UK Critical Minerals Intelligence Centre

BRITISH GEOLOGICAL SURVEY

Study on future UK demand and supply of lithium, nickel, cobalt, manganese and graphite for electric vehicle batteries

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Foreword

This report has been produced by the British Geological Survey (BGS) under the auspices of the Department for Business, Energy and Industrial Strategy (BEIS)-funded UK Critical Minerals Intelligence Centre (CMIC). It is the first output from CMIC, which aims to provide up to date, accurate, high resolution data and dynamic analysis on primary and secondary minerals resources, supply, stocks and flows of critical minerals, in the UK and globally

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Key messages

- To decarbonise the economy and support the automotive sector, the Government plans to build an internationally-competitive electric vehicle supply chain in the UK.
- Planned domestic battery manufacturing plants or 'gigafactories' are an essential part of this commitment, and are also required to fulfil the requirements of agreed UK-EU trade rules of origin.
- UK battery manufacturers will require lithium, nickel, cobalt and manganese to synthesise cathode active materials (CAM), together with natural or artificial graphite for the production of anodes.
- Several companies plan to expand existing facilities or establish new gigafactories in the UK that will ramp up production to 2030. If these commitments are realised they equate to an estimated cumulative UK annual battery production capacity in 2030 of 135 gigawatt hours.
- Based on current information on the most likely battery chemistries that will make up this production, this study estimates that in 2030, the UK will have an annual requirement for about 15 000 tonnes of lithium, 90 000 tonnes of nickel, 11 000 tonnes of cobalt and 10 000 tonnes of manganese to produce CAM; and 135 000 tonnes of graphite to produce anodes.
- These demand estimates indicate that the UK is set to become a major consumer of battery minerals. For example, based on the scenarios assessed, it is estimated that in 2030 the UK would consume 12–17 per cent of the lithium produced globally in 2019, and a significant proportion of the current world production of some of the other battery minerals. In reality, UK demand will account for a smaller share of global production in 2030 than is outlined above, as by 2030 global production of all the battery minerals is likely to have increased significantly.
- The UK is currently dependent on the global market for its battery mineral needs. Even under more conservative scenarios, global demand projections indicate that all of the battery minerals will experience triple digit percentage demand growth increases up to 2030 and beyond. Many other countries are building gigafactories at pace to support their automotive sectors and these actors are already competing to access supplies of battery minerals.
- The UK currently has no commercial-scale production of primary (mined) battery minerals and limited refining capacity, and is therefore reliant on imports. To meet estimated UK demand for nickel, manganese and graphite in 2030 would require a 12-, 8- and 6-fold respective increase in current imports of sulphates of nickel, manganese dioxide and graphite. A major factor that the UK needs to consider when assessing the risks associated with its import dependence are the potential trade barriers that could disrupt existing global supply chains.
- A significant ramping-up of primary production of battery minerals is required to meet projected UK and global demand in 2030 and beyond. Although long-term geological availability is not an issue, bringing adequate new supply on-stream in the near term may be problematic due to a range of factors, including the long lead times for mining projects.
- Battery manufacturing scrap, derived from the UK's gigafactories is expected to be an important source of recycled CAM as early as 2030. By

2040, flows of end-of-life vehicles will have increased very significantly which means that recycling could make a significant contribution to total UK CAM supply by this time.

- The international supply chains, on which the UK is currently dependent for its supplies of battery minerals, are complex, dynamic, and generally have poor end-to-end visibility. As a consequence, the UK is vulnerable to supply disruptions arising from geopolitical, economic, environmental and social issues.
- There has been no systematic exploration for battery minerals in the UK, and the scale of potential resources is highly uncertain. Based on current knowledge and recent developments the greatest potential for domestic production appears to be associated with lithium and nickel.
- Despite the potential for domestic production of certain battery minerals, the scale of local demand and the variety of minerals required means that UK will remain heavily-dependent on international trade for the majority of its battery mineral needs, particularly in the period up to 2030.

1 Background

The pathway to a low carbon economy requires the deployment of an energy system powered by clean-energy technologies accompanied by major improvements in energy efficiency. This clean energy system is more diverse than the traditional fossil fuel-based system and involves numerous different technologies such as wind and solar power, battery and hydrogen storage, and electrification of transport and other sectors. These technologies and the supporting infrastructure are significantly more material intensive than traditional fossil fuel-based energy supply systems (Arrobas et al., 2017; IEA, 2022a; World Bank Group, 2020). For example, a typical electric car requires six times more mineral inputs than a conventional internal combustion engine (ICE) car (IEA, 2022a). The UK has set a world–leading, legally-binding target to achieve net zero emissions by 2050 and additional interim targets to reduce emissions by 78 per cent by 2035 (Department for Business Energy & Industrial Strategy, 2021a; HM Government, 2020).

Decarbonising transport

The transport sector is the largest carbon dioxide-emitting sector in the UK, accounting for almost 30 per cent of carbon dioxide emissions in 2020, principally from road transport (Department for Business Energy & Industrial Strategy, 2021b). Fifty-five per cent of 2019 domestic greenhouse gas (GHG) emissions were from cars and taxis (Department for Transport, 2021a). To address this challenge the UK has announced that the sale of new petrol and diesel cars and vans will be phased out by 2030, and all new cars and vans will be fully zero emission at the tailpipe from 2035 (Department for Transport, 2021a). The UK is not alone in these aspirations with many countries having similar ambitious plans to achieve net-zero emissions. In 2020 China, the world's largest market for sales of new vehicles (OICA, 2022), released a 'New Energy Vehicle Industrial Development Plan for 2021 to 2035'. This outlines its intention to develop a globally competitive automotive sector based around electric and low emission vehicles, with electric vehicles (EV) becoming the majority of new vehicle sales beyond 2035 (ICCT, 2021). The United States, the second largest market globally for sales of new vehicles (OICA, 2022), has also set an ambitious new target to make half of all new vehicles sold in 2030 zero-emission (The White House, 2021).

The electromobility revolution

These ambitions have led car manufacturers to embrace electrification and announce ambitious plans to capture market share (BMW Group, 2021; Volkswagen, 2021). Technological change, economies of scale and improvements in manufacturing processes have contributed to significant cost reduction in EVs in recent years, with the average price of an automotive battery pack decreasing by almost 90 per cent in real terms between 2010–2021 (IEA, 2020). This has led to rapid growth in EV sales in many regions (IEA, 2022b) and a global rush to develop lithium-ion battery (LIB) production capacity via a burgeoning pipeline of planned battery manufacturing plants, commonly termed gigafactories (Benchmark Mineral Intelligence, 2022). Even under the International Energy Agency's (IEA) more conservative, 'Stated Policies Scenario' (STEPS)[1] the global EV stock across all transport modes expands from over 11 million in 2020 to almost 145 million vehicles by 2030, an annual average growth rate of nearly 30 per cent. Under the more ambitious 'Sustainable

[1] The Stated Policies Scenario (STEPS) reflects all existing policies, policy ambitions and targets that have been legislated for or announced by governments around the world. It includes current EV related policies and regulations, as well as the expected effects of announced deployments and plans from industry stakeholders.

