HOUSES OF PARLIAMENT
PARLIAMENTARY OFFICE OF SCIENCE & TECHNOLOGY

POSTNOTE

Number 609 September 2019

Access to Critical Materials

Critical materials (CMs) – such as cobalt, helium and rare earth elements – are vital commodities for UK manufacturing, including for the aerospace, automotive, chemical and energy sectors. Such sectors rely on materials typically extracted and processed abroad. This note looks at the demand and supply of CMs in the UK and ways to improve supply security.

Overview

- Materials may be deemed critical because of their economic or national security importance, or high risk of supply disruption.
- Rising consumption has led to high demand for materials used in products such as wind turbines, computers and electric vehicles.
- Access to critical materials may be restricted by political, environmental, economic, legal and social factors.
- Security of supply may be improved by opening mines, diversifying suppliers and increasing resource efficiency through recycling, reuse or substitution of materials.
- UK industry relies on critical materials but the UK Government does not have a specific critical materials strategy.

Background

Global consumption of raw materials is rising due to rapid population growth and the increasing amount of disposable income spent on goods and services.[1] Rapid development and adoption of digital devices and low-carbon technologies (such as wind turbines, solar panels, and electric and hydrogen vehicles) has also boosted demand for materials; smartphones typically contain around 60 metals.[2,3] Many UK manufacturers rely on a range of materials to make products such as jet engines, alloys and catalytic converters.[4–6]

Manufacturing has become more globalised, increasing both competition for resources and the likelihood that the supply of materials will be affected by geopolitical events.[7] For example, rare earth elements (REEs) are widely used in modern technologies; some are relatively abundant in the Earth's crust, but often not in high enough concentrations to make mining economically viable.[8,9] China, which accounts for an estimated 71% of global mine production of REEs,[10] introduced export restrictions in 2010 that led to prices of some REEs rising by between 10- and 40-fold.[11] Despite a subsequent decline in prices, the introduction of new trade tariffs between China and the US in May 2019 has prompted speculation that China may limit REE exports to the US, currently worth trillions of dollars to US industry.[12]

Assessing Criticality

Governments and other organisations may evaluate the materials in their supply chain to identify those that are 'critical'.[13] A material may be considered critical if it has properties (such as being magnetic or emitting light) that are essential for a product and cannot readily be provided by other materials, or if it is at risk of supply disruption. Methods for assessing material criticality vary and are usually based on a range of inputs, including data or expert judgement.[11,13,14] Most include measures of economic importance and likelihood of supply disruption, while some include factors such as environmental impact.

Criticality can vary over time and between users. For instance, battery materials such as cobalt may be deemed critical by some countries that make electric vehicles but not by others. It may be expressed in binary terms (critical or non-critical) or as a criticality score. Methods include those used by the European Commission (Box 1), the British Geological Survey and the US Geological Survey.[15,16]

This POSTnote considers the CMs on the 2017 European Commission (EC) list (Box 1) and lithium, a near-critical material important for battery technology. It covers current and future demand for CMs, supply of CMs, and approaches for addressing supply chain security.

Demand for CMs

Current Demand

No official list of CMs has been published for the UK, but the Government Office for Science has noted that ensuring the supply of key materials is an ongoing challenge for UK industry.[7] Materials on the 2017 EC list are used to create products of strategic importance for UK sectors, such as:

- **Energy.** Wind turbines use magnets that contain REEs such as neodymium, dysprosium and praseodymium (POSTnote 602);[17] certain solar panels use gallium;[18] and lithium-ion batteries contain lithium, cobalt and graphite.[19]
- **Transport.** Electric motors use rare earth magnets, electric vehicles use lithium-ion batteries,[5] and hydrogen fuel cells require platinum group metals (PGMs).[20]
- **Healthcare**. Platinum group metal catalysts are used for drug synthesis,[21] and helium (Box 2) is a vital coolant for magnetic resonance imaging (MRI) scanners.[22]
- **Defence**. Infra-red detectors and thermal imaging cameras use germanium.[23]
- **Electronics**. Energy-efficient components, such as light emitting diodes (LEDs), use gallium, indium and yttrium; speakers and smartphones use rare earth magnets.[24,25,26]

