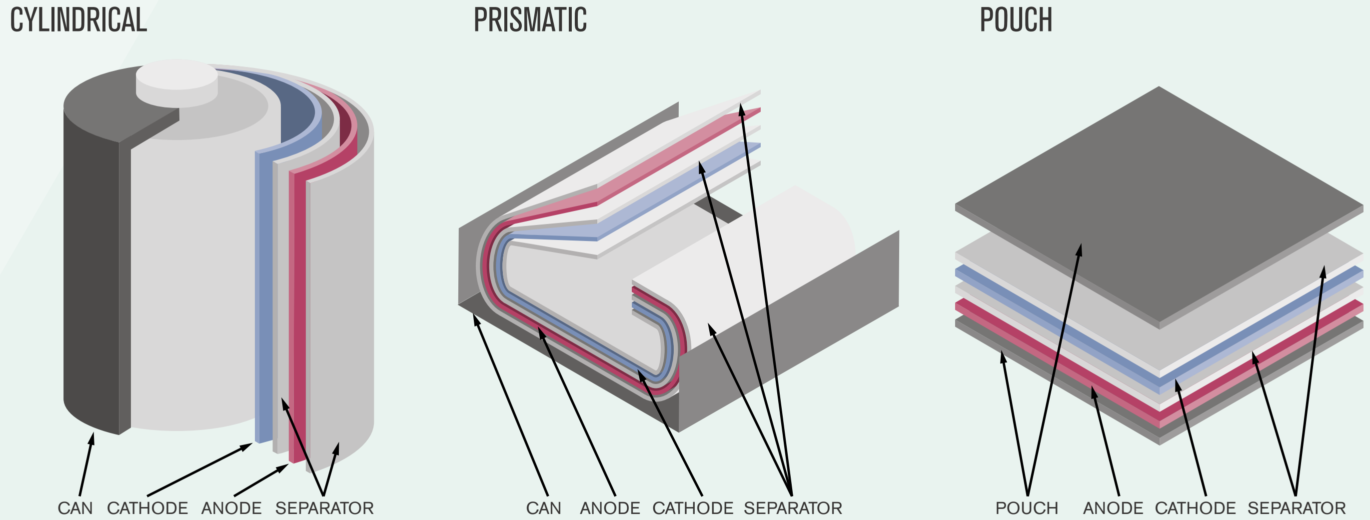


Figure 113: Cylindrical, prismatic, and pouch battery-cell configurations[159].

Pyrometallurgical processes are capable of processing larger components like modules, depending on the size of the furnace, without prior shredding. However, hydrometallurgy and direct recycling techniques require an intermediate "cell-breaking" step to access the contents. This could be accomplished via shredding or disassembly. Some recyclers have suggested a "hub and spoke" model, where initial pack processing – the cell-breaking step – could occur in a distributed fashion, separating and concentrating the waste for onward transportation for future processing[160].

Unlike the familiar lead-acid batteries that have been a component of every car for decades and have recycling rates of close to 100%[161], lithium-ion batteries are much more difficult to recycle. This is primarily because of the many different ways in which they are configured, the complexity of their construction and the design of the constituent parts, which makes them difficult to separate.

Lithium-ion batteries come in different designs. There is no consensus around the form factor, or style of different batteries among manufacturers. Some make a flat "pouch" cell, with layers of material stacked one on top of another. Others wind these layers into a spiral, much like a swiss roll, and put them into a can, forming a "cylindrical" cell, much like a larger version of the consumer batteries that we are familiar with. Others fold the layers and encase them within a rigid box, known as a "prismatic" cell. The enormous variety of different cells makes more sophisticated resource recovery at the end of life challenging.

To process the contents of a lithium-ion battery it must be broken apart: this can either be done in a 'chaotic' way, by shredding the module, or in a more structured way through disassembly. As is the case with rare earth magnets, at its end-of-life a lithium-ion battery cannot be broken apart in a conventional shredder, but in this case owing to the risk of explosion and fire, potentially putting workers at considerable risk. Specialist equipment must be used to make the battery safe prior to manual removal and/or shredding[162]. Only then can it be sent for subsequent downstream processing. A review of current automotive-battery recycling processes was recently published in Nature by Harper et al. 2020. Figure 95 on Page 101 summarises the many challenges of disassembling lithium-ion batteries at different levels of scale.

Many researchers have concluded that recycling outcomes could be improved through disassembly rather than shredding. Designing cells for disassembly could facilitate this process, as there are challenges to the recycling of existing cells that are not designed to be easily taken apart. Given the volume of batteries requiring end-of-life treatment, manual disassembly would be labour-intensive and uneconomic. Robotic automation has the potential to improve dramatically the economics of disassembly in a similar way to rare earth magnets[163,164,165].

Re-processing

The recycling of lithium-ion batteries is possible through a number of routes. Figure 114 shows five example commercial routes for lithium-ion battery materials recovery. These can be divided into two categories.

The simplest is pyrometallurgical recovery, which uses high temperatures to reduce the component metal oxides to an alloy containing nickel, copper and cobalt. This process is already commercialised, but has environmental drawbacks, such as the high energy costs, production of CO_2 and the limited number of materials that can be reclaimed. The process transforms the material into a form where a significant amount of effort is needed to transform it back to a state where it can be used in recycled batteries. The value embedded in the structure of the cathode material is destroyed in this process.

Another option is hydrometallurgical recovery, which involves the use of aqueous solutions to leach the desired metals from the cathode material. Here the problem is environmental, with a lot of sulphuric acid used in some hydrometallurgical recycling processes. This process is happening at scale. Some plants in China have capacities in excess of 25,000 tonnes per year, and recently Brunp announced investment in a plant with a capacity of over 100,000 tonnes per year[166].

A third possibility is direct recycling, where the cathode and anode materials are removed for reconditioning and re-used in a similar way to the magnet routes being proposed in an earlier section. In principle, such cathode materials can be reincorporated into a new cathode electrodes with minimal changes to the material. There could be considerable advantages to direct recycling if the technology matures, as it could lead to enhanced cathode value recovery[167]. The challenge is ensuring the quality of the cathode material being recycled, and making certain that the material is not contaminated or degraded during the recycling process [167]. This is not possible with existing pre-treatment techniques.

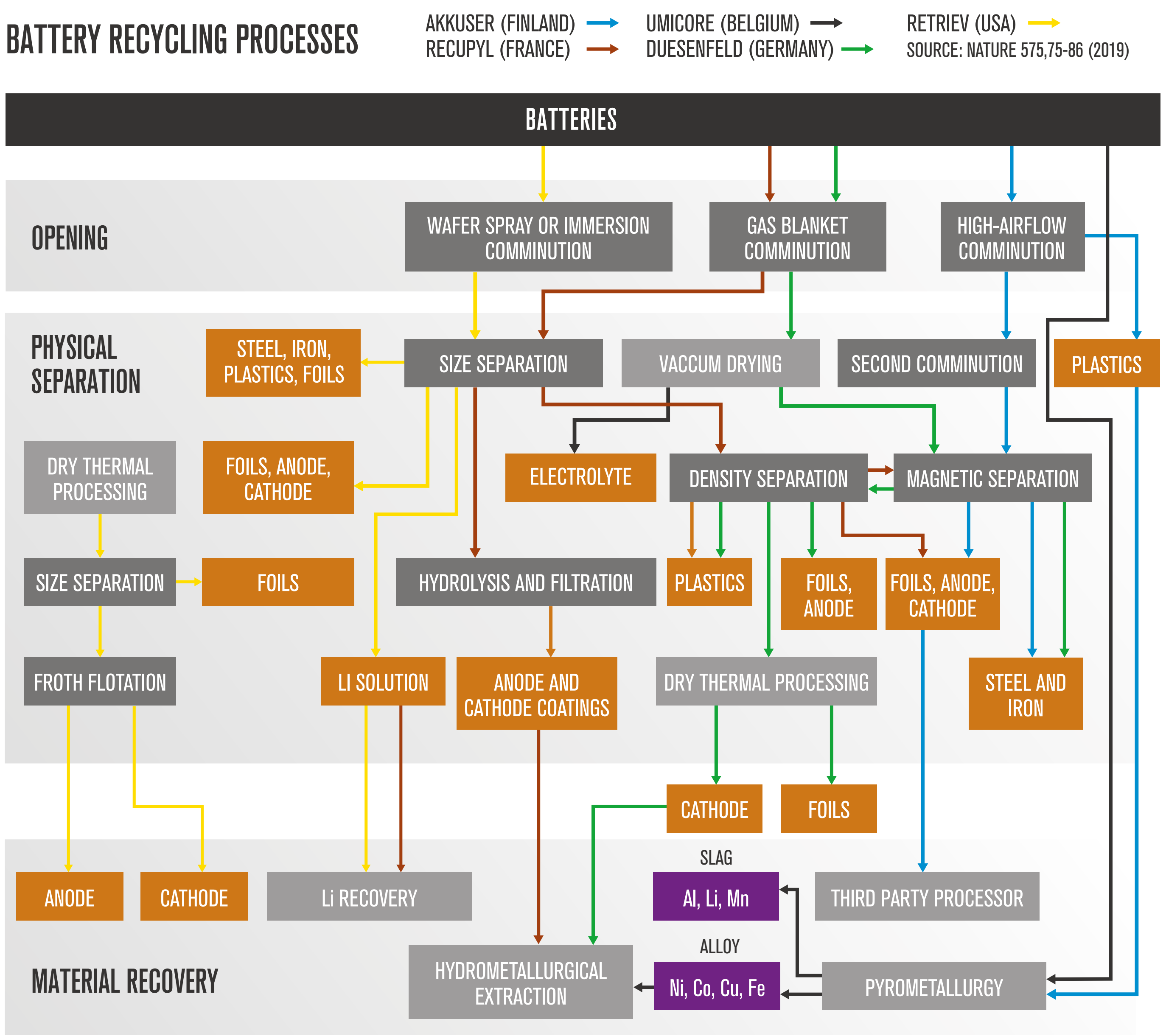


Figure 114: Five of the common processe for recycling of lithium-ion batteries. Source: Nature paper - Harper et.al (2019)[126]

There are potential opportunities for this material to be processed in the UK within existing material supply chains. The UK already has processing capability for some materials used in batteries, e.g. the Vale 'Mond' refinery in Clydach[168] which processes nickel. It is anticipated that in the years to come, the proportion of nickel in electric vehicles (EV) batteries[169] will increase as formulations change and cobalt is engineered out of batteries. Nickel is fully recyclable without loss of quality. Potentially battery wastes could be an attractive proposition for UK refiners, as they could provide a more concentrated feedstock than raw, mined material.