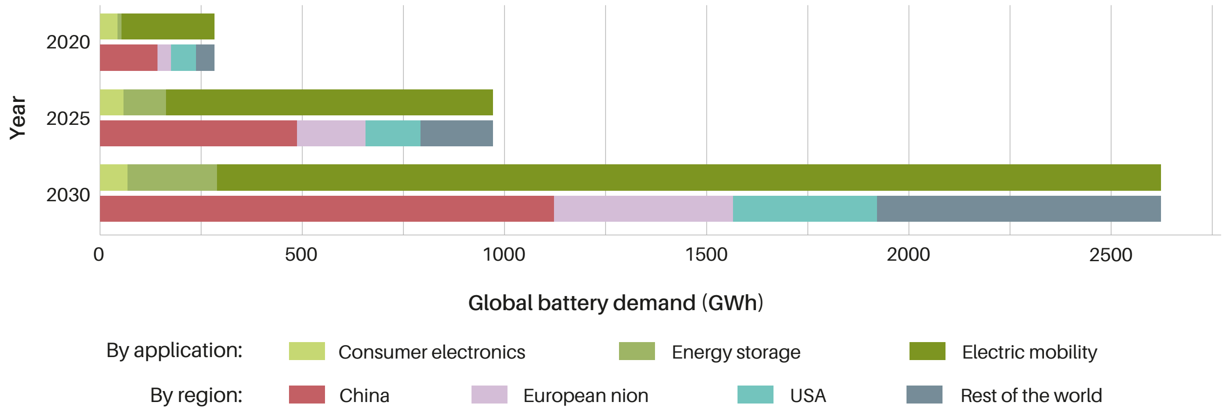


Figure 1 Global battery demand by application (top) and region (bottom) between 2020 and 2030. Data source: Global Battery Alliance World Economic Forum (2019).

Development Scenario' (SDS)[2], which is consistent with the Paris Agreement goals, the global EV stock reaches almost 70 million vehicles in 2025 and 230 million vehicles in 2030. Therefore, global battery demand is set to increase greatly over the coming decade, reaching 1.6 TWh in the STEPS and 3.2 TWh hours in the SDS. For comparison, global LIB automotive battery manufacturing capacity in 2020 was about 300 gigawatt hours (GWh) (IEA, 2021b).

As a consequence of the scale and pace of the transition to electric mobility (Figure 1), rapid growth in demand for the minerals used in batteries (herein referred to as battery minerals), namely lithium, nickel, cobalt, manganese and graphite is projected over the next two decades. EV and battery storage is estimated to be responsible for about half of the mineral demand growth from clean energy technologies over the next 20 years (IEA, 2022a). The magnitude of the projected demand growth for these minerals has led to global concerns about the adequacy of existing production capacity to keep pace with growing demand. Increased global competition for resources and issues related to the sustainability of production are also likely to present additional challenges.

UK supply of most minerals and metals required for advanced manufacturing and for reducing emissions across the economy via a clean energy system, are derived almost entirely from overseas through complex, dynamic international supply chains that often have poor end-to-end visibility (Wilton Park, 2021). As a consequence, the UK is vulnerable to supply disruptions arising from numerous potential causes of geopolitical, economic, environmental and social nature. The 'UK criticality assessment of technology critical minerals and metals' identified the battery minerals as having 'high' to 'elevated' criticality, owing to their economic importance and global supply risk (Lusty et al., 2021). The House of Lords Science and Technology Select Committee has emphasised the risk to the UK battery strategy if potential issues with the future availability of critical raw materials are not addressed (House of Lords, 2021).

This study introduces LIBs, their key components, battery types, and their associated mineral requirements. It considers the key drivers for developing a domestic LIB manufacturing sector in the UK. UK demand for battery minerals for electrification of light-duty vehicles up to 2030 is assessed using two scenarios. The implications

[2] The Sustainable Development Scenario (SDS) rests on three pillars: ensure universal energy access for all by 2030; bring about sharp reductions in emissions of air pollutants; and meet global climate goals in line with the Paris Agreement. The SDS reaches net-zero emissions by 2070 and global temperature rise stays below 1.7–1.8°C with a 66 per cent probability, in line with the higher end of temperature ambition of the Paris Agreement.

of these UK demand projections are examined in relation to estimated world demand for battery minerals under key global scenarios. The global value chains on which the UK is reliant for supplies of battery minerals are described. Historical production of battery minerals, price trends and the impact that price volatility has on battery manufacturing costs is explored. Data on global and UK trade flows in battery minerals are presented to highlight key global exporters and importers of battery minerals and UK import dependence. The projected future supply-demand balance of battery minerals is assessed, considering the potential role of both primary and secondary supplies. The study concludes by considering future options for securing supplies of battery minerals for the UK economy and the potential challenges faced.

2 Lithium-ion batteries, components and associated mineral raw materials

Battery fundamentals

An electric battery is a mobile rechargeable power source, consisting of one or more electrochemical cells with external connectors that allows the storage and release of energy on demand. A battery converts chemical energy directly into electrical energy via a reduction and oxidation process. All batteries comprise two electrodes, a separator, an electrolyte and two current collectors. LIBs have become the preferred choice of car manufacturers for electromobility. In a LIB, the cathode and anode constitute the poles and host the element lithium (Li). The electrolyte allows the circulation of free lithium ions (Li+) from one pole to the other, producing electric energy to power a connected device, such as a mobile phone or an EV. During a discharge, the anode releases free Li ions to the cathode, providing an equal number of electrons to the electrical circuit. As a LIB is being recharged, electric power causes imbalance of the redox equilibrium between the anode and cathode, forcing the Li ions to migrate back to the anode (Figure 2).

Battery types and chemistry

The chemistry and structure of LIBs have evolved significantly in recent years with the primary aims of improving: (i) energy density, which is related to how many lithium ions the cathode and anode accommodate; (ii) energy output, which is dependent on the rate at which the lithium ions can circulate between the electrodes; and (iii) the number of charge and discharge cycles, which is linked to the structural integrity of electrodes to repeated migration of ions over time.