The variety of materials used in products is increasing. For example, microchips now contain about 60 metals, whereas in the 1990s around 20 were commonly used.[13] The rate of metal usage has risen in recent decades, with more than 80% of the total global production of REEs, indium, gallium and PGMs, occurring since 1980.[13]

Future Demand

Several trends are likely to shape future UK demand for CMs. These include a global transition towards low-carbon energy sources, the development of electric vehicles and advancements in digital technologies.[11]

Batteries and Electric Vehicles

The UK Government has set a target for all new cars and vans to be effectively zero-emission by 2040.[27] Other countries, including France and China, have announced similar plans.[28,29] This is likely to increase competition for the raw materials involved in the production of these technologies.[4] For example, the global demand for lithium is forecast to grow by over 20% a year in the next decade.[30–32]

The UK Government says it will invest up to £274 million to support the innovation needed for the UK to establish a market for battery technology, through the Faraday Battery Challenge (FBC) strand of the Industrial Strategy Challenge Fund.[33,34] This includes funding research and development projects, and working with UK manufacturers to establish new infrastructure to make and recycle batteries. Recently funded projects include a study looking to develop a UK lithium supply. Through the FBC, £108 million has been announced for the UK Battery Industrialisation Centre, which is expected to open in 2020.[35]

Lithium-ion batteries also require cobalt, for which global demand is predicted to at least double by 2035.[36] Global use of neodymium and dysprosium is projected to double over the same period.[36,37] Demand for other materials associated with electric vehicles, such as magnesium for lightweight alloys, is also projected to increase.[36]

Digital Technologies

Demand for certain materials is projected to rise over the next decade due to the development and adoption of digital technologies. For example, demand for indium in the EU is predicted to grow from approximately 200 t (tonnes) in 2015 to 270 t in 2030, driven by its use in touch screens.[36]

Box 1: Criticality of Materials in the EU

The European Commission's criticality assessment method gives each raw material a score, based on its economic importance to the EU and vulnerability to supply disruption. High scores for both economic importance and vulnerability of supply lead to a 'critical' classification. This method does not consider the extent of criticality: a material is either critical or non-critical. It also does not consider the environmental impact on producing countries.[38] Other assessments, such as that developed at Yale University, consider the environmental impacts on human health and ecosystems,[39] but data for reliable environmental impact assessments are limited.[38] The most recent EC list, released in 2017, contains 44 individual materials, 20 of which are divided into 3 sub-groups (Table 1).[40] A new list is due in early 2020.

Table 1: The 2017 European Commission list of CMs.

Antimony	Germanium	Niobium
Baryte	Hafnium	PGMs***
Beryllium	Helium	Phosphate rock
Bismuth	HREEs*	Phosphorus
Borate	Indium	Scandium
Cobalt	LREEs**	Silicon metal
Coking coal	Magnesium	Tantalum
Fluorspar	Natural graphite	Tungsten
Gallium	Natural rubber	Vanadium

*** HREEs (Heavy Rare Earth Elements):** Dysprosium, Erbium, Europium, Gadolinium, Holmium, Lutetium, Terbium, Thulium, Ytterbium and Yttrium.
**** LREEs (Light Rare Earth Elements):** Cerium, Lanthanum, Neodymium, Praseodymium and Samarium.
***** PGMs (Platinum Group Metals):** Iridium, Palladium, Platinum, Rhodium and Ruthenium.

Box 2: Case Study: Helium

Helium has the lowest boiling point (-269°C) of all the elements and is often used as a cryogenic liquid coolant for MRI scanners.[24] It is primarily used for welding, semiconductor manufacturing, filling balloons, and creating inert atmospheres,[24] but also has a range of research applications, such as microscopy.[41,42] Helium has a very low density and can therefore be permanently lost from the atmosphere into space. It can be reused to avoid loss, but this is technically difficult.[22] The price of helium has risen by 500% in the last 15 years, and there have been three supply shortages.[43,44] Despite the discovery of a sizeable deposit in Tanzania in 2016, enough to fill 1.2 million MRI scanners, another global shortage occurred in 2019.[44,45]

Supply of Critical Materials (CMs)