It is vital that the UK develops the capacity to recycle lithium-ion batteries. As electric vehicles take over in the 2030s, companies in the vehicle-manufacturing sector will only be locating in regions and countries that have expertise in manufacturing and recycling of key electric vehicle components like lithium-ion batteries. From an environmental perspective, recycling battery material can significantly reduce the energy required to make new batteries. Recycling lithium-ion batteries could reduce battery material production energy demands by 50%[170] This is significant, as by way of example, in an NMC111 type cell, the manufacture of the cathode powder accounts for 36.4% of the cradle-to-gate energy use and 39.1% of the greenhouse gas emissions of cell manufacture [171].

RECYCLING LITHIUM-ION BATTERIES COULD REDUCE BATTERY MATERIAL PRODUCTION ENERGY DEMANDS BY 50% [170]

The proposed new European battery legislation sets targets for the introduction of recycled content in the manufacture of batteries. If the UK wants to sell batteries into the European market, it will need to comply with these regulations and find a route to sourcing recycled material. Any country that wishes to be active in this area will need to be able to access cobalt and nickel, and recycling existing batteries is likely to be the major source of these metals over the longer term. If the UK is to build the eight gigafactories anticipated to meet 2040 demand for lithium-ion batteries, it will need a strategy for sourcing materials to supply these factories.

Technologies to recycle Li-ion batteries do exist, although they are hampered by being inefficient and less-than environmentally benign. One key to improving processes, is in being able to separate battery materials cleanly. Presently, many recycling processes are reliant on comminution – shredding – of batteries.

These enhanced processes have the potential to conserve more value within a circular lithium-ion batteries supply chain than some existing methods where value is destroyed. Recent Techno-Economic Analysis has shown that the cost saving through making batteries using recycled shredded material was generally < 20% whereas separation and disassembly could potentially result in cost savings in the range 40 to 80% depending on purity.[172]

It is important therefore, that the UK invests in the right sort of technologies – ensuring that its battery recycling industry has the right technology, at the right moment – when lots of end-of-life batteries start reaching the marketplace. Premature investment in suboptimal recycling technologies could result in the creation of stranded assets as the technology advances.

The UK has a vibrant innovation ecosystem and already there are a number of ongoing projects which seek to improve the recycling of lithium-ion batteries. The ReLiB project is one of the Faraday Institution's initial fast-start projects addressing the challenges around the Recycling & Re-use of Lithium-Ion Batteries. In addition, the Faraday Battery Challenge is funding innovation and scale up of a number of projects related to the recycling and re-use of lithium-ion batteries. The Advanced Propulsion Centre is also funding projects of this type, including the RECOVAS project which aims to establish a lithium-ion batteries re-use and recycling supply chain in the UK[173].

At present, recycling is often seen as an "end-of-pipe" solution, to deal with waste after it has arisen. As we can anticipate the growth in use of lithium-ion batteries, and the challenges that these will present at the end-of-life, there is a unique opportunity to design smarter batteries. This will be necessary to achieve profitability in the recycling of many battery types[172].

The new European Battery Directive[131] proposes some solutions that will make batteries easier to recycle at the end of life: mandating open access to battery management systems, to allow data about the condition of the battery to be ascertained; product labelling to allow easier understanding of the contents of lithium-ion batteries; and a "battery passport" system[174], which allows for the tracking of battery data containing information about the batteries in a database. This has also been one of ten guiding principles established by the World Economic Forum's Global Battery Alliance.

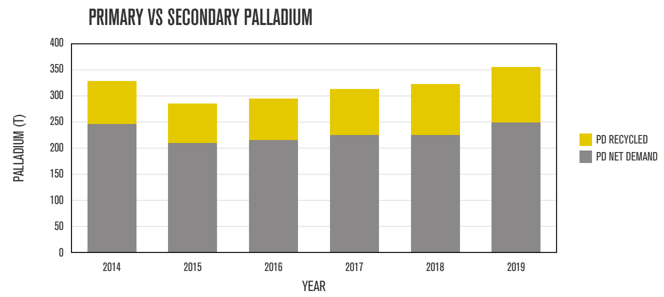
RECYCLING OF PLATINUM GROUP METALS

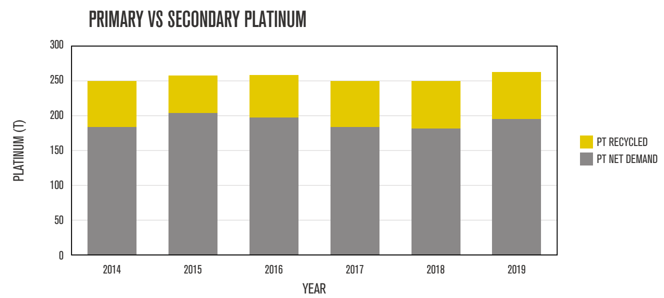
Unlike rare earths, the platinum group metals are recovered on an industrial scale from all their major markets, those being automotive catalysts, industrial catalysts and products, and electronics. Platinum, and to a much lesser extent palladium, are used in jewellery and both metals are also used as investment products. Overall in 2019 recycling provided around 31% of global rhodium demand, 30% of palladium and 25% of platinum (see figure 115)[125].

The recycling rates for some industrial markets, such as petrochemical refining and the glass industry, can be as high as 80-90%. In these applications the secondary market forms an integral part of the supply chain. Likewise, industrial PGM catalysts are often provided on a supply and refine basis as part of a closed loop with the end user. In such cases, the PGM metal on the catalyst is part of the initial capital expenditure for the plant, and ownership of the metal is retained by the user when the end-of-life catalyst goes to the refiner for recycling. The situation is different for the autocatalyst market, where ownership of the PGM in the catalyst ends up in the hands of each vehicle owner (see figure 117). Reclamation of PGMs is then driven by metal prices and depends on a network of collectors, which has built up since the first autocatalysts were introduced in the 1970's. Now, the end-of-life recycling rates of PGMs in the automotive sector are around 60-70% (global average), with much higher rates in some of the more developed auto markets. This recycle rate is very high compared to a lot of other minor metals and also compared to PGMs in the waste electronics sector where recovery is around 5-10%.

Among the principal causes for low PGM recycling rates are the low concentrations of PGM, and the fact that they are present in a complex mixture of other components; one calculation suggests that PGMs, gold and silver constitute 0.3% of the weight of a leading brand mobile phone, but that they contribute 93% of the value. Because of this, it is necessary to use high temperature pyrometallurgical processes to achieve the recycling efficiencies that make refining commercially viable.

There are several PGM refining facilities across Europe that rely on pyrometallurgical processes including smelting for bulk separation and concentration of PGMs. Smelting has repeatedly proven to have the highest efficiency in recovering PGMs, in a business where most is not enough. Once the PGMs have been concentrated, they pass through numerous hydrometallurgical separation steps, which are necessary to deliver the extremely high purity final metal. The UK is home to the world's largest recycler of PGMs, Johnson Matthey, who around 150 years ago were the official refiner to the Bank of England. Johnson Matthey run a smelting operation in Enfield near London and carry out the purification and product fabrication in Royston near Cambridge. The long history of technical leadership in PGMs makes them one of the only companies able to refine all the PGMs, including iridium and ruthenium, to market grade sponge.





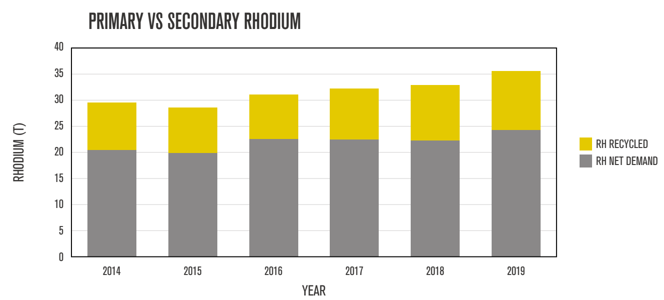


Figure 115: Quantities of PGM's produced worldwide from primary and secondary sources [114].

Recycling PGMs is a developed market because there are larger economic drivers compared to other metals, for example Rare Earth metals , lithium and cobalt. In January 2021, the monthly average trading values for platinum, palladium and rhodium were £26,000, £56,000 and £466,000 per kilogram respectively, whereas neodymium prices are around £100/kg and cobalt is currently trading at around £37/kg. Conversely, the concentration of PGM in applications is often far lower than for rare earths and battery materials. For example, a typical catalytic converter will contain 2-10 grams of PGMs, whereas a car's lithium ion battery can contain 2-11 kg of cobalt and the motors in an electric SUV can contain 1.5-2 kg of neodymium. It is possible that the rare earth market could develop in a similar way to PGMs, with large industrial applications working in closed loops with refiners, however there is also a role for regulation in ensuring the circularity of developing product lifecycles.

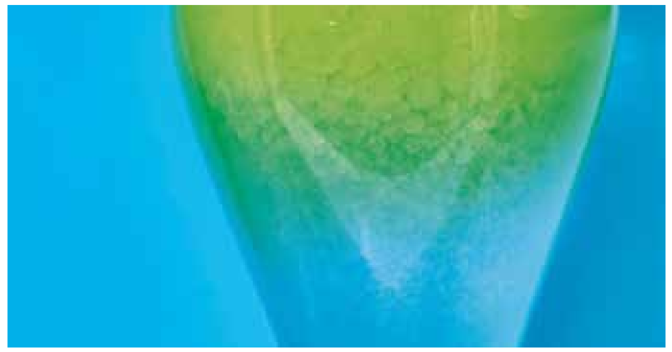


Figure 116: Lab experiment on hydrometallurgical separation of PGMs

Although the recycling loops for current PGM markets are well established, PGM recovery will continue to be a challenge in the future where PGMs are thrifted to smaller and less accessible amounts. Over time, the feeds into PGM recovery processes will change as new PGM-based products gain market foothold. In the longer term, PGMs have a key role in products that contribute to net zero targets, in particular in the fuel cell and "green" hydrogen economies, and PGM recycling technology will need to develop to keep pace with these changes.