These factors have influenced the evolution of battery chemistries that are currently being used to power EVs. In parallel, research is investigating new electrode crystalline structures and compositions, as well as new electrolyte components (e.g. solid-state batteries). LIB cathodes commonly utilise various proportions of nickel (Ni), cobalt (Co), manganese (Mn), iron (Fe), and phosphorus (P) (Table 1 and Figure 3), whilst the anode principally employs natural or artificial graphite. Numerous battery chemistries have been developed for specific end-use applications, for example consumer electronics, energy storage and electromobility. The latter have evolved to optimise vehicle range, charging time, security, safety and autonomy, whilst balancing the cost of raw materials and ethical issues associated with supply chains. The batteries currently in use in the global EV and plug-in hybrid vehicles (PHEV) fleet are dominated by LMO, NCA, NMC and LFP types (Table 1). The early 2000s saw the slow uptake of PHEVs and the emergence of the first fully EVs, dominated by NiMH, LMO, LFP, and NCA chemistries. The last decade marked the emergence of NMC batteries, which have rapidly grown in use as passenger EV sales have expanded. NMC chemistries

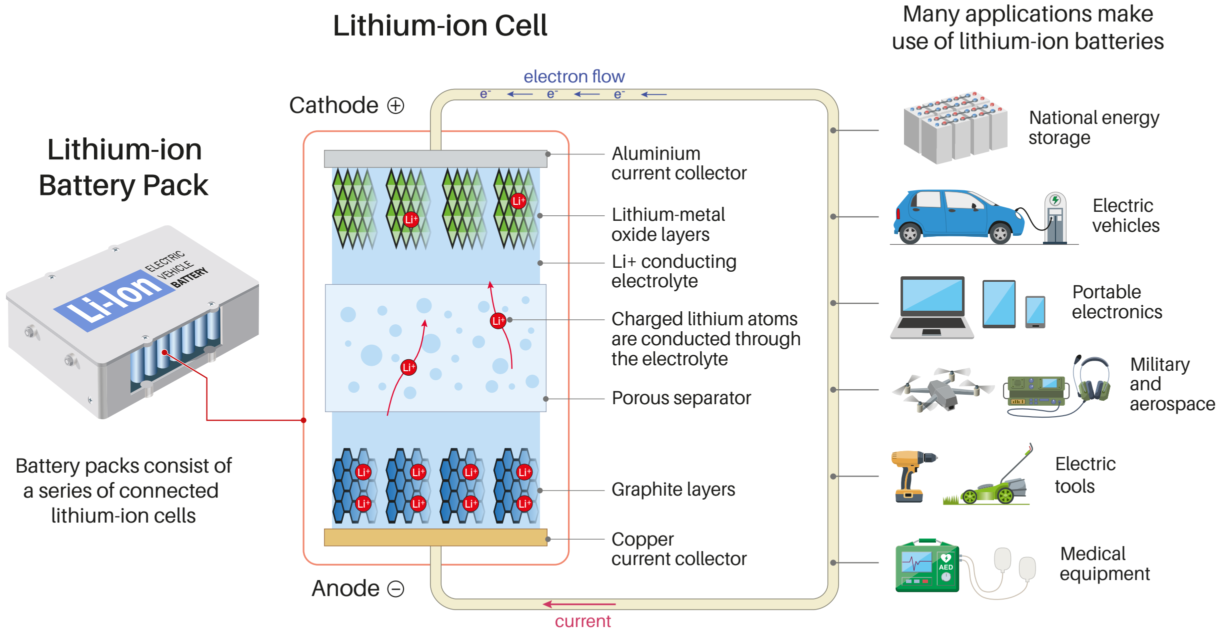


Figure 2 Schematic diagram of a lithium-ion battery and example end-use applications. During discharge, the anode releases free lithium ions to the cathode, providing an equal number of electrons to the electrical circuit. As a lithium-ion battery is being recharged, electric power imbalances the redox equilibrium between the anode and cathode, forcing the lithium ions to migrate back to the anode. BGS © UKRI.

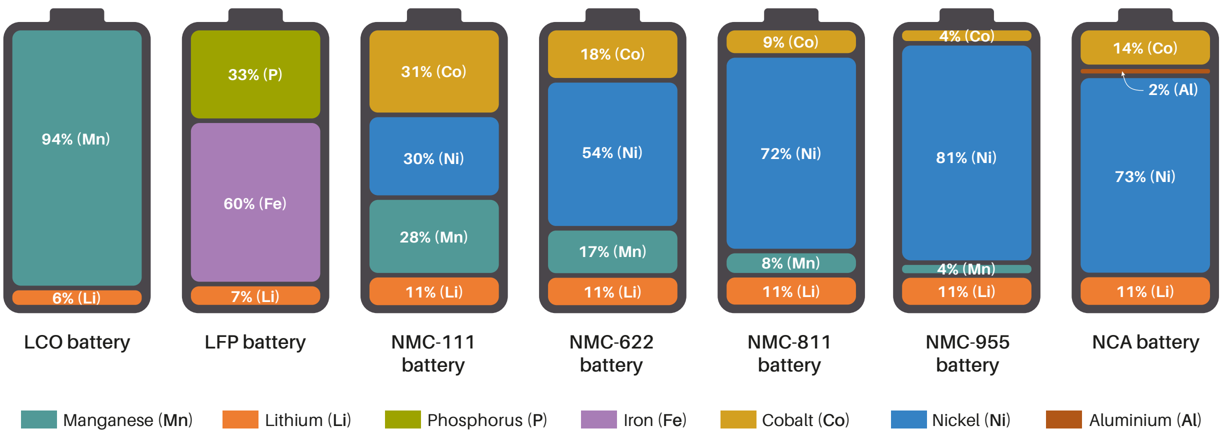


Figure 3 Key lithium-ion battery types and their key cathode constituents. Adapted from Gunn and Petavratzi (2018) and BloombergNEF (2020). BGS © UKRI.

represented 37 per cent of EV sales in 2018 and are expected to account for 63 per cent of global EV battery sales by 2027 (Zhao et al., 2021). Despite this broad trend, the market share of different battery types varies across the world. LFP batteries have become increasingly important in China, whilst the European and American markets are currently dominated by NMC types. On average, LFP cells were almost 30 per cent cheaper than NMC cells in 2021 (BloombergNEF, 2021), due to the lower cost of the raw materials used. They also offer greater thermal stability and safety but have lower energy outputs for a similar weight relative to NMC batteries. This makes them a more suitable choice for energy storage applications, and for city cars and buses that require more limited energy density output and range (Nguyen et al., 2021). In contrast, NMC batteries have a greater energy density owing to their high nickel content, which provides greater range and more rapid energy output, a crucial factor for many passenger EVs. However, thermal runaway, resulting in fire and the risk of explosion, was an issue with early nickel-based chemistries. This problem has been overcome by the addition of cobalt to the cathode (Greenwood et al., 2021).