Global Sources

China is the main producer of 31 of the 44 CMs on the 2017 EC list (Box 1).[24] For example in 2018, it accounted for 71% of the estimated global production of antimony, 71% of REEs, 82% of tungsten and 95% of gallium.[10,46–50] A small number of countries dominate the production of other CMs:

- Niobium – Brazil, 88% of global production[51]
- Beryllium – USA, 74%[52]
- Cobalt – Democratic Republic of Congo (DRC), 64%[53]
- Helium – USA, 56%[54]
- PGMs (platinum and palladium) – South Africa, 48%.[55]

Global supply figures may not reflect the sources accessed by a given user. For example, China supplies 66% of scandium globally, but the EU sources 67% of its supply from Russia.[24] Of the materials on the 2017 EC list, only baryte and fluorspar are mined in the UK.[56]

Extraction
Most of the materials on the 2017 EC list (Box 1) are obtained as co-products (extracted with other minerals) or by-products (secondary material from the extraction of another mineral).[24] Examples of co-products include REEs, which are usually extracted collectively as they share similar chemical properties. Examples of by-products include cobalt (from copper and nickel mining) and indium (from zinc and lead mining). The prices of by-products are 'inelastic' because, for instance, more zinc will not be mined to produce more indium when indium prices are high.[57] Most non-metal CMs (e.g. fluorspar) and only a few metal CMs (e.g. lithium) are primary products of extraction.[24] CMs are generally produced in far lower quantities than non-CMs.[58] Material extraction and processing can have significant impacts on the environment and local communities (Box 3).

Security of Supply

The supply of materials may be limited by factors such as the cost and time required to establish new mines or processing facilities, suppliers intentionally limiting supply to drive up prices, a small number of producers, low recycling rates, and the environmental impacts of extraction and processing.[15] When assessing criticality, a high risk of supply disruption does not necessarily imply an actual physical shortage of resources (material that could be extracted).[13] Supply may be limited by a lack of verified reserves (resources that have been assessed to be commercially and legally mineable).[13,38] Security of supply also depends on access to those materials at subsequent stages in the value chain (Box 4). While larger companies are more likely to have the capacity to assess the risks associated with the resources they use, assessments may be more difficult for smaller companies.[59]

Demand for a greater variety and quantity of materials led to the global mine production of many metals increasing by between 10- and 1000-fold between 1900 and 2012.[60] Some scarcity analyses predict the future depletion of the resources of some materials.[13] Such predictions are based on a material's 'static lifetime' and involve dividing estimates of existing resources or reserves by estimates of demand.[61] They can vary over time if resource and reserve levels change, for example because of improvements in extraction technologies or new investigations that show extraction is economically viable.[13] Such investigations may themselves only become economically viable when prices have risen sufficiently. Tungsten reserves grew by over 50% from 2000 to 2011, and reserves of REEs grew by 25% from 2008 to 2011.[13]

Addressing Supply Chain Security

The UK Government does not have a specific CM strategy and no single department has responsibility for policy in this area.[59,62] However, the Department for Environment, Food and Rural Affairs set out plans in 2018 to reinvigorate its 2012 Resource Security Action Plan, including improving government oversight of raw materials critical to the UK economy.[74] Other associated initiatives largely focus on research and development. In addition to the Faraday Battery Challenge (see above), UK Research and Innovation funds programmes covering CMs, such as SoS MinErals, focussed on the science behind securing the supply of materials.[75] Other research centres and collaborations include the Birmingham Centre for Strategic Elements & Critical Materials; the Critical Metals Alliance, formed by the British Geological Survey and the Camborne School of Mines; and the Critical Elements and Materials Network, with aims that include developing a UK elements strategy.[76,77] 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.[74,78,79]

In 2008, the EC adopted the Raw Materials Initiative (RMI), a strategy to secure EU access to raw materials.[80] This led to the creation of the EC list (Box 1) and supports over 70 projects funded through EU programmes such as Horizon 2020.[81] It also funds initiatives such as EIT RawMaterials,[82] which supports businesses, including some in the UK, to