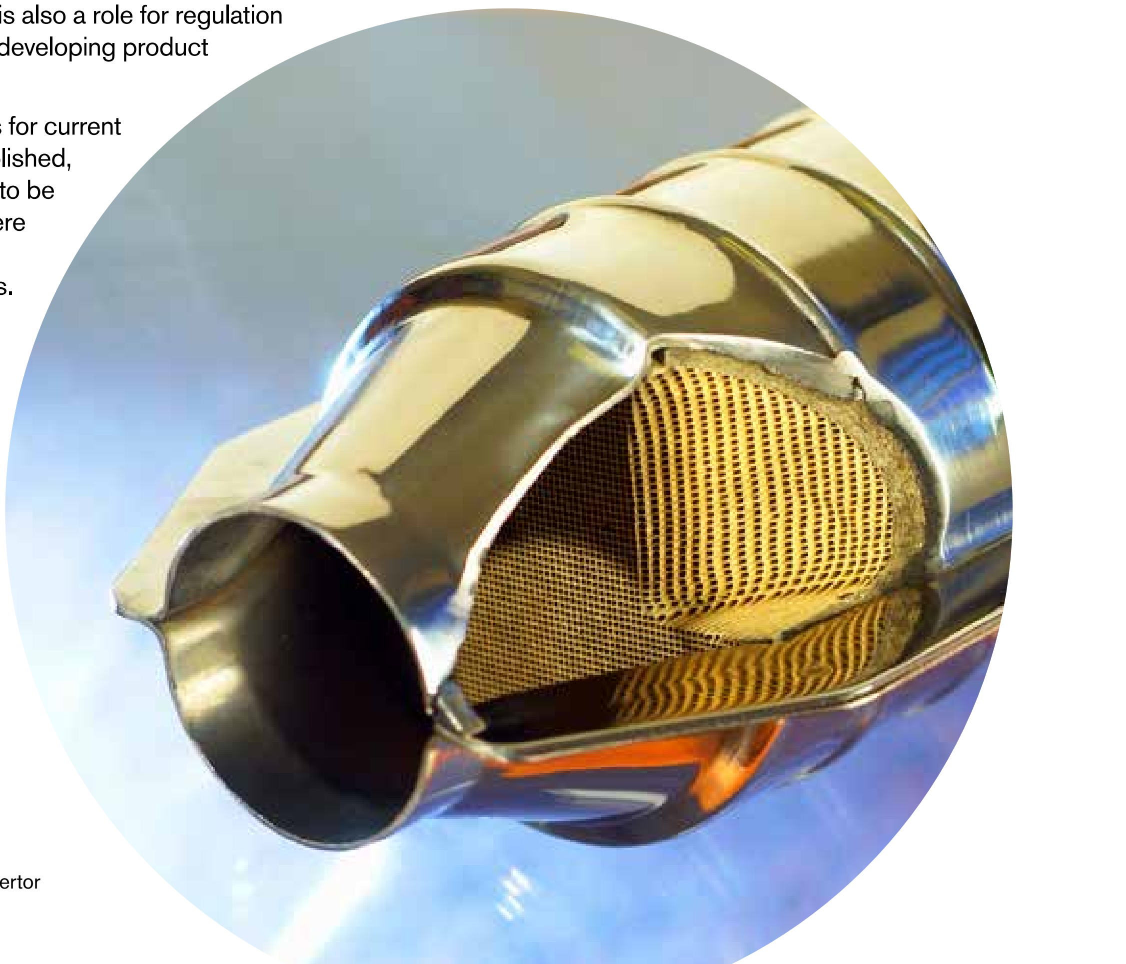


Figure 117: Cutaway catalytic convertor

AEROSPACE MATERIALS

Turbine blades used in jet engines contain a range of technology critical metals including for example Co and Rhenium. The aerospace industry very effectively short loop recycles its own scrap in a closed loop circular economy. The value of the materials is such that manual disassembly of the engines makes economic sense and the turbine blades are removed. The blades are rmelted and converted back into new turbine blades.

Superalloy melters use vast quantities of revert/scrap (in some alloys up to 80% scrap) of the same, or similar, alloy to achieve the required alloy chemistry. Large OEMs also have closed-loop revert programmes that capture machined turnings and solid scraps. These are returned to contracted melters to reduce the costs.

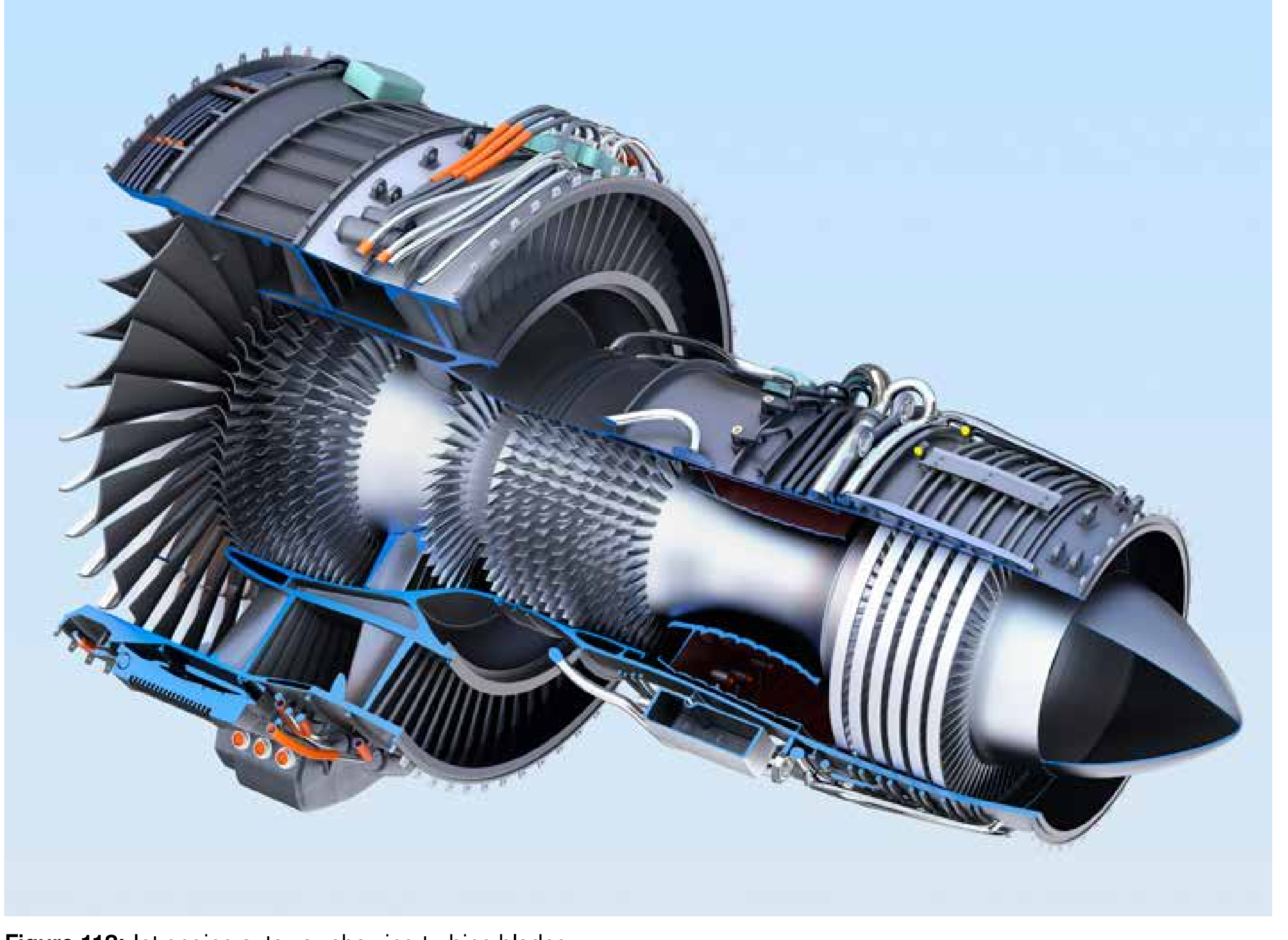


Figure 118: Jet engine cutaway showing turbine blades

SUMMARY OF SECONDARY SECTION

It is clear that many of the processes used for sensing, sorting and separation of bulk metals from end of life waste are unsuitable for processing of technology-critical metals and there is a need to invest in technologies that can improve these processes. This could involve new sensing technologies, automated sorting and novel chemical and metallurgical processes to improve the efficiency of separation and to reduce the cost. Some examples of this are presented in this chapter.

From the evidence presented at the commission it was also clear that there is a lack of data, which means that recyclers do not know how much of these elements are likely to be in waste streams or where they are located within products.

As we transition to a green economy it is an imperative that products are designed with re-use and recycling in mind. This is clearly not the case today and requires action to address this. It is likely to require changes to environmental regulation as the technology-critical metals often fall foul of the weight based targets in place today. This is covered in detail in the governance section of the report.

There are good examples where significant recycling rates are achieved for some technology-critical metals which provides strategic access to PGMs and aerospace alloys. However, to develop a secondary market for battery materials and rare earth permanent magnets, this will require investment in new infrastructure if the UK is to be a global player and to secure access to the technology-critical metals it needs.

GOVERNANCE & REGULATION

CRITICAL MATERIALS GOVERNANCE

The governance structure for critical materials is driven by, and needs to respond to, a range of policy issues, beginning with national security and security of supply. Any governance structure will need to consider primary production, trade and related issues of protectionism, protection of the environment and human health, and realising value from the waste chain. By governance, we refer not only to legislation and regulation, but also to industrial initiatives and standard setting, which might help facilitate access to critical materials.

In February 2021, President Biden signed one of his earliest executive orders mandating a 100-day review of critical product supply chains in the US with critical minerals, strategic materials, computer chips and large batteries receiving explicit mention. In fact, the US has sought to protect its access to critical materials since the passage of the Federal Critical Materials Stockpiling Act of 1939. This allows for the determination of materials thought to be critical and to make provision for sufficient supply reserves. Over time, the US has defended this stockpiling approach by reference to its security and defence needs. It is regularly updated, including a revised list published in 2019. The European Commission has created a list of critical raw materials (CRMs) for the EU, which is also subject to a regular review and updates. Inclusion on the list of CRMs depends on the significance of the material to the EU economy combined with the significance of the risk associated with supply shortfall.