The cathodes of NMC batteries are the most expensive to produce on account of the metals that are utilised. Furthermore, concerns about the security of supply of these metals and the ethics of their production, most notably surrounding cobalt, are influencing developments in battery chemistry (Zhao et al., 2021). Therefore, NMC

Table 1 The principal types of lithium-ion batteries, their cathode composition and associated benefits and drawbacks (Guan et al., 2020; Olivetti et al., 2017).

Cathode material		Composition	Benefits	Drawbacks
NCA	Lithium Nickel Cobalt Aluminium	$LiNiCoAlO_2$	High specific energy	Safety issues
			Power density	Co price volatility
			Long life cycles	Co ethical issues
LFP	Lithium Iron Phosphate	$LiFePO_4$	Inherently safe	Low operating voltage
			Large thermal stability	Low capacity
			High current rating	Low energy density
			Long life cycles	
LMO	Lithium Manganese Oxide	$LiMn_2O_4$	Inexpensive	Poor high-temperature performance
			High thermal stability	
			High discharge plateau	
LNO	Lithium Nickel Oxide	$LiNiO_2$	Ni offers high rate capability	Thermal runaway risk (Ni)
NMC	Lithium Nickel Manganese Cobalt	$(Li_xNi_yMn_zCo_{1-y-z})O_2$	Highest specific energy (Ni)	Thermal runaway risk (Ni)
	NMC-111	$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$	Mn lowers internal resistance	Low specific energy (Mn) Low Mn compatibility with electrolytes
	NMC-622	$LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$		
	NMC-811	$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$		
	NMC-955	$LiNi_{0.9}Mn_{0.05}Co_{0.05}O_2$		

technologies are tending to move away from cobalt-rich compositions by increasing the proportion of nickel whilst maintaining safe thermal operating conditions. Higher nickel content generally enhances energy density with a trade-off in stability and processing costs. NMC compositions are commonly referred to by the ratio of their nickel, manganese, and cobalt content, respectively, such as NMC-111, NMC-622 and NMC-811 (Table 1). The car industry has moved away from using NMC-111 in EVs, replacing it with NMC-622. However, NMC-811 is becoming more common and it is expected to be the dominant NMC chemistry over the next decade (Xu et al., 2020). Research suggests a continuing trend towards nickel-rich cathodes, with both NMC-955 (90per cent Ni, 5per cent Mn, and 5per cent Co), and cobalt-free, lithium nickel oxide batteries expected to be in commercial use by 2030 (Kim et al., 2021; Zhao et al., 2021).

The pursuit of EVs with similar power and range to ICE vehicles means the rate of commercial adoption of new battery chemistries has been far more rapid than anticipated over the last decade, resulting in a highly diversified battery landscape. It is anticipated that a similar level of innovation in battery technology will continue in the future.

Current efforts are focused on: (i) optimising the performance of existing designs, charging speed and lifespan; (ii) reducing environmental footprint and costs by exploring alternative materials; and (iii) creating new battery designs. The UK has a major programme of battery-related research supported by the EPSRC/UKRI-funded Faraday Battery Challenge (UKRI, 2021), which is investing up to £330 million in research and innovation projects and facilities in partnership with the automotive and battery manufacturing industries. Several potentially transformative next-generation technologies (Table 2) may be of importance for electromobility beyond 2030 (The Faraday Institution, 2022b), with associated implications for demand for the specific mineral raw materials they require.

In the UK and globally LIBs are used in a diverse range of applications, for example, electric mobility, energy storage, portable electronics, medical equipment, and military and aerospace (Figure 2). However, with the rapid transition from ICE vehicles to EVs, the dominant market by volume and value in the period up to 2030 will be in electric cars and light goods vehicles (LGVs), collectively referred to as light duty vehicles (LDVs) (Global Battery Alliance World Economic Forum, 2019) (Figure 4).

Table 2 The next generation of potential battery technologies (The Faraday Institution, 2022a).

Technology	Innovation benefits
Cobalt-free high nickel-manganese (LNMO)	Stable structures with high energy density
Silicon anode (LIB-Si)	Better performance than a graphite anode
Solid-state battery (SSB)	Solid mediums permit extremely fast charging rates and energy outputs
Sodium-ion battery (NIB)	Cost-effective alternative to lithium
Lithium-sulphur battery (Li-S)	2–3 times greater specific energy than LIBs
Metal-Air battery (M-Air)	High electrochemical potential between a metallic anode and oxygen from air as the cathode results in higher energy capacity and density
Flow battery	Theoretical unlimited longevity due to the physical separation of components

3 The principal drivers for developing a UK lithium-ion battery manufacturing sector

The economic importance of the UK automotive sector and demand for electric vehicles

The UK automotive industry is a major part of the economy, worth more than £60 billion in turnover and contributing £11.9 billion in value in 2020 (SMMT, 2022b). More than 82 per cent of vehicles made in the UK are exported, principally to the EU, which accounts for 55 per cent of UK-built vehicle exports (SMMT, 2022a). To support this sector and address its net zero emissions targets the Government has announced plans to build an internationally-competitive EV supply chain at pace and scale in the UK (Department for Transport, 2021a).

Total UK sales of electric cars (including PHEVs) and LGVs (LDVs) have increased on average by 35 per cent year-on-year between 2015–2020. Since 2018, sales of electric cars have grown more rapidly, with year-on year change increasing from 40 per cent to 100 per cent between 2018 and 2021 (Department for Transport, 2021b). This expansion in privately-owned EVs will rapidly become the main driver of growth in the UK EV fleet. This high rate of uptake has been favoured until recently by UK government subsidies and the declining costs of manufacturing. Furthermore, it is estimated that by 2025 the purchase cost of an EV will be lower than for a conventional ICE vehicle, which, combined with lower maintenance and fuel costs, will further accelerate demand for EVs (CRM4EV, 2022).