Box 3: Environmental and Social Impacts of Mining

Environmental
Mining is an energy intensive process and one of the largest contributors to global greenhouse gas emissions.[63,64] It can lead to ground-water, surface water and soil being affected by the overflow, collapse or leaking of tailings dams (used to store mine waste and by-products).[26] Waste water from mining can contain toxic compounds, such as radioactive elements, heavy metals, acids and fluorides.[26] Mitigating these risks requires environmental impact assessment and long-term monitoring of sites.[26,65] Adopting low-carbon energy technologies is predicted to increase demand for many CMs.[66] Sustainable CM supplies will likely require low-carbon extraction technologies,[67] such as extracting metals from mine waste using microorganisms.[68]

Social
Mining can affect local communities both positively and negatively.[69] Mines can provide opportunities for employment and community development, for example by installing infrastructure such as telecommunications, power and water supplies. However, the extraction of some CMs are linked to humanitarian concerns, including child labour and conflict. For instance, some cobalt is extracted from artisanal (independent, small-scale) mines. In 2014, the United Nations Children's Fund estimated that about 40,000 children were working in such mines in the DRC, the world's largest cobalt source.[70]

Box 4: Value Chain Dominance
Dependence on a monopolised value chain may leave users open to risk of supply disruption and restrict the ability of market entrants to open new mines, refineries or recycling centres.[71] Over 90% of REEs used for permanent magnet generators in wind turbines (mainly neodymium and dysprosium) are mined in China, the only country with a complete mine-to-magnet value chain.[72] A typical material value chain includes the following processes:[73]

1. **Extraction** of primary material, e.g. ore from mine
2. **Production** of refined material, e.g. separation and purification of individual elements that have been extracted together
3. **Fabrication** of intermediate products, e.g. magnetic alloys
4. **Manufacturing** of products, e.g. magnetic motors (scrap material produced at this stage may be re-used at stages 2 and 3)
5. **Distribution, sale and use** of products
6. **Waste management and recycling**.

improve European CM supply security.[83] Despite EU level strategies, member states control their own materials and mining policies. Some countries outside of the EU are taking a more strategic approach to CMs, including securing access across the value chain (Box 5).

Mining

As long as demand for a material continues to increase, recycling alone cannot meet demand, and primary raw material will still be needed, according to the European Academies' Science Advisory Council.[38] Opening new mines, including in the UK (Box 6), and expanding existing mines provides extra sources of raw material, but supply issues could still be encountered at later stages of the value chain (Box 4). Innovations in mining may make it possible to extract materials from previously inaccessible resources. For example, deep sea mining involves extracting minerals from areas of the ocean below depths of 500 metres (POSTnote 508). A potentially rich source of material, it is currently restricted by high cost, technical difficulties and a poor understanding of the environmental impacts.[84]

Improving Resource Efficiency

Recycling

Recycling reduces waste and demand for primary material, reducing extraction and its associated environmental impacts (Box 3).[38] Recovering metals from recycled material can also significantly reduce energy and water consumption, compared to producing metals from ore.[38] For example, recovering cobalt from scrap requires 7–14% of the energy needed to extract it from ore. However, successful recycling is dependent upon the whole recycling chain being economically viable, from waste collection to the sale of recycled materials. Recycling rates in the EU are low. Only 12 of the 44 materials on the 2017 EC list have an end-of-life recycling input rate of 10% or higher (a measure of how much of products' raw materials come from recycling).[24,31]

Recovering critical materials from waste electrical and electronic equipment (WEEE) is difficult as they are usually present in low concentrations.[85] For example, recovering 1 t of indium would require 3.85 million liquid crystal display (LCD) TVs.[15] Recovered material is often of lower quality than primary material, which can limit the range of suitable uses.[86] For some CMs, such as gallium and germanium, no technology is available to recover them.[38] The small number of low-carbon technology products (such as solar panels) that can be recycled are typically processed in Europe.[4,85,87]

Recycling could be made easier and cheaper with circular economy approaches (POSTnote 536) such as 'design-to-recycle' practices that consider product disposal, for example by avoiding complex metal mixtures.[38,88] Other circular economy approaches include developing ways to sense and separate CMs from waste (which can be technically challenging),[89] and extended producer responsibility (EPR) schemes that make manufacturers responsible for the entire product life-cycle, including collection, recycling and disposal.[38,90] The EU has EPR schemes that set targets for the collection, recycling and recovery of batteries, vehicles, packaging and WEEE.[90] Most targets focus on the mass of material recovered, which may limit the effectiveness of existing EPR schemes for CM recycling.