Given the coverage of the strategic need to consider access to critical materials throughout this report, it will be apparent why both the US and Europe engage in such policies. Post-Brexit, the EU policy will no longer have meaning and the UK will play no part in revising the list of CRMs. The UK will continue, no doubt, to give consideration to its access to CRMs but the question is whether it might do so formally, with a stated policy of producing and reviewing a strategic list, or whether any policy goes unstated. There will be other immediate points of departure from Europe as the UK has not implemented the EU's regulation on conflict minerals which is effective in Europe from 1 January 2021. Producing a policy for the UK, whether enshrined in legislation or promulgated in the form of guidance, could have some disadvantages in drawing attention to vulnerability and to attempts to control material flows on world markets. Producing a transparent, stated policy is likely, on the other hand to direct greater efforts to secure supplies to future advantage.

PRIMARY PRODUCTION AND TRADE IN CRITICAL MATERIALS

While minerals production in the UK is not extensive, it is certainly possible that further production in the UK is held back by the complexity of both ownership rights and the multiplicity of consents necessary to commence operations. Property law begins with the assumption that land owners will own minerals beneath their land allowing them to licence exploitation rights to third parties, but in some cases, rights to explore for and exploit minerals is reserved for the Crown. Thus even the rights of reconnaissance may depend on the type of minerals which in turn will drive ownership rights.

On completion of any exploration, which may or may not require planning permission, exploitation will require a production licence either from the owner of the mineral deposit, or from the Crown in statutory form, which may itself vary for onshore and offshore working. The terms and conditions under which operations may take place will emanate from many documents including: mineral leases, planning conditions, environmental permits and health and safety controls. Moreover certain segments of this agenda such as planning and environmental permitting are devolved across the four nations of the UK, so that a variety of agencies could be involved working under increasingly different legal regimes. A review of the regulatory paths to primary production in the UK, bearing in mind other contextual factors such as the drive to net zero carbon targets and Brexit, might reduce some of the administrative difficulties facing investors and would-be producers.

Even with increased primary production in the UK, however, we are likely to depend primarily on imports to meet the requirements of green development. Trade policy is likely to be crucial therefore in ensuring a steady and adequate supply of primary critical raw materials from international markets. This needs to be borne in mind in the negotiation of further trade agreements post-Brexit and Government needs to take greater interest in and influence over data collection and collation which might point to vulnerbilities and inform trade policy. Again there may be room for simplification of trade codes for critical materials that guide the necessary declarations and paperwork for import and export, govern any duty or tax payable and highlight any relief on duties.

As in other areas of the economy, efficient global markets are necessary to allow access to critical materials and to guard against price volatility. The limited points of production for certain critical materials make this problematic and there are examples of market manipulation such as unilateral export controls on the part of producing countries. International trade law, which has historically focussed on restrictions on imports, is not always well placed or speedy in addressing such issues. It follows that, outside of the EU, the UK will need to continue a dialogue and pursue active cooperation with international partners to help secure continuing access to critical materials.

CHEMICALS' REGULATION

It is not unusual for regulation to intervene when goods are placed on the market which, it is feared, may pose the threat of harm to human health or the environment. There are examples of such laws in specific sectors (e.g., for novel foods) and there are more general, overarching regulations that may cut across sectors. In relation to chemical elements, the main form of regulation is REACH, the Regulation of the Registration, Evaluation, Authorisation and Restrictions of Chemicals (EC Regulation No. 1907/2006).

REACH oversees the production, import and use of chemicals to ensure health and environmental protection and the mechanisms of risk governance are as stated in the REACH title. Chemical substances on the EU market must be registered and this can then lead to evaluation of potential harms, authorisation or restriction on use. Since its inception, the UK has been operating under REACH, which applies across all EU member states to businesses manufacturing and/or importing chemical substances into the European single market. The European Chemicals Agency (ECHA) acts as the regulatory agency and provides an infrastructure that the UK is rapidly trying to replicate post-Brexit.

Although most critical materials may be notifiable under REACH, not all may need to be registered; it is necessary to check the list of substances subject to registration and assessment and there are exemptions for naturally occurring substances that have not been chemically modified. Once modified, substances produced from critical raw materials are likely to be caught within the regulation. The main consequence of this concerns the future availability of these materials on the market. REACH carries a candidate list of substances of very high concern (SVHCs) and, to take an example, chromium has a number of derived substances on the candidate list. Such substances are not banned as such but are more likely to be restricted in future use.

It follows that, post-Brexit, a company established in the UK will not be governed by REACH in placing substances on the UK market or if exporting to non-EU countries. If exporting to the EU then supply chains will still be policed by REACH. In order to sell into the EU (in fact the EEA) market, UK companies might need to transfer their registrations to an affiliate in the EEA. The UK will need to monitor closely future determinations made in relation to substances by ECHA to safeguard continuing availability, while deciding how it will deal with SVHC materials on the UK market.

LABELLING AND PACKAGING OF CHEMICAL SUBSTANCES AND MIXTURES

Alongside REACH are rules on classification, labelling and packaging (CLP) of substances and mixtures in accordance with Regulation (EC) No 1272/2008. As this suggests, it constitutes an attempt to harmonise safety information, data and measures in the placing on the market of potentially hazardous substances. Suppliers and importers of relevant substances must inform ECHA, and REACH dossiers supporting registration are often the source of the underpinning hazard assessment.

Outside of the EU, the UK will continue to operate under CLP. It would be open to the UK to depart from the CLP but because it is based on the UN initiative for a Globally Harmonised System (GHS) the UK is likely to remain in broad harmony with the EU in the longer term.

There may be room, however, for separate labelling requirements for goods on the UK market which incorporate critical materials. Many such goods would not be caught by CLP. Labelling of component materials in this way would improve data flows in the value chain and help build good practice in the handling and use during and at the end of life of key products. In some instances, there may be a safety case for labelling. At present there are no specific requirements to label lithium ion batteries in terms of their chemistry or even to indicate that a battery is lithium ion, which is proving increasingly problematic for those handling waste streams of batteries or products which may contain batteries. In December 2020, the EU proposed to introduce such labelling in a revision of the Batteries Directive' again leaving the UK Government to determine whether it will follow suit - see boxout 15.

STANDARDS AND STANDARD SETTING

It may well be that issues such as labelling could be promoted by agreed standards. There are examples of this. Three European Standardisation Organisations, CEN, CENELEC, and ETSI have produced recent standards, one of which EN 45558 of 2019 sets a standard for the declaration of CRMs in energy related products. Alongside this EN 45559 of 2019 establishes a method for the presentation of information relating to material efficiency in energy-related products.

The aim of these standards is to promote both circular-economy approaches and the need for material efficiency. Although conformity with such standards is not a legal requirement, wide acceptance and reliance on such standards can ensure industrial compliance much more effortlessly than can regulation. Moreover, the adoption of international standards can assist in facilitating the trade in the relevant products.

Standard setting can be used much more widely to support the security of critical materials, for example by supporting eco-design and brokering agreement on design for disassembly. For example, there is a recent publicly available specification (PAS 7061:2020 – in effect a code of practice) from the BSI on the safe and environmentally-conscious handling of electric vehicle battery packs and modules. In the early days of green technology, competition in innovation means that companies in the same sector might be reluctant initially to share information in a manner that supports the setting of standards. As these markets mature, however, there may be greater appetite to engage in the setting of common standards.

Whether or not this is so, may depend on wider regulation so that, for example, standardisation to allow ease of disassembly might itself be driven by targets for recycling. Although standard setting agencies have an obvious interest in promoting standards, the Government may wish to consider how it could incentivise the development of appropriate standards.

ECO-DESIGN

Eco-design can help in the reduction and recycling of critical materials in waste flows and can promote best use of these materials to advance resource efficiency. Products subject to eco-design may be built to be more easily repairable or prove more robust, requiring fewer repairs. Oddly, and often wrongly, eco-design has been criticised in the British press as having produced less efficient vacuum cleaners or poorer quality lighting, meaning that this is an area which might receive calls for divergence post-Brexit, though this is not the present intention of the UK Government.

For UK companies with European markets, meeting EU products standards will remain a necessary condition of selling into that market. The UK would be free to depart from such criteria domestically, but that might allow lower quality imports which could undercut a UK market attuned to higher standards.

Politically there may be a reluctance to abide by EU eco-design standards when the UK has no input into the underlying design standards. Yet in the area of critical materials, the gains from design for durability and recyclability in areas such as solar panels could prove considerable. Although the UK will not be covered by these rules as such, it is not a difficult matter to ensure, by statutory instruments, that technical requirements in the UK map on to those in Europe. Whether the UK Government would be minded to take this approach may depend on whether trade agreements with countries outside of the EU would allow for the maintenance of current standards. It is possible that the UK could seek to promote ever greater innovation in eco-design in an attempt to build competitive advantage through product quality. Whatever the policy decisions made in this area, there are advantages in marshalling scarce resources through effective design.

EXTENDED PRODUCER RESPONSIBILITY AND WASTE STREAMS

The UK departs the EU at the point at which the EU is adopting a Circular Economy Package to further resource management; for example, as mentioned above the EU plans to apply a new Batteries Regulation from 1 January 2022. While existing producer responsibility models will be copied over into UK law as EU retained law, the UK needs to consider the extent and future scope of producer responsibility regimes. Such schemes help shift the costs of waste management from the public to the private sector where they can be internalised into the costs of the product.

Producers then have an incentive to reduce such costs by eliminating poor design and by ensuring materials' recycling. A circular economy will not only reduce waste and produce savings but it can extend employment opportunities in the UK economy and drive down costs of raw materials, including the environmental and social costs.

By way of example, proposals in the EU Batteries Regulation for a minimum share of recovered materials such as cobalt, lead, lithium and nickel in new batteries are aimed, according to the Preamble of the Regulation, at strategic autonomy and increased resilience in preparation for potential disruptions in supply.

EPR schemes require carefully devised and robust regulation to eliminate freeriding but can be supported by fees and taxes on goods sold which can be designed to cover recycling costs, produce incentives to buy easily recyclable goods or offer incentives for re-use. Arguably current effort in EPR schemes has been directed at low quality waste streams for which unambitious and poorly policed targets have been set. Increasingly, however, there is a push from industry for better directed schemes which might realise better value from waste streams; for example low quantities of critical materials are being recycled from waste electrical or electronic goods and end-of-life vehicles.