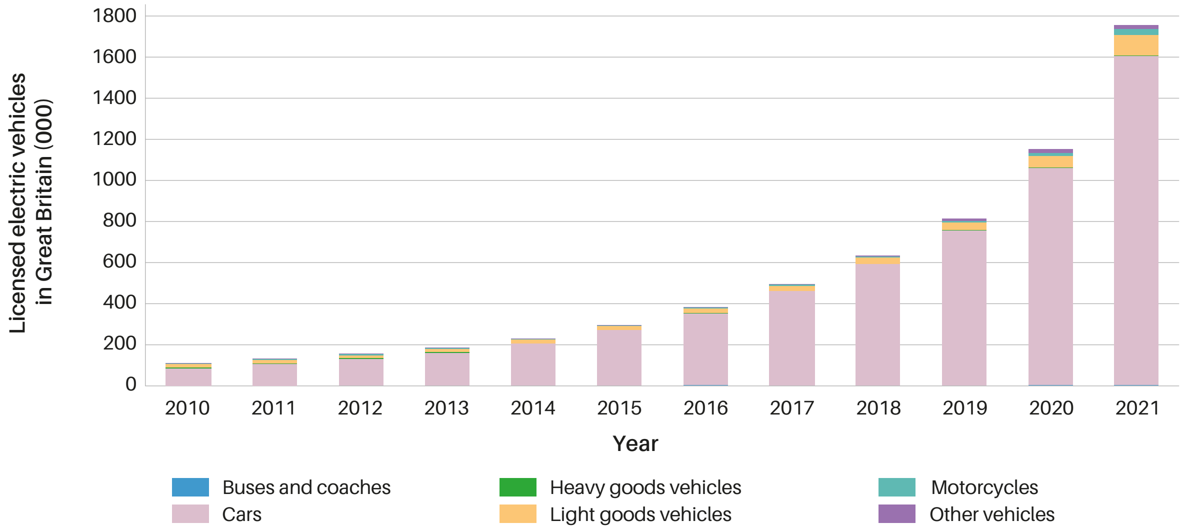


Figure 4 Licensed electric vehicles (hybrid, plug-in hybrid, battery electric, range extended electric) in Great Britain. Data source: Department for Transport (2021b).

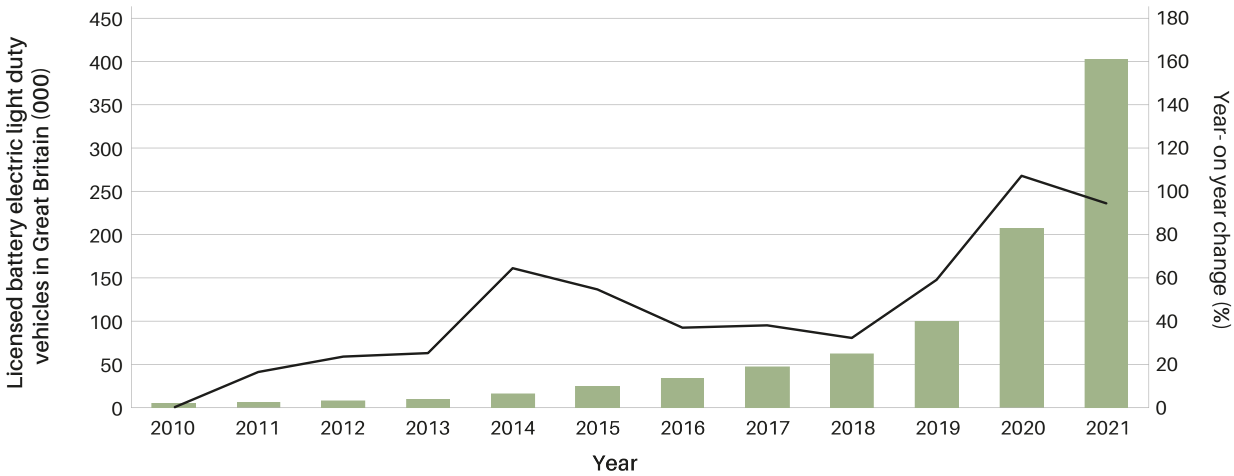


Figure 5 Evolution of the battery electric light duty vehicle fleet in Great Britain. Data source: Department for Transport (2021b).

Implications of the UK-EU free trade agreement for the UK automotive industry

The importance of vehicle exports to the UK means the UK-EU Trade and Cooperation Agreement (TCA) has significant implications for the UK automotive industry. The TCA permits zero tariffs or quotas on trade between the UK and the EU if the goods 'originate' in the UK, as defined by the 'Rules of Origin' stipulated in the TCA. These rules specify the proportion of the product in terms of value that has to be produced in the UK or the EU in order to be classed as a UK/EU originating product. There is a six-year phase-in period, which commenced in January 2021. To avoid tariffs, from January 2024 to December 2026 electric battery cells and battery packs must have a maximum 'non-originating' material content of 50 and 40 percent, respectively.

From January 2027 onwards, the UK will only be able to export unlimited numbers of EVs and PHEVs into the EU market with zero tariffs if the following conditions are satisfied: (i) EVs have at least 55 per cent cumulative UK-EU content and an 'originating' battery pack; and (ii) an originating battery pack must have either at least 65 per cent UK-EU content for the cell or 70 per cent for the battery pack (The Faraday Institution, 2021). Therefore, in order meet the conditions of the TCA and maintain unrestricted access to its largest export market for vehicles, it is imperative that the UK quickly establishes its own battery gigafactories and associated raw material supply chains.

Committed production of lithium-ion batteries in the UK

To date, four companies and consortia have announced plans to expand existing facilities or establish new battery gigafactories in the UK (Table 3). Expected development timescales, planned annual production capacity and information on the battery types they intend to manufacture are summarised in Table 3. If fully realised, together they would equate to an estimated cumulative UK annual battery production capacity in 2030 of 135 GWh. This estimate is 6 per cent greater than the annual capacity predicted by The Faraday Institution for 2040 (The Faraday Institution, 2019), highlighting the rapidly evolving nature of the industry and market. To place current UK gigafactory development plans in context, as of May 2022 more than 300 gigafactories are planned or being developed worldwide, equating to about 6400 GWh of LIB capacity, a 68 per cent year-on-year increase since 2019 (Benchmark Mineral Intelligence, 2022).

Table 3 Announced plans to expand existing facilities or establish new battery gigafactories in the UK, their development timescales, planned annual production capacity and available information on the battery types they intend to manufacture (based on company announcements and other public domain information).