Box 5: Case Studies of CM Strategies in Other Countries

Japan

Japan is dependent on imports for its supply of CMs. In 2008, 90% of its REEs came from China.[87] Over the last decade, Japan has developed a comprehensive strategy to guide policy on securing supplies of raw materials, which aims to increase self-sufficiency in rare metals to 50% by 2030.[87] Measures include recycling scrap and end-of-life products, promoting the use of alternative materials and stockpiling strategic materials.[87] They also include diversifying supply sources through strategic resource diplomacy, involving technology transfer, infrastructure development and trade agreements with resource-rich countries.[87] Such initiatives are commonly public-private partnerships where public institutions, such as the Japan Oil, Gas and Metals National Corporation (JOGMEC), undertake overseas field surveys and fund mine development projects in other countries.[87]

USA

For many decades, US Government policy has sought to address the supply security of raw materials.[87,91,92] In May 2019, a bill known as the American Mineral Security Act (S. 1317) was introduced in the US Senate to reduce US dependence on foreign mineral supplies, avoid supply shortages, mitigate price volatility and prepare for growth in demand and other market changes.[93] The bill would provide approximately $50 million per year for activities that include national resource assessments of CMs, reforming the permitting process for mineral exploration, and research into the recycling and substitution of CMs.[94] The US also has a dedicated Critical Materials Institute that aims to assure the supply chains of materials deemed critical for US manufacturing and energy security.[95]

Box 6: Mining in the UK

The UK has several CM resources.[96] Current operations include Milldam Mine in the Peak District, which produces fluorspar.[97] Drakelands Mine, Devon, is one of the world's largest deposits of tungsten.[98] Out of full operation since 1944, Drakelands was reopened in 2014 but closed again in 2018 after losing £100 million.[98] Exploration is currently underway in Cornwall for tungsten and tin, and for hard rock lithium.[99] Geothermal brines (hot saline solutions found underground), also in Cornwall, may contain significant resources of lithium. The British company Cornish Lithium has received £2 million of investment since 2017 and is evaluating potential brine extraction sites.[100,101] A planning application to develop a baryte mine in Aberfeldy, Scotland, was approved in 2016.[102]

Reuse and Substitution

Reusing products in other applications could prolong the use of CMs and reduce supply risk. For example, when lithium-ion batteries are no longer suitable for use in electric vehicles, they might be re-used for other energy storage applications.[103,104] Substitution of CMs for more readily available alternatives could also help to improve supply security. However, there are limits to substitution, especially with regards to CMs.[105] Their often unique (for example magnetic or catalytic) properties mean that there are generally few alternatives available. Substitution may simply shift demand to the substitute. For example, substituting platinum for palladium in vehicle catalytic converters swaps one material in short supply for another material produced in low quantities.