In all of this, targets set as part of the EPR obligation are vitally important. Carefully devised, easily measurable targets will drive investment not only in recycling but in resource efficiency more generally. Experience from Wales suggests that more ambitious waste targets can generate greater efforts towards compliance. Thought needs to be given as to how targets would be set for critical materials. In the new EU Batteries Regulation these are set in relation to the percentage of recovered individual elements in a battery, though there are still technical issues of measurement and functionality. This type of model might serve as a blueprint for downstream electrical systems more generally, though It may also be useful to move away from simple weight based or percentage targets and look for other indicators of value.

While it is difficult to construct models of extended producer responsibility that work efficiently and effectively, if we are to take critical materials security seriously, it is imperative to devise schemes that guarantee access to these resources on a secure and reliable basis. This is challenging as EPR schemes tend to be product based and here we are advocating recovery of critical materials across a wide variety of applications. Nonetheless, extended producer responsibility schemes carefullly devised as part of a wider circular economy approach offer an important route to critical materials' security. One significant issue is whether EPR should operate through individual or collective responsibility. Under individual EPR systems a producer will assume responsibility for take back and treatment of its own end-of-life products but responsibility can be discharges through collective schemes under which producers within the same product market discharge obligations for end-of -life management collectively via a producer responsibility organisation (PRO) which will meet legislative requirements for (fee-paying) members.

Collective approaches have proved efficient to organise and run, not least because they reduce administrative burdens inherent in individual schemes and improve the quality of data on waste product flows. They help collect large volumes of waste which may include otherwise orphaned products. The presence of a collective scheme does not prevent the assumption of individual responsibility but it may make an individual system harder to operate. The number of PROs in a particular product sector may be important as too few may lessen competition and heighten recycling prices. One important factor is that individual responsibility is more likely to drive product eco-design to ease end-of-life management and may help produce much tighter supply loops in which recycled materials are returned to the same use. It follows that careful thought needs to be given to the question of where the responsibility is allocated by policy makers in devising EPR schemes.

At the moment, as part of the Resource and Waste strategy for England, Defra has embarked on a review of current EPR schemes in order to 'incentivise producers to redesign products in support of a more circular economy' and is also exploring whether the UK might implement more stretching targets than those under the EU's circular economy package. It states the objective is to double resource productivity and eliminate avoidable waste of all kinds. Alongside this there may be room to review wider aspects of the waste law inherited from the European Union including perhaps the working of the waste hierarchy and the definition of what constitutes waste, which may at times have inhibited re-use and remanufacturing. As part of this work, it is crucial that attention is paid to the need to utilise valuable resources in the form of critical materials in the waste stream.

ENVIRONMENTAL, SOCIAL AND GOVERNANCE (ESG) RISKS AND OPPORTUNITIES

Access to critical materials is beset by ESG risks both in terms of sourcing, supply chain vulnerabilities and end of life management. As we have shown, demand for critical materials will increase in the foreseeable future not least to support efforts to decarbonise to mitigate climate change. As we have also seen only a small fraction of these materials are sourced by recycling rather than by primary production. Although recycling may reduce reliance of mining of metals, it is idle to think that demand can be met purely by recycling our existing stock of critical materials. There are ESG risks attaching to further primary production, and these may increase as the more easily winnable stocks dwindle, but there are equally important ESG issues facing the waste management sector. The governance of metal recycling has shown promising but relatively recent improvement.

Many of the ESG risks attach to the extraction of minerals are well recognised. We might include impacts on:

- The landscape with large volumes of often hazardous waste generated;
- Land use and the loss of land for other economic purposes;
- The water environment in terms of abstraction, water stress and pollution;
- Human health in terms of safety and exposure of workers;Biodiversity in terms of harm to or loss of habitats;
- Biodiversity in terms of harm to or loss of habitats;
- Cultural heritage including destruction of sites of historical significance;
- Indigenous populations through displacement or shifts to artisanal labour.

These examples are not exhaustive but they do suggest that thought needs to be given to where and how primary materials are sourced and the extent to which the UK can provide these materials from domestic sources as well as supporting the need to carefully harness existing resources won at significant ESG costs by a national programme of recycling. Ultimately, the wider political support for the technologies and products developed utilising critical materials may depend on how responsible the sourcing of those material is seen to be.

There are also potential large rewards for metals production. The World Bank has launched a Climate-Smart Mining initiative to encourage sustainable development through provision of the raw materials needed to combat climate change[175].

The UN, too, are developing new resource governance measures[176].

Sustainable development opportunities are present even in the UK, as well as in the developing world.

The Regulation on conflict minerals has now widened towards a more general responsible sourcing agenda for Europe. Manufacturers are increasingly required to demonstrate their environmental and social credentials and are taking additional interest in their supply chains. High profile companies such as Tesla, Google, Apple are 'reaching' back through their supply chains and, for example, working on assurance at the smelter/refiner stage, buying mines or working with artisanal and small scale miners. The Rare Earths Industry Association[177] are creating a life cycle inventory database to measure and communicate the environmental impact of rare earth oxide-containing (REO) products. Lynas Rare Earths[60] has established itself as the main rare earth supplier outside China and makes responsible supply of rare earths one of the selling points for its products.

The child labour issue in cobalt in particular has also influenced organisations who now have wider aspirations for responsible sourcing and materials stewardship. The Global Battery Alliance who are setting up a 'Battery Passport' have three targeting impact actions [178]. A European Battery Alliance was launched in 2017 to 'make Europe a global leader in sustainable battery production and use'. In the UK, the International Council on Mining and Metals is based on London, and the UK led the establishment of the Extractive Industries Transparency Initiative. The Cobalt Institute (in Guildford) have introduced a responsible sourcing scheme as has the London Metal Exchange.

BOX OUT 015

EU proposals for battery regulation

December 2020: Highlights

- Mandatory requirements on sustainability including -
  - Carbon footprint declarations from 2024; maximum carbon footprint threshold by 2027 (Article 7) Labelling requirements (e.g. hazardous substances, sustainability information, data on expected lifetime) (Article 13)
- Mandatory requirements on minimum recycled content for industrial / EV batteries (Article 8) -
  - Obligation to report recycled content by 1 January 2027
  - Batteries to contain minimum amount of recycled cobalt, lithium, nickel and copper by 1 January 2030
- End of life management
  - EPR for EV batteries to secure waste management obligations (Article 47)
  - New reporting obligations for collection of EV, automotive and industrial batteries
  - Increased collection targets for portable batteries
- Mandatory supply chain due diligence (Article 39)
- Reducing use of toxic substances measures
- Total prohibition of landfilling of waste batteries
- Increased recycling efficiency targets for lead-acid and lithium batteries:
- Recycling efficiency targets for LIBs:
  - 50% currently
  - Rising to 65% in 2025
  - Rising to 70% in 2030
- Improved battery design and lifetime
  - Proposed minimum requirements for EV battery performance/durability (Article 10)
  - Design for removal and dismantling
- Specific recovery targets for valuable technology-critical metals
  - Cobalt: 90% by 2025, 95% by 2030
  - Nickel: 90% by 2025, 95% by 2030
  - Lithium: 35% by 2025, 70% by 2030
  - Copper: 90% by 2025, 95% by 2030

Recommendations

- The UK needs to consider the development of policies which seek overtly to promote critical materials' security;
- The UK should have regard to access to critical materials in monitoring determinations by the European Chemicals Agency in addressing substances of very high concern and in its own future policy on chemical risk;
- Consideration should be given to labelling of the chemical composition of technology products with significant incorporation of critical materials;
- Greater deliberation on the role that standards might play in facilitating a circular economy in technology metals would be welcome;
- There are advantages in employing eco-design to ensure ready access to scarce resources at the products' end of the life;
- Carefully devised and easily measurable targets embedded in extended producer responsibility schemes aimed at critical materials should be employed to drive investment in recycling technologies and infrastructure;
- There are a number of initiatives on responsible sourcing of key minerals, emphasising the increasing attention paid to ESG risks and Government needs to consider how to encourage the development and harmonisation of such private transnational regulation and harness the benefits that they could bring.

CONCLUSIONS & RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

It is clear from the evidence gathering sessions that the market for some technology-critical metals is failing with significant levels of state intervention in parts of the world. This has led to a near monopoly situation for some technology-critical metals which makes many UK industries vulnerable to future supply constraints. The use of these technology-critical metals will expand rapidly in the coming years as we shift to green technologies that underpin many of the UK's key industrial sectors, and the UK's Ten Point Plan for a Green Industrial Revolution. The UK economy will be even more dependent on these materials during this transition, and access to them will to a great extent determine where downstream product manufacturing is located.

There is no single department in UK government that is responsible for critical materials, and there is no specific critical materials strategy unlike in many other countries. As a result the investment and interventions that have gone into supporting supply chain development in the UK have come through various organisations funded through the Department for Business, Energy & Industrial Strategy (BEIS), such as the Faraday Battery Challenge, the Advanced Propulsion Centre, the Automotive Transformation Fund and Driving the Electric Revolution, which are often targeted at specific industrial sectors.

The fact that there is no national strategy means that multiple organisations are working on different challenges related to technology-critical metals but without a common plan. For example the Department for International Trade, British Geological Survey, Camborne School of Mines (University of Exeter) and the Critical Minerals Association have a focus on the mining and the minerals processing sectors; organisations such as DEFRA, WRAP and the Green Alliance are focused on the secondary economy, including technology-critical metals, and research funding bodies such as NERC and EPSRC have had separate research activities but in similar fields.

The UK needs a national plan to target current and future investments and to maximise the benefit to the UK economy. A well formulated plan would underpin resource diplomacy, target strategic investments and be used to direct governance structures to promote mining, refining and the circular economy.

In order to produce a national plan for technology-critical metals the UK should set up a single body to develop a coherent strategy, which would coordinate activity across different government departments including BEIS, DEFRA, MoD, FCDO, DIT, MHCLG and the Cabinet Office This body should draw on national expertise from the entire supply chain from a broad range of stakeholders.