Company	Location	Timeline	Annual capacity GWh	Battery type(s)
Envision	Sunderland	2012	1.9	LMO
		2024	11	NMC-811
		2030	35	NMC-811
AMTE	Thurso	2022	0.5	Diversified BEV LIB, NIB, public transport, and storage
		2025	10	
Britishvolt	Blyth	2024	4	NMC-811 + eLNO-Nb
		2027	30	NMC-811 + eLNO-Nb
West Midlands Gigafactory	Coventry	2025	-	-
		2030	60	EV and storage LIBs
Total		2030	**135**	-

4 UK demand for battery minerals

One approach to estimating future UK cathode and anode material demand for the domestic manufacture of EV batteries is to base it on forecasts for UK EV production. However, initial uncertainty arises from variation in the production forecasts, for example the National Grid estimates that UK EV production will be in the range of 1–2.5 million units annually by 2030 (National Grid ESO, 2021). The Advanced Propulsion Centre (APC) forecasts that the UK will produce 1.5 million light duty EVs by 2030 (Advanced Propulsion Centre, 2022a). Additional uncertainty arises because it is necessary to make assumptions about the evolution of battery energy density and the vehicle models that will make up the forecast production. These need to be estimated in order to obtain an equivalent total energy requirement (in GWh), from which the battery mineral requirements can be estimated based on the battery chemistries and their market share. An alternative approach, employed in this study is to estimate the demand for battery minerals based on EV battery production that is currently committed to take place in the UK (Table 3), and for which battery minerals will be required irrespective of battery energy density and the vehicle models that they are used in.

Two scenarios were used in order to estimate future UK demand for battery minerals for producing cathode and anode active materials for LDVs to 2030. Both scenarios are based on the announced capacities of gigafactories planned for the UK, and assume a total output capacity of 135 GWh in 2030 (Table 3). The UK-NMC scenario is based on the various battery chemistries that the announced gigafactories plan to produce (principally NMC) (Table 3). The UK-NMC/LFP scenario explores the potential influence of a major shift towards LFP batteries, with the planned gigafactories producing 50 per cent LFP batteries. This could arise because of: (i) performance improvements in LFP technologies; and/or (ii) the production of LFP batteries becoming more cost competitive than NMC chemistries, owing to them not requiring nickel and cobalt (CRM4EV, 2022). The likelihood of this market evolution is supported by recent industry developments, for example Tesla reported that in Quarter 1 2022 more than 50 per cent of the cars they manufactured (standard range vehicles) were equipped with LFP batteries (Tesla, 2022). Many other major automakers plan to use LFP batteries in standard-range and entry-level vehicles (Asad, 2021). Both scenarios use published data on battery chemistries (Table 4) to calculate mineral demand based on the planned GWh of battery production, considering the market share of specific battery types in each scenario.

Table 4 The chemistries of cathode active materials (kg required per kWh) used to calculate battery mineral demand in this study (Olivetti *et al.*, 2017).

	kg/kWh			
Cathode type	Lithium	Manganese	Cobalt	Nickel
LFP	0.1	0	0	0
NCA	0.112	0	0.143	0.759
NMC-111	0.139	0.367	0.394	0.392
NMC-622	0.126	0.2	0.214	0.641
NMC-811	0.111	0.088	0.094	0.75
NMC-955	0.137	0.046	0.05	0.82

The quantity of lithium that the UK will require to supply its planned gigafactories differs little between the two scenarios, with 14–15 thousand tonnes (kt) of lithium (74–80 kt lithium carbonate equivalent) required to fulfill the entire planned production capacity (Table 5). The UK-NMC/LFP scenario results in a reduction in UK demand for nickel, cobalt and manganese that is proportionate to the LFP market share (Table 5 and Figure 6). The APC have estimated future UK cathode and anode raw material demand based on forecasts for UK light duty EV production (96 GWh) and assuming all cells use NMC-811 (Advanced Propulsion Centre, 2022a). Their estimates are 20–40 per cent lower than the estimates based on planned UK gigafactory capacity and battery chemistries, owing to the differences in the underlying assumptions used in the two approaches.

Table 5 Estimated annual UK demand for battery minerals in 2030 based on the announced capacity of UK gigafactories (Table 3), under two scenarios: i) the UK-NMC scenario is based on the various battery chemistries that the announced UK gigafactories plan to produce; and ii) the UK-NMC/LFP scenario assumes that 50per cent of the announced UK capacity is used to make LFP batteries. The third demand assessment (APC NMC-811) is based on forecasts of UK light duty electric vehicle production and assumes all cells use NMC-811 (Advanced Propulsion Centre, 2022a). Based on Advanced Propulsion Centre (2022a) demand for graphite for anode production in all the scenarios assumes that a GWh of battery capacity requires 1 kt of either natural or artificial graphite. kt = thousand tonnes.

		Annual UK demand (kt)				
Scenario	Assumed production in 2030 (GWh)	Lithium	Nickel	Cobalt	Manganese	Graphite
UK-NMC	135	14.9	90.4	11.2	10.2	135.0
UK-NMC/LFP	135	14.2	49.6	5.9	5.3	135.0
APC-NMC-811	96	10.7	72	9.1	8.5	96.0

Given the pace at which battery technologies are evolving, a multitude of other scenarios based on varying market shares for different combinations of battery chemistries and evolving technologies (Table 2) up to 2030 could be explored. However, the value in this is limited, as reliable predictions cannot be made about which technologies will reach commercial maturity and when.

Opportunistic switching to production lines that can produce new battery chemistries remains a possibility for UK gigafactories that are only in the planning stages. However, it is likely that commercial inertia may lock future plants into their announced production plans if significant investments are required to adapt production to alternative technologies. Commercialisation of solid-state batteries, Li-Air or Li-S would have a comparable impact to the emergence of LFP on UK battery mineral demand, as these technologies do not require significant quantities of nickel, cobalt and manganese. A transition towards sodium-ion batteries and the use of silicon anodes would influence demand for lithium and graphite. New battery technologies and chemistries are continuously emerging and the uncertainty in the associated mineral requirements increases significantly beyond 2030 as the range of options and applications expand.

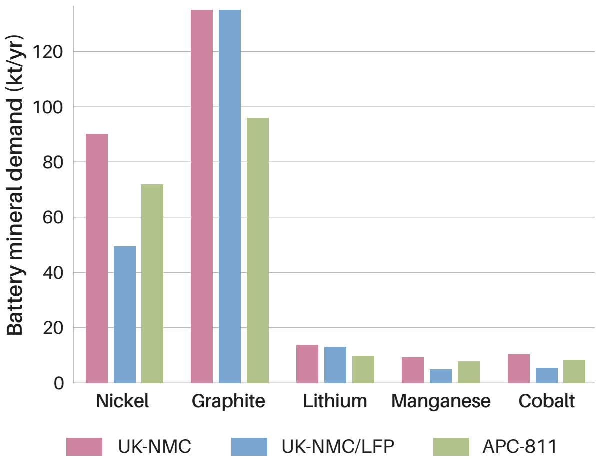


Figure 6 Estimated annual UK demand (kt = thousand tonnes) for battery minerals in 2030 based on the announced capacity of UK gigafactories (Table 3 and Table 5), under two scenarios: i) the UK-NMC scenario is based on the various battery chemistries that the announced UK gigafactories plan to produce; and ii) the UK-NMC/LFP scenario assumes that 50 per cent of the announced UK capacity is used to make LFP batteries. The third demand assessment (APC-NMC-811) is based on forecasts of UK light duty electric vehicle production and assumes all cells use NMC-811 (Advanced Propulsion Centre, 2022a). BGS © UKRI.