Endnotes

1. McKinsey & Co. *et al.* (2016). Raw materials: Unlikely return of the 2003-2013 supercycle.
2. Smartphones: smart chemistry. *American Chemical Society*. (Accessed 04/07/19)
3. Montalvo, C. (2016). A Longer Lifetime for Products: Benefits for Consumers and Companies. 105.
4. House of Commons Science and Technology Committee (2011). *Strategically Important Metals, Fifth Report of Session 2010–12*.
5. Achzet, B. *et al.* (2011). *Materials critical to the energy industry. An introduction*.
6. Tzimas, E. (2015). Critical Materials in Energy Technologies - Evangelos Tzimas, Joint Research Centre | SETIS - European Commission.
7. Government Office for Science *et al.* (2013). *Foresight Report: The Future Impact of Materials Security on the UK Manufacturing Industry*.
8. Balaram, V. (2019). Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geoscience Frontiers*, Vol 10, 1285–1303.
9. POST (2010). *POSTnote 368, Rare Earth Metals*.
10. United States Geological Survey (USGS) (2019). *Rare Earths Statistics and Information*. United States Geological Survey (USGS).
11. Hofmann, M. *et al.* (2018). Critical raw materials: A perspective from the materials science community. *Sustainable Materials and Technologies*, Vol 17, e00074.
12. BBC News (2019). China's precious metals the US can't do without. (Accessed 04/07/19)
13. Graedel, T. E. *et al.* (2014). Metal resources, use and criticality. In *Critical Metals Handbook*. John Wiley & Sons.
14. Hayes, S. M. *et al.* (2018). Critical minerals: A review of elemental trends in comprehensive criticality studies. *Resources Policy*, Vol 59, 192–199.
15. Griffin, G. *et al.* (2019). A framework for firm-level critical material supply management and mitigation. *Resources Policy*, Vol 60, 262–276.
16. Buijs, B. *et al.* Critical Thinking about Critical Minerals: Assessing Risks Related to Resource Security. 19.
17. POST UK (2019). *POSTnote 602: Developments in Wind Power*.
18. Ansari, Z. A. *et al.* (2019). Photovoltaic solar cells based on graphene/gallium arsenide Schottky junction. *Optik*, Vol 182, 500–506.
19. Huang, T. *et al.* (2019). Recovery of cobalt, lithium, and manganese from the cathode active materials of spent lithium-ion batteries in a bio-electro-hydrometallurgical process. *Hydrometallurgy*, Vol 188, 101–111.
20. Pollet, B. G. *et al.* (2019). Current status of automotive fuel cells for sustainable transport. *Current Opinion in Electrochemistry*, Vol 16, 90–95.
21. Roundtable, N. R. C. (US) C. S. (2012). *Replacing Critical Materials with Abundant Materials*. National Academies Press (US).
22. Sunarso, J. *et al.* (2017). Membranes for helium recovery: An overview on the context, materials and future directions. *Separation and Purification Technology*, Vol 176, 335–383.
23. Pavel, C. C. *et al.* *Raw materials in the European defence industry*. 126.
24. European Commission (2017). *Study on the review of the list of critical raw materials: final report*.
25. Wilburn, D. (2012). *Byproduct Metals and Rare-Earth Elements Used In the Production of Light-Emitting Diodes—Overview of Principal Sources of Supply and Material Requirements for Selected Markets*.
26. Schüler, D. *et al.* (2011). *Study on Rare Earths and Their Recycling*.
27. Department for Transport (2018). *The Road to Zero*. 147.
28. BBC News (2017). France plans ban on petrol cars by 2040. (Accessed 04/07/19)