It was clear during the course of the Commission that, although there are many common issues surrounding access to these materials, more in-depth discussions are required about specific material supply chains. As part of the national plan there should be targeted activities and task forces to develop specific strategies for strategically important technology-critical metals.

Generally most of the national materials strategies developed in other nations have 3–5 pillars: securing access through developing domestic resources, the circular economy, developing substitutes and efficient processing, resource diplomacy, and stockpiling. The last of these has previously been ruled out as a viable strategy for the UK.

Japan has a comprehensive raw materials strategy to guide policy on critical raw materials. This includes: re-use and recycling, diversifying supplies through resource diplomacy, promoting the use of alternative materials and stockpiling. Japan has invested heavily in R&D with funding from the New Energy and Industrial Technology Development Organization (NEDO), the Japan Science and Technology Agency (JST) and the Japan Society for the Promotion of Science (JSPS)[179,180,181].

Japan has trade agreements with resource-rich countries based on public–private partnerships through the Japan Oil, Gas and Metals National Corporation (JOGMEC)[3], which has made overseas field surveys and provides financial assistance to high-risk mine developments. As an example, JOGMEC invested in rare earth mining in Australia to secure access to these materials. Japan's raw materials strategy is probably the most interventionist of any country.

The EU adopted a Raw Materials Initiative (RMI) in 2008 and has funded multiple research projects which have focused on specific materials. This has now resulted in the setting up of the EIT on Raw Materials and targeted investment to take processing technologies to industrial scale through the European Raw Materials Alliance (ERMA)[182]. The UK has been a key partner in many of these programmes but it is unclear to what extent they will benefit UK industry post-Brexit. The ERMA alliance recently announced that it is developing a cluster to strengthen the EU domestic supply chain for rare earth magnets and motors with large scale investment.

Similarly the EU recently announced a £2.5 billion public investment in the battery supply chain which includes developing batteries with a lower cobalt content, developing greener methods to recycle lithium-ion batteries and links through to the mining sector. This funding was made through the EU executive's "Important Project of Common European Interest" (IPCEI) regulation, which allows EU countries exceptionally to circumvent the bloc's strict state aid rules [183]. Similar proposals are being suggested for rare earth magnets.

The UK needs to consider the effectiveness of its engagement with the large EU funded research projects on technology-critical metals in the EU Horizon Programmes where it has been a major contributor. It also needs to consider how it engages with the EIT KIC on Raw Materials, where major investments in the technology-critical metals supply chains are imminent.

The UK has unique technologies for processing of technology-critical metals but unless these are taken to scale quickly with similar public–private investment as in the EU and the US, the shelf life of any advantage to UK companies will be short.

As the UK has few indigenous supplies of technology-critical metals, any future strategy must include resource diplomacy and this should form a key part of current and future trade negotiations for example the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP). The UK should also consider using overseas development funds to build capacity in other regions of the globe.

The UK has a major mining centre in London, with multinational mining company headquarters, the International Council on Mining and Metals, the London Metals Exchange, mine finance specialists, specialist technology-critical metals exploration and mining companies listed on the London stock exchange and a Critical Minerals Association[8]. It also has equipment manufacturers and consultancies distributed throughout the UK and mining is identified as a 'high potential opportunity' by the Department for International Trade. This is a resource that can be harnessed both in specific element strategies and in making sure that UK mining and manufacturing is at the forefront of responsible sourcing and international resource governance.

The UK should also consider measures to accelerate projects that seek to develop its indigenous sources of technology-critical metals (lithium and tungsten), including updating the regulatory environment. Some regional authorities, such as Cornwall, have already identified their geo-resources as distinctive opportunities.

It is important to note, however, that without the refining capacity to convert raw materials into metals, alloys or chemicals there is no point in accessing the minerals which contain technology-critical metals. Frequently, the valuable parts of the supply chain are in these refining steps and in the materials that are manufactured from them (e.g. cathode material or magnet). Without these metallurgical or chemical processes the UK will not capture the full value of the products that will enable the greening of the economy.

At the moment many of the environmental impacts from our economy are 'offshored' to countries where the materials are manufactured and in many cases disposed of. With respect to longer term sustainability goals, it should be recognised

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that a circular economy is necessarily a processing and manufacturing economy.

In developing refining and processing capacity in the UK there is a compelling case to connect both ends of the supply chain, processing both primary and secondary materials. The secondary market offers increased security of supply, and often a lower environmental footprint and reduced cost, but it will not meet the huge demand from the rapidly expanding markets in these materials.

Therefore the UK needs to incentivise large-scale private investment in the processing of these materials by 2025 if it wants to secure access. This could be by large scale targeted investments which are directed by the new national body on critical materials through existing and future funding routes (APC, ATF, DER, Faraday Battery Challenge/Faraday Institution or the wind turbine sector). In addition, tax incentives for processing or recycling of technology-critical metals could be introduced and tariff-free trade in these minerals or semi-processed metals, alloys and chemicals could be negotiated in trade deals. The UK already has key companies that process technology-critical metals who should be supported to expand their activities whilst identifying and filling supply chain gaps in key industrial sectors.

The UK should, anticipate and support future international legislation aimed at reducing the environmental burden and enhancing the social and economic value of technology-critical metals production from both primary and secondary sources. As outlined in the report, this is already starting to happen in EU regulations for batteries and we should invest in responsible sourcing and mining, processing and refining technologies which could give our companies a competitive advantage.

The UK should seek to drive innovation through its national technology-critical metals strategy by investing in R&D – targeted at key materials and processes – in areas such as the circular economy, developing substitute materials and efficient processing techniques, which would provide an additional competitive advantage to UK industry. The projects will need to bridge funding councils, and technology-readiness levels, to have real impact. This should include transnational funds and initiatives to work with other nations on supply chain developments for targeted technology-critical metals.

Research areas to target could include, for example, refining, separation, sensing, automated sorting, and re-processing of technology-critical metals, and should also include efficient processing routes for selected materials to reduce the environmental burden of production, reduce waste and improve performance. This would give the UK a competitive advantage in terms of cost, particularly if the environmental footprint of materials production is factored into the cost of products. It is also clear that we have funding gaps in fundamental research around rare earth materials and permanent magnets.

There is a lack of data on technology-critical metal flows into the UK which urgently needs to be addressed in order to guide policy. The UK should be mapping its strategic secondary resource, in particular, from the larger markets. The case for this has been well made by Velenturf et al. through the NERC programme Resource Recovery from Waste [41]. The Office for National Statistics is exploring the feasibility of a National Materials Datahub to provide access to reliable data on the availability of materials to the UK's public and private sectors and this should be accelerated and supported [42].

KEY RECOMMENDATIONS

1. The UK should create a single body responsible for developing strategic access to technology-critical metals and effective inter-departmental collaboration at government level. This body should link the primary and secondary markets for technology-critical metals and develop, and oversee, a full UK technology-critical metals strategy.
2. Seek opportunities to diversify its access to primary resources of technology-critical metals, through resource diplomacy. This should form part of any new trade negotiations.
3. Actively attract and provide support for large-scale strategic private investments for supply-chain development of technology-critical metals both at home and abroad, and aim to make the UK an international refining centre for specific technology-critical metals by 2025.
4. Create individual task forces bridging primary and secondary materials for targeted technology-critical metals. These should identify the investments that would be required to set up primary processing, refining and recycling facilities for these materials.
5. Introduce incentives to encourage recycling, refining and processing of technology-critical metals in the UK, particularly for processes that deliver a lower environmental footprint.
6. Consider measures to accelerate projects that seek to develop our indigenous sources of technology-critical metals (lithium, tungsten), including updating the regulatory environment.
7. Prioritise technology-critical metals in UK research and innovation strategies in areas such as the circular economy, developing substitute materials and efficient processing techniques for technology-critical metals. In particular, this could be in the form of transnational funding initiatives to work with other nations on supply-chain developments for targeted technology-critical metals. The projects will need to bridge funding councils, and TRL levels, to have real impact.
8. Invest in the skills base in advanced materials processing and refining of technology-critical metals.
9. Urgently address the lack of data on material flows for technology-critical metals into and out of the UK economy.
10. Review waste management law with a view to promoting recovery of technology-critical metals and ensure that there are no unnecessary regulatory barriers.
11. Encourage information exchange through the whole supply chain to ensure the challenges for recyclers are well understood by the product designers. This will evolve through time and the new UKRI Met4Tech hub[184] could and should be used as a vehicle for this. Schemes like the new battery passports could be implemented across different sectors.
12. Consider how appropriate governance structures might ensure sustainability and resilience in the supply chain for technology-critical metals (see detailed recommendations in the Goverance section of the report).

APPENDIX 1
THE POLICY COMMISSION PROCESS

APPENDIX 1 - COMMISION WORK PROGRAMME

The Policy Commission heard and deliberated on evidence from a range of sources. These were explored through a variety of tools including consultations and group discussions.

Scoping Phase Activities included:
Developing the idea for the Policy Commission with University of Birmingham academics and partners.
Appointing the Commissioners.
Survey of the Commissioners by email to agree the content and process of the Policy Commission and who to approach for evidence.

Evidence Gathering
Research of literature and data in the public domain.

Evidence Gathering Workshops
Four evidence gathering workshops were held, followed by an additional workshop to agree recommendations:

Session 1 – Overview of Critical Materials and Primary Sources (28th October 2019)
10 St. James Square, London

Session 2 – Supply Chain, Demand and Processing Capability (12th November 2019)
The Institution of Engineering & Technology, Austin Court, Birmingham

Session 3 – End of Life, Substitution and Efficient Use (13th January 2020)
Royal Academy of Engineering, London

Session 4 – Trade Investment, Economic, Ethical Considerations (14th January 2020)
Royal Society, London

Session 5 – Discussing Findings, Formulating the Report (4th March 2020)
The Institute of Materials, Minerals & Mining, London

Review and Writing Phase
Activities included:
Reviewing written evidence submitted to the commission.
Commissioners' meeting to finalise the content and format of the report
Finalising the findings and recommendations of the Commission.

Policy Commission Launch
The policy commission was originally scheduled to launch in Westminster in April 2020.
The rapidly changing situation with the Coronavirus pandemic stymied several attempts to organise an in-person launch of the report. The report has been updated to reflect the changing context in the intervening period, and the report will initially be launched virtually. It is our intention to convene face-to-face engagement events around the report as soon as the situation permits.