5 Global demand for battery minerals

The International Energy Agency (IEA) provides an extensive scenario-based[3] assessment of the global mineral requirements for a range of clean energy technologies up to 2040. The relative demand growth is particularly high for the battery minerals. They are estimated to increase between 3 and 13 times under the STEPS and between 8 and 42 times under the SDS in 2040 relative to 2020 levels from all clean energy technologies (IEA, 2022a). The significantly greater mineral demand under the SDS results from more extensive efforts to realise near-term emissions reductions associated with a surge in clean energy policies and investment. Considering mineral demand from batteries alone under these two scenarios, the IEA data indicates that between 2020 and 2030 global demand for all of the battery minerals will increase dramatically (Table 6 and Figure 7).

Another study that estimates mineral demand for clean energy technologies in 2050 draws similar conclusions, estimating that under the SDS lithium, cobalt and nickel demand will increase by more than 2100 per cent, 403 per cent and 168 per cent, respectively (KU Leuven, 2022). Other global projections for mineral demand associated with the clean energy transition and notably batteries (Global Battery Alliance World Economic Forum, 2019; Nguyen et al., 2021; World Bank Group, 2020; Xu *et al.*, 2020) also highlight unprecedented growth, reaching similar orders of magnitude over the next 20–30 years. However, as these projections are updated, there is a tendency to bring forward these estimates in accordance with the recent increases in the rate of uptake of EVs (CRM4EV, 2022; Global Battery Alliance World Economic Forum, 2019). Whilst e-mobility will clearly be a significant driver

Table 6 Estimated global battery mineral demand associated with electric vehicles in 2020 and under the IEA STEPS and SDS. Data source: IEA (2022a). kt = thousand tonnes.

	Demand in 2020 (kt)	Projected demand in 2030 under the STEPS (kt)	Projected demand increase in 2030 relative to 2020 under the STEPS (%)	Projected demand in 2030 under the SDS (kt)	Projected demand increase in 2030 relative to 2020 under the SDS (%)
Lithium	20	152	660	358	1690
Nickel	80	647	709	1567	1859
Cobalt	21	106	405	257	1124
Manganese	25	102	308	246	884
Graphite	141	1065	655	2499	1672

[3] The analysis is based on two main IEA scenarios: SDS and STEPS, and also considers the raw material requirements to hit net-zero globally by 2050. It considers a range of clean energy technologies deployed in the SDS, including renewable power (solar photovoltaics, onshore and offshore wind, concentrating solar power, hydro, geothermal and biomass), nuclear power, electricity networks (transmission and distribution), electric vehicles, battery storage and hydrogen (electrolysers and fuel cells). For each of the clean energy technologies, the study estimates overall mineral demand using four main variables: clean energy deployment trends under different scenarios; sub-technology shares within each technology area; mineral intensity of each sub-technology; and mineral intensity improvements.

for battery mineral demand, it is not the only industrial sector in which these minerals are used. It is, therefore, important to analyse and monitor future demand in other sectors such as construction, renewable energy, aerospace, defence and digital systems. Furthermore, other countries moving towards a low carbon economy in general and aspiring to develop their own e-mobility sector in particular, will also compete for access to minerals in the future.

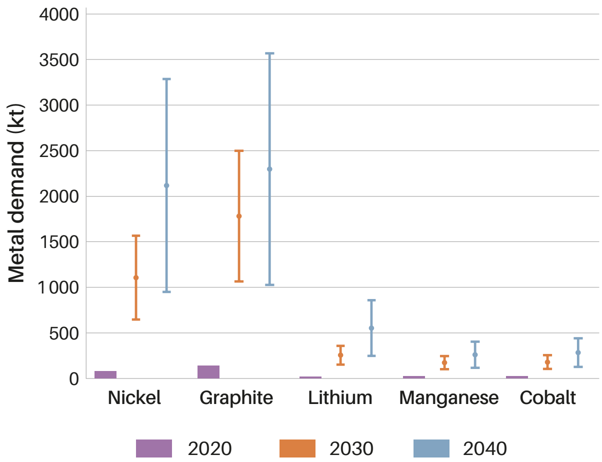


Figure 7 Global battery mineral demand associated electric vehicles in 2020 and the projected range in demand under the IEA STEPS (base of the range bars) and SDS (top of the range bars) in 2030 and 2040. Data source: IEA (2022a).

6 Battery mineral value chains

The minerals needed to produce raw materials for the manufacture of LIBs are extracted from the ground in various forms using a range of extraction methods. These minerals undergo a series of mechanical and/or chemical processing stages which concentrate them in various 'intermediate' chemical products. These intermediates are generally further refined using chemical methods, which ultimately yield products of the composition and purity required for the manufacturing stages that follow. Manufacturing produces items (components, parts, assemblies, etc) for incorporation into the final product for industrial or consumer use (Figure 8).

For many minerals and metals individual stages of the value chain are undertaken by different companies commonly operating remote from the extraction site and frequently in different countries. A complete vertically integrated value chain whereby a single company controls all stages of the lifecycle remains relatively rare, although it is becoming more widespread as original equipment manufacturers (OEMs) seek to ensure reliable and sustainable supply chains (The Economist, 2022). It is important to understand the existing value chains of battery minerals in order to determine where vulnerabilities to supply security may exist, commonly associated with unsustainable practices, environmental degradation and social issues in producing countries. Detailed understanding of these systems can be derived from the application of material flow analysis, which aims to quantify the flows and stocks of material within a particular system (Petavratzi and Josso, 2021). This approach underpins strategy development for sustainable resource use and may permit the identification of opportunities for the procurement of materials required for UK gigafactories.