29. McDonald, J. (2017). China to ban all petrol and diesel cars. *The Independent*.
30. Martin, G. *et al.* (2017). Lithium market research – global supply, future demand and price development. *Energy Storage Materials*, Vol 6, 171–179.
31. European Commission (2017). *Study on the review of the list of critical raw materials: non-critical raw materials factsheets*.
32. Roskill (2019). *Lithium. Outlook to 2028, 16th Edition*.
33. Faraday Battery Challenge - UK Research and Innovation. (Accessed 04/07/19)
34. UKRI Industrial Strategy Challenge Fund - UK Research and Innovation. (Accessed 04/07/19)
35. UKBIC *et al.* (2019). New Boost For UK Ambition to Lead the World in Zero Emissions Vehicles. (Accessed 04/07/19)
36. Tercero-Espinoza, L. (2016). *SCRREEN Report on the future use of critical raw materials*. SCRREEN.
37. Goodenough, K. M. *et al.* (2018). The Rare Earth Elements: Demand, Global Resources, and Challenges for Resourcing Future Generations. *Nat Resour Res*, Vol 27, 201–216.
38. European Academies Science Advisory Council (2016). *Priorities for critical materials for a circular economy*.
39. Graedel, T. E. *et al.* (2012). Methodology of metal criticality determination. *Environ. Sci. Technol.*, Vol 46, 1063–1070.
40. EU Commission Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU COM/2017/0490 final.
41. Murata, K. *et al.* (2018). Cryo-electron microscopy for structural analysis of dynamic biological macromolecules. *Biochimica et Biophysica Acta (BBA) - General Subjects*, Vol 1862, 324–334.
42. Kouzes, R. T. *et al.* (2015). Progress in alternative neutron detection to address the helium-3 shortage. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Vol 784, 172–175.
43. Murphy, H. (2019). The global helium shortage is real, but don't blame party balloons. *The New York Times*. (Accessed 04/07/19)
44. Torre, B. (2019). World's helium supply 'could run out within a decade', expert warns. *The Independent*. (Accessed 04/07/19)
45. Sample, I. (2016). Huge helium gas find in east Africa averts medical shortage. *The Guardian*.
46. United States Geological Survey (USGS) (2019). *Magnesium Statistics and Information*. United States Geological Survey (USGS). (Accessed 04/07/19)
47. United States Geological Survey (USGS) (2019). *Antimony Statistics and Information*. United States Geological Survey (USGS). (Accessed 04/07/19)
48. United States Geological Survey (USGS) (2019). *Bismuth Statistics and Information*. United States Geological Survey (USGS). (Accessed 04/07/19)
49. United States Geological Survey (USGS) (2019). *Tungsten Statistics and Information*. United States Geological Survey (USGS). (Accessed 04/07/19)
50. United States Geological Survey (USGS) (2019). *Gallium Statistics and Information*. United States Geological Survey (USGS). (Accessed 04/07/19)
51. United States Geological Survey (USGS) (2019). *Niobium Statistics and Information*. United States Geological Survey (USGS). (Accessed 04/07/19)
52. United States Geological Survey (USGS) (2019). *Beryllium Statistics and Information*. United States Geological Survey (USGS). (Accessed 04/07/19)
53. United States Geological Survey (USGS) (2019). *Cobalt Statistics and Information*. United States Geological Survey (USGS). (Accessed 04/07/19)
54. United States Geological Survey (USGS) (2019). *Helium Statistics and Information*. United States Geological Survey (USGS). (Accessed 04/07/19)