Parliamentary Preview of the Report Findings (4th March 2021)
Online

Public Launch of the Policy Commission Report (27th April 2021)
Online

APPENDIX 2
THE COMMISIONERS

APPENDIX 2: THE COMMISSIONERS

Sir John Beddington

FORMER GOVERNMENT CHEIF SCIENTIFIC ADVISOR

John Beddington started his studies initially at the LSE where he took a BSc and MSc. He then moved to Edinburgh to do a PhD in what was then the rather new discipline of Mathematical Ecology. His academic career was initially at York University and subsequently at Imperial College. He was elected Fellow of the Royal Society in 2001 and appointed CMG in 2004.

He was from 2008 until 2013 the Government Chief Scientific Adviser (GCSA) reporting directly to the Prime Minister. As GCSA, he was responsible for increasing the scientific capacity across Whitehall by encouraging all major departments of state to recruit a Chief Scientific Adviser.

During his time as GCSA he set up the Scientific Advisory Group in Emergencies (SAGE) that reported to the COBRA committee. He ran the Foresight Team that reported on such varied issues as Food Security, Climate Change Threats and High Speed Financial Trading and was responsible for reviews on inter alia Nuclear Energy, High Speed Computing in Climate Science and the Scientific Contribution to National Security.

He was awarded a Knighthood in 2010 and in June 2014 received The Order of the Rising Sun from the Japanese Government.

He is Senior Fellow at the Oxford Martin School and Professor of Natural Resource Management at Oxford University. Amongst other activities he is a Non-Executive Director of the Met Office, chairs the Boards of Rothamsted Research and the Systemic Risk Institute at the LSE. He is President of London Zoo and a Trustee of the Natural History Museum.

Allan Walton

PROFESSOR OF CRITICAL AND MAGNETIC MATERIALS, UNIVERSITY OF BIRMINGHAM.

Prof Walton is the co-director of the Birmingham Centre for Strategic Elements and Critical Materials (BCSECM) and he leads the Magnetic Materials Group (MMG) at the University of Birmingham. He is the principal investigator for the UKRI funded network on Critical Elements and Materials (CrEAM).

He has an extensive portfolio of interdisciplinary research projects funded through the EU and UK on processing and recycling of rare earth magnetic materials. He was previously the chair of the UK Magnetics Society.

Dr Paul Anderson

READER IN INORGANIC AND MATERIALS CHEMISTRY, UNIVERSITY OF BIRMINGHAM.

Paul Anderson is the co-director of the Birmingham Centre for Strategic Elements and Critical Materials (BCSECM) and principal investigator for the Faraday Institution ReLiB project, dedicated to the development of new technologies for efficient end of life management of automotive lithium ion batteries.

The synthesis and development of improved materials for energy applications has been the major focus of his research for over two decades, with particular interests in ion mobility in hydrogen storage materials and related lithium and proton electrolyte systems.

Andy Abbott

PROFESSOR OF PHYSICAL CHEMISTRY, THE UNIVERSITY OF LEICESTER

Professor Andy Abbott is Professor of Physical Chemistry at the University of Leicester. His research focusses on material processing using sustainable wet methods to optimise process efficiency and ensure optimum selectivity of recovery. He developed a novel type of solvent called Deep Eutectic Solvents and exploited these through a spin-out company Scionix Ltd. He was Deputy Pro-vice Chancellor for Enterprise and is developing courses to embed entrepreneurial skills into undergraduate and postgraduate teaching programs.

Andy has worked on numerous circular economy projects covering a wide variety of metals and technologies including printed circuit boards, magnets, steel waste, lithium ion batteries, aerospace metals and car catalysts. He is also engaged in developing new methods of primary metal extraction and methods of metal processing. He is a Fellow of the Royal Society of Chemistry.

Andrew Bloodworth

POLICY DIRECTOR, BRITISH GEOLOGICAL SURVEY

As Policy Director, Andrew's role is to lead and co-ordinate BGS interaction with policy- and decision-makers in the public sector. He is also Deputy Chief Scientist for the BGS Decarbonisation and Resource Management challenge area. His own interests include UK resource security, critical minerals and the impact of mining on developing countries. He has worked extensively in Africa and elsewhere in the developing world and was formerly Mining Advisor to the then UK Department for International Development (FCDO).

Andrew is a Chartered Geologist and a Council Member and Trustee of the Geological Society of London. He is also a member of the UK Minerals Forum, the Confederation of British Industry Minerals Group and the Mineral Resources Expert Group of EuroGeosurveys.

Rob Chaddock

STRATEGIC DEVELOPMENT MANAGER, EUROPEAN METAL RECYCLING LTD.

Rob has a 30 year career in the waste and recycling industry, with half of that spent at EMR, a global leader in the supply of sustainable secondary raw materials.

Much of that time has been focussed on positioning the business and industry to deal with future opportunities and challenges, created by legislation, technology and market development.

Rob is currently working on a range of projects including preparing to recycle the vehicles of the future, returning the new materials they will contain to the value chain, building new recycling capacity and capabilities in the UK and maximising the recycling rates of metals, plastics and other materials from complex post consumer goods.

Vernon Gibson

Vernon Gibson is an adviser to industry, academia and government on science and technology. A chemist by background, he holds Visiting Professorships at the Universities of Manchester, Oxford and Imperial College London and is Executive Director of the BP International Centre for Advanced Materials centred in Manchester. He was Chief Scientific Adviser to the Ministry of Defence 2012-2016 and Chief Chemist at BP 2008-2012. He is currently an adviser to the Integrated Review Taskforce within the Prime Minister's Office.

Neil Glover

HEAD OF MATERIALS RESEARCH, ROLLS ROYCE

Neil is Head of Materials Research at Rolls-Royce, based in Derby, and is a Fellow and President of the Institute of Materials, Minerals and Mining.

Neil has over 20 years of experience of materials engineering for aerospace and other high integrity applications. His current role is focused on materials technology to support new product opportunities in Rolls-Royce including electric and hybrid flight. Previous roles have spanned multiple business sectors and materials engineering across the product life-cycle.

For many years Neil was responsible for Rolls-Royce's aerospace materials research portfolio, including the company's extensive external network for materials research.

He is a regular speaker at national and international events and has been a member of numerous national advisory groups. He is a strong advocate of STEM education and a regular speaker at schools events.

Robin Grimes

PROFESSOR OF MATERIALS PHYSICS, IMPERIAL COLLEGE

Robin Grimes is the Steele Chair of Energy Materials at Imperial College. In 2017 he became Chief Scientific Adviser (nuclear) to the Ministry of Defence. Between 2013 and 2018 he was Chief Scientific Adviser to the Foreign & Commonwealth. In his research, he uses computer simulation techniques to predict the behaviour of materials for energy applications including nuclear fission and fusion, fuel cells, batteries and solar cells. Robin is a Fellow of the Royal Society and the Royal Academy of Engineering.

Robert Gross

DIRECTOR OF THE UK ENERGY RESEARCH CENTRE (UKERC)

He is Professor of Energy Policy and Technology at Imperial College London, where he was the Director for the Centre for Energy Policy and Technology (ICEPT) and the Director of Policy at the Energy Futures Lab. He has extensive teaching and post-graduate training experience.

Robert is a Fellow and Council member of the Energy Institute. He is also Council member and former Chair of the British Institute of Energy Economists (BIEE). Robert is currently a member of the Academic Advisory Panel for Ofgem (2018 to date). He has been a specialist advisor to 3 Parliamentary Select Committees, has extensive engagement with UK policymaking, and has published extensively on energy policy, economics and technological innovation.

Gavin Harper

RESEARCH FELLOW, BIRMINGHAM CENTRE FOR STRATEGIC ELEMENTS AND CRITICAL MATERIALS

Gavin is a Faraday Institution Research Fellow, working on the ReLiB project, recycling Lithium Ion Batteries. Prior to this, he was Energy Development Manager at the University of Birmingham, developing the Birmingham Energy Institute under the Directorship of Professor Martin Freer. In this role he worked with Professor Allan Walton and Paul Anderson to develop the Birmingham Centre for Strategic Elements & Critical Materials.

He is a Fellow of the Royal Society of Arts, Manufactures and Commerce and the Higher Education Academy and a Member of the Institution of Engineering and Technology and Chartered Management Institute. He is a Chartered Manager. He is a Researcher Co-Investigator on the new UKRI Interdisciplinary Circular Economy Centre for Technology Metals.

Robert Lee

EMERITUS PROFESSOR OF LAW, THE UNIVERSITY OF BIRMINGHAM

Professor Robert Lee is former Head of Birmingham Law School and Director of the Centre for Professional Legal Education and Research (CEPLER). Before taking up this post, Bob was Co-Director of the ESRC Research Centre on Business Responsibility, Accountability, Sustainability and Society at Cardiff University. Bob has written books on the regulation of biomedicine and food regulation He is an editorial board member of the Journal of Law and Society and of Environmental Liability.

Bob is an honorary life member of the UK Environmental Law Association and has acted as special adviser both the UK and the European Parliament and the National Assembly for Wales as well as to UN bodies such as UNEP and UNDP. He is a Fellow of the Royal College of Medicine and of the Academy of Social Sciences and holds a higher doctorate (LL.D.) for his work on regulation.

Rupert Lewis

CHIEF SCIENCE POLICY OFFICER, THE ROYAL SOCIETY

Rupert's role is to lead the Society's policy work across a range of topics including data, climate and energy, natural resources and the biosphere, emerging technology and innovation, and science policy. Before joining the Royal Society Rupert led the Government Office for Science (GO-Science) which supports the Government's Chief Scientific Adviser, providing science advice to the Prime Minister and to the Cabinet, carrying out strategic Foresight projects, and the science of emergency response. His previous roles include head of Automotive policy in the Department of Business, Energy, and Industrial Strategy, where he also led work on business risks and contingency planning and was deputy Chief Scientific Adviser. In Defra he headed Climate Adaptation policy, leading the UK's first cross-economy climate risk assessment. He also set up the Prime Minister's 'Business Council for Britain'. Rupert has a BSc in Marine Biology, a PhD in genetics, and worked on aquaculture development and start-ups in SE Asia, South Africa, and Europe prior to joining Government in 2002.

Dave OudeNijeweme

HEAD OF TECHNOLOGY TRENDS, ADVANCED PROPULSION CENTRE UK

Dave has spent over 18 years in automotive companies and consultancies, with a focus on research and development of clean and efficient vehicles.