55. United States Geological Survey (USGS) (2019). *Platinum Group Metals Statistics and Information*. United States Geological Survey (USGS). (Accessed 04/07/19)
56. British Geological Survey (2017). Minerals Produced in the United Kingdom in 2017. In *UK Minerals Handbook*. 1. (Accessed 04/07/19)
57. Benton, D. *et al.* (2013). Resource Resilient UK. A report from the Circular Economy Task Force. 44.
58. Brown, T. *et al.* (2019). *World Mineral Production 2013-2017*. British Geological Survey.
59. BIS *et al.* (2012). *Resource Security Action Plan: Making the Most of Valuable Materials*.
60. Graedel, T. E. *et al.* (2012). Will metal scarcity impede routine industrial use? *MRS Bulletin*, Vol 37, 325–331.
61. British Geological Survey What is the difference between resources and reserves?
62. DEFRA (2012). *A Review of National Resource Strategies and Research*. 109.
63. Liu, D. *et al.* (2019). What causes growth of global greenhouse gas emissions? Evidence from 40 countries. *Science of The Total Environment*, Vol 661, 750–766.
64. Wall, F. *et al.* (2017). Responsible sourcing of critical metals. *Elements*, Vol 13, 313–318.
65. Ali, S. H. (2014). Social and environmental impact of the rare earth industries. *Resources*, Vol 3, 123–134.
66. World Bank Group (2017). *The Growing Role of Minerals and Metals for a Low Carbon Future*. World Bank.
67. Lusty, P. A. J. *et al.* (2015). Challenges to global mineral resource security and options for future supply. *Geological Society, London, Special Publications*, Vol 393, 265–276.
68. Potysz, A. *et al.* (2018). Perspectives regarding the use of metallurgical slags as secondary metal resources – A review of bioleaching approaches. *Journal of Environmental Management*, Vol 219, 138–152.
69. Oxfam Impacts of Mining. *Oxfam Australia*. (Accessed 04/07/19)
70. Democratic Republic of Congo: Government must deliver on pledge to end child mining labour by 2025. Amnesty International. (Accessed 04/07/19)
71. Rabe, W. *et al.* (2017). China's supply of critical raw materials: Risks for Europe's solar and wind industries? *Energy Policy*, Vol 101, 692–699.
72. FP Analytics Special Report (2019). *Mining the Future. How China is set to dominate the next Industrial Revolution*. foreignpolicy.com.
73. United Nations Environment Programme (2013). *Metal Recycling Opportunities, Limits, Infrastructure*.
74. DEFRA (2018). *Our waste, our resources: a strategy for England*.
75. SoS MinErals Security of Supply of Mineral Resources. (Accessed 04/07/19)
76. Critical Elements and Materials (CrEAM) network launch. (Accessed 04/07/19)
77. EPSRC, Grants on the web: Critical Elements and Materials Network (CrEAM). (Accessed 04/07/19)
78. DSC-69 National Materials Datahub (1). (Accessed 04/07/19)
79. DSC-69 National Materials Datahub (2). *Data Science Campus*. (Accessed 04/07/19)
80. European Commission (2008). The raw materials initiative — meeting our critical needs for growth and jobs in Europe. Koninklijke Brill NV.
81. Løvik, A. N. *et al.* (2018). Improving supply security of critical metals: Current developments and research in the EU. *Sustainable Materials and Technologies*, Vol 15, 9–18.
82. European Commission (2014). *Commission Staff Working Document: On the Implementation of the Raw Materials Initiative, Brussels, Belgium*.
83. Partners. *EIT RawMaterials*. (Accessed 30/08/19)
84. Henriques, M. (2019). Japan's grand plans to mine deep-sea vents. (Accessed 04/07/19)
85. Parker, D. *et al.* (2012). *WRAP Summary Report. Mapping consumption and waste of raw materials in electrical products in the UK*. WRAP.
86. Verhoef, E. V. *et al.* (2004). Process knowledge, system dynamics, and metal ecology. *Journal of Industrial Ecology*, Vol 8, 23–43.
87. Barteková, E. *et al.* (2016). *Critical Raw Material Strategies in Different World Regions*. UNU Merit.
88. POST (2016). *POSTnote 536, Designing a Circular Economy*.
89. Steinbeis-Europa-Zentrum (SEZ) EU Project SUSMAGPRO: Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy. (Accessed 04/07/19)
90. Monier, V. *et al.* (2014). *Development of Guidance on Extended Producer Responsibility (EPR) Final Report*. 227. European Commission – DG Environment.
91. Presidential Executive Order on a Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals. *The White House*. (Accessed 04/07/19)
92. Interior Releases 2018's Final List of 35 Minerals Deemed Critical to U.S. National Security and the Economy. (Accessed 04/07/19)
93. Murkowski, L. (2019). *American Mineral Security Act - S.1317*. (Accessed 04/07/19)
94. Murkowski, Manchin, Colleagues Introduce Bipartisan Legislation to Strengthen America's Mineral Security, U.S. Senator Lisa Murkowski of Alaska. (Accessed 04/07/19)
95. What CMI Does, Critical Materials Institute. (Accessed 04/07/19)
96. Mine & Quarry Minerals UK. (Accessed 04/07/19)
97. British Fluorspar Limited. (Accessed 04/07/19)
98. Telford, W. (2018). How Hemerdon mine lost £100m in just three years. *Plymouth Herald*. (Accessed 04/09/19)
99. Métampère Lithium Exploration. (Accessed 04/07/19)
100. Smallcombe, M. (2019). Why Cornwall is sitting on a new multi-billion pound jackpot. *Cornwall Live*. (Accessed 04/07/19)
101. BBC News (2017). 'Excitement' over £1m lithium boost. (Accessed 04/07/19)
102. Amos, J. (2019). UK drones map Chernobyl's 'Red Forest'. (Accessed 04/07/19)
103. Tong, S. *et al.* (2017). Demonstration of reusing electric vehicle battery for solar energy storage and demand side management. *Journal of Energy Storage*, Vol 11, 200–210.
104. Martinez-Laserna, E. *et al.* (2018). Battery second life: Hype, hope or reality? A critical review of the state of the art. *Renewable and Sustainable Energy Reviews*, Vol 93, 701–718.
105. Hagelüken, C. *et al.* (2010). Complex Life Cycles of Precious and Special Metals. In *Linkages of Sustainability*. The MIT Press.

POST is an office of both Houses of Parliament, charged with providing independent and balanced analysis of policy issues that have a basis in science and technology. POST is grateful to Andrew Stretton for researching this briefing, to the Engineering and Physical Sciences Research Council for funding his fellowship, and to all contributors and reviewers. For further information, please contact the co-author, Dr Lydia Harriss.