This included a stint at JLR getting new engines & technologies to market, time at MAHLE powertrain working in low CO2 technology demonstrator projects including a downsized engine, a range extender electric vehicle and a solar-driven Stirling engine as well as running a number of client projects. More recently Dave worked at E4tech, which is a strategic consultancy in sustainable energy.

At the APC Dave is responsible for providing strategic insights into future automotive technologies (road mapping) and how the UK should position itself to benefit most. His remit includes automotive propulsion as well as Connected and Autonomous Vehicle (CAV) technologies. Currently he is helping to build the supply chain for electrified vehicles.

Emma Schofield

PLATINUM GROUP METAL (PGM) RESEARCH FELLOW, JOHNSON MATTHEY (JM), UK

Emma joined JM in 2004, keen to use inorganic chemistry to make the world a cleaner and healthier place in a company dedicated to creating the sustainable technologies of the future. As Recycling and Separation Technologies Research Manager, Emma focussed on understanding and improving the environmental impact of the industrial processes by which PGMs and lithium ion battery metals are recycled. She became a JM Research Fellow in January this year, with the remit to promote the understanding and application of PGMs in sustainable technologies globally.

Frances Wall

PROFESSOR OF APPLIED MINERALOGY, CAMBORNE SCHOOL OF MINES (CMS), UNIVERSITY OF EXETER

Frances Wall specialises in technology raw materials, especially rare earth elements, with interests in geology, processing, responsible sourcing and circular economy. A former Head of CSM, Frances is PI for the new UKRI Interdisciplinary Circular Economy Centre in Technology Metals and has recently been leading two international consortium research projects on critical metals (www.sosrare.org, www.carbonatites.eu). She also leads a large Deep Digital Cornwall project to encourage business RD&I, is part of the MIREU (mining and metallurgy regions of Europe Horizons 2020 project) project and a member of the Geological Society Decarbonisation Group. Frances was named one of the 100 Global Inspirational Women in Mining 2016 and awarded the William Smith medal of the Geological Society of London for applied and economic aspects of geology in 2019.

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APPENDIX 3
THE WITNESSES

APPENDIX 3: WITNESSES

Andy Abbott – Professor of Physical Chemistry, University of Leicester

Eoin Bailey – UK Innovations Manager, Celsa Steel UK

Hugo Brodie – Vice President, Sustainability, London Metal Exchange

David Brown – Research Specialist, SG Technologies Ltd.

Carlo Burkhardt – Scientific Director, Institute for Precious and Technology Metals, Pforzheim University

Rob Chaddock – Strategic Development Manager, European Metal Recycling

Susanne Coles – Business Growth Manager, Knowledge Transfer Network

Wavell Coulson – Buyer, Rolls Royce plc.

Tony Davis – Managing Director, Sycamore Environmental Ltd.

William Dawes – Chief Executive, Mkango Resources Ltd.

James Goddin Manager – Strategic Relationships, Granta Design

Gareth Hatch – Managing Director, Strategic Materials Advisors

Tony Hartwell – Director, Sustainable Materials Engineering Ltd.

Ian Higgins – Managing Director, Less Common Metals Ltd.

Robert Lee – Director, Centre for Professional Legal Education and Research, Birmingham Law School, University of Birmingham

Dylan McFarlane – Senior Programme Officer, Pact, Mines to Market

David Peck – Associate Professor, Faculty Architecture and Built Environment, Delft University of Technology

Carol-Lynne Pettit – Senior Manager – Sustainability, Cobalt Institute

Darryn Quayle – Mining Engineer and Business Specialist, UK Government Department of International Trade

Rupen Raithatha – Market Research Director, Johnson Matthey

Jon Regnart – Automotive Trend Strategist, Advanced Propulsion Centre

Vikki Roberts – Global Supply Chain Manager, Johnson Matthey

Neil Rowson – Laboratory Manager, Bunting – Redditch

Luis Tercero Espinoza – Head of Business Unit Systemic Risks, Competence Centre Sustainability and Infrastructure Systems, Fraunhofer Institute for Systems and Innovation Research ISI

Arwyn Thomas – Head of Drive Train Design, Siemens Gamesa Renewable Energy

Simon Trevenna – Implementation and Outcomes Manager, Department for Business, Energy and International Strategy

Rustam Stolkin – Director, UK National Centre for Nuclear Robotics, University of Birmingham

Andrew Stretton – Policy Fellow, Parliamentary Office of Science and Technology (POST)

GLOSSARY
FIGURES
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GLOSSARY OF TERMS, ABBREVIATIONS AND ACRONYMS

Artisanal Mining	Informal mining employing rudimentary methods.
ATF	Authorised Treatment Facility
BCSECM	Birmingham Centre for Strategic Elements & Critical Materials, University of Birmingham
BEIS	Department for Business, Energy & Industrial Strategy
Beneficiation	A process that improves the economic value of an ore resulting in a higher-grade product and a waste stream (tailings).
Carbon Budget	Carbon budgets tie an anticipated level of future warming to a total amount of CO_2 emissions.
CAV	Connected and Autonomous Vehicle
CEPLER	Centre for Professional Legal Education and Research, University of Birmingham
Clean Technologies	Technologies that can aid in decarbonisation with improved environmental performance.
Conflict Minerals	Currently include tantalum, tin, tungsten and gold and are often referred to as 3TG.
CREAM	The EPRSC Critical Elements and Materials Network.
CRMs	Critical Raw Materials (See Critical Materials)
Critical Materials	Critical materials are materials of high economic importance whose supply is associated with a high risk.
Critical Raw Materials	See Critical Materials
CSM	Camborne School of Mines, University of Exeter
DEFRA	Department for Environment, Food & Rural Affairs
DRC	Democratic Republic of Congo
DIT	Department for International Trade
Downstream	Processes in the supply chain to create finished goods.
Earth Abundant	Raw materials which are existing in plentiful supply and are commonplace in the Earth's crust.
ECHA	European Chemicals Agency
Economic Importance	One of the main assessment parameters (in addition to supply risk) of the revised EC methodology to assess the criticality of a raw material indicating the importance of a raw material to the EU economy.
Energy Vector	An energy vector allows for the transfer in space and time of a quantity of energy. Increasingly carbon intensive hydrocarbon fuels are being replaced with low carbon energy vectors such as electricity and hydrogen.
EPSRC	Engineering and Physical Science Research Council
ERECON	European Rare Earths Competency Network
ETFs	Exchange Traded Funds
EV	Electric Vehicles
FCDO	Foreign, Commonwealth & Development Office
GCSA	Government Chief Scientific Adviser
GHS	Globally Harmonised System
HEV	Hybrid Electric Vehicles
Heavy Rare Earth Elements (HRE)	Yttrium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium are the "heavy rare earths." Yttrium is lighter than the light rare earth elements but is included in the heavy rare earths because of its chemical and physical associations with heavy rare earth deposits.
Hydrogen Economy	The hydrogen economy is an envisioned future in which hydrogen is used as an energy vector in many applications.
Hot Pressing	A high-pressure, low-strain-rate powder metallurgical process employing temperatures high enough to induce sintering and creep processes when processing powders.
Hydrometallurgy	A technique within the field of extractive metallurgy for obtaining of metals from their ores using aqueous solutions.
Light Rare Earth Elements (LRE)	Lanthanum, cerium, praseodymium, neodymium, promethium, and samarium
LME	London Metals Exchange
Mineral Resources	Mineral resources are a concentration of material of intrinsic economic interest in or on the earth's crust.
MHCLG	Ministry of Housing, Communities and Local Government
MMG	Magnetic Materials Group, University of Birmingham
MoD	Ministry of Defence
NERC	Natural Environment Research Council
NOx	nitrogen oxides
OECD	Organisation for Economic Co-operation and Development
Primary Materials	Materials that are mined or extracted from the Earth, as opposed to materials that are extracted from previously used material through recycling. (See also Secondary Material).
Platinum Group Metals (PGMs)	The platinum group metals are six transition elements that are chemically very similar (palladium, rhodium, iridium, osmium and ruthenium). They are known for their purity, high melting points and unique catalytic properties.
POST	Parliamentary Office of Science and Technology
Pyrometallurgy	The use of high temperatures to extract and purify metals.
Rare earth Elements (REE)	The rare earth elements are defined as the group of 17 elements that include the 15 lanthanoids and scandium and yttrium. The rare earth elements are found in applications that exploit their magnetic, catalytic and optical properties.
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals, A European Regulation
REE	See Rare Earth Elements, See also HRE, LRE
Refining	The process of taking a raw material and transforming it into a usable product. Often there are many refining and intermediate steps before a raw material reaches applications.
Reserves	The economically mineable part of an Indicated Mineral Resource demonstrated by a Preliminary Feasibility Study.
Resources (Mineral)	Resources, in the context of minerals are a concentration of material of intrinsic economic interest in or on the earth's crust.
SAGE	Scientific Advisory Group in Emergencies
Secondary Materials	Materials that have been produced through the recycling of previously used materials, rather than materials which are extracted from the earth.
Sintering	Where powdered materials are coalesced into a solid or porous mass through heating and sometimes compression, without taking that material into a liquid phase.
Smelter	An installation or factory for smelting a metal from its ore.
Superalloys	Alloys based on Group VIIB elements, capable of withstanding high temperatures, high stresses and often highly oxidising atmospheres. The three major classes of superalloy are nickel-, iron- and cobalt based alloys.
Supply Risk	One of the main assessment parameters (in addition to economic importance) of the revised EC methodology to assess the criticality of a raw material. The supply risk parameter is based on the concentration of primary supply from countries and their governance incorporating other factors such as trade, import dependency and supply mix to the EU.
SVHCs	Substances of Very High Concern
Technology-Critical Metal (TCM)	Metals used in high technology products that are also considered Critical Materials. (See also: Critical Materials)
Technology Metals	Metals used in high technology products.
TRLs	Technology Readiness Levels
UKRI	UK Research & Innovation
WEEE	Waste Electrical & Electronic Equipment
WRAP	Waste & Resource Efficiency Programme - registered charity established to work with businesses, individuals and communities to achieve a circular economy by helping them reduce waste, develop sustainable products and use resources in an efficient way.

FIGURES

BOXOUTS

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