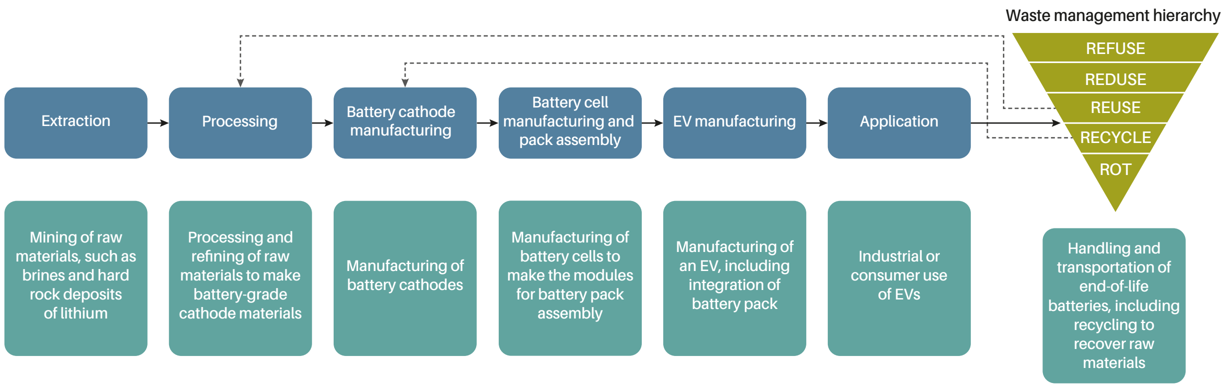


Figure 8 A generic battery mineral supply chain. BGS © UKRI.

Lithium

Lithium is extracted from two principal sources, hard-rock deposits and continental brines. Global production is dominated by hard-rock mining in Australia and brine operations in Chile and Argentina (Figure 9). In Australia spodumene is the main lithium-bearing mineral in the ores. Following mining, various physical methods are used to increase the lithium content and produce a spodumene concentrate (Brown et al., 2016). Subsequent chemical processing is employed to create either lithium carbonate or lithium hydroxide. In South America solar evaporation in a series of ponds is the first stage in the concentration of lithium from continental brines (Evans, 2014). Following the removal of impurities, sometimes accompanied by further chemical processing dependent on the composition of the source brine, a brine saturated with lithium chloride is produced. This is treated with sodium carbonate to produce a lithium carbonate with purity exceeding 99 per cent (Brown et al., 2016).

Further purification of the concentrated brine or the spodumene concentrate may be undertaken locally or the intermediate products may be shipped overseas for further treatment in a lithium refinery. There is also currently considerable interest in Direct Lithium Extraction (DLE) methods as alternatives to evaporation (Stringfellow and Dobson, 2021). DLE uses various chemical and physical techniques to extract lithium from brines. They are essentially closed-loop systems, which use considerably lower volumes of water than evaporation. They operate much more rapidly than open evaporation, which can take about two years and which has a very large physical footprint. Cornish Lithium Ltd, a mineral exploration and development company based in south-west England has commissioned a DLE pilot plant at its Geothermal Waters Test Facility at the United Downs site (Cornish Lithium, 2022). The production of refined lithium is dominated by China, with about 60 per cent originating from hard-rock mining operations in Australia (Tan, 2022) and Chile (from brine operations) (European Commission, 2020d). There is little

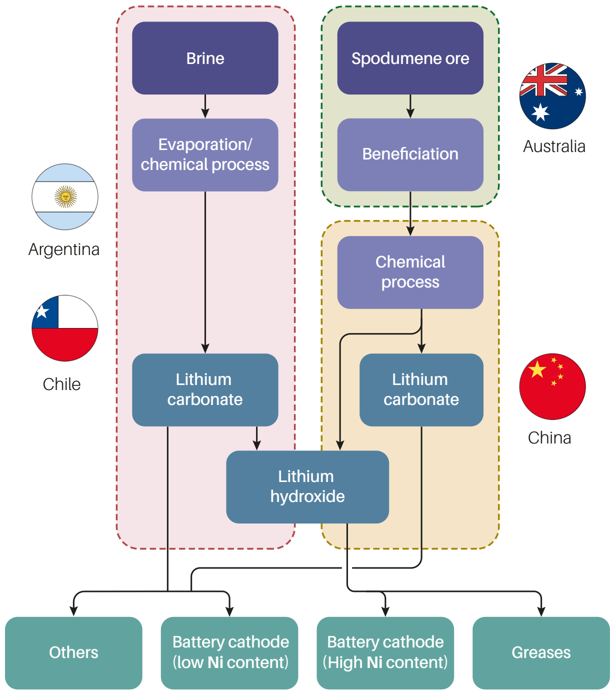


Figure 9 Lithium value chain. The flags denote the principal countries in which selected parts of the value chain are concentrated. Reproduced with permissions. Source: IEA (2022a) The Role of Critical Minerals in Clean Energy Transitions, World Energy Outlook Special Report. All rights reserved.

installed lithium refining capacity in Europe and no commercial-scale refining in the UK. Consequently, cell manufacturers and producers of battery packs are currently highly dependent on imported supplies of battery grade chemicals. However, there are several companies that are planning to establish lithium refining capacity in the UK to meet the demand from UK and European gigafactories, although they are all in the early stages of development. Green Lithium Refining Limited has announced plans to construct and operate a 'large-scale' lithium refinery in the in the north of England that would produce high-purity lithium hydroxide (Green Lithium Refining Limited, 2022). Green Lithium Refining Limited recently received the support of commodities trader, Trafigura that would source feedstock for its planned 50 kt a year facility (Hume, 2022a). Tees Valley Lithium Ltd intends to establish a lithium 'processing hub' in the Teeside Freeport, UK to supply the European market. The facility would process feedstock imported from various sources, to produce 96 kt of lithium hydroxide annually. In April 2022 the company completed a feasibility study that evaluated the economic viability of the project using various assumptions (London Stock Exchange, 2022a). The company has subsequently announced that following test work the specifications of the battery-grade lithium hydroxide it will produce are higher than the usual industry standards (London Stock Exchange, 2022b). A further company, Livista Energy Ltd has recently secured financial backing from the APC to support its plans to develop a lithium conversion facility in the UK. The planned initial capacity of the plant would be 30 kt per annum of lithium chemicals, with the potential to increase to 60 kt per annum. It is reported that the plant may be constructed in Blyth, Northumberland, UK (Hume, 2022b).

The dominant end-use of lithium is in LIBs, which account for about 74 per cent of total consumption. Other important applications of lithium are in ceramics and glasses (14per cent) and lubricating greases (3per cent) (USGS, 2022a).

Nickel

Nickel is extracted from ores of two distinct types: nickel-copper sulfides and nickel laterites (Petavratzi et al., 2019) (Figure 10). Resources of these ores are abundant and widespread with mines operating in more than 25 countries today (Nickel Institute, 2022). In recent years production from laterites has increased significantly and accounted for about 65 per cent of the total in 2019 (Azevedo et al., 2020).

Given the diversity of nickel ores, a range of metallurgical processing is employed to extract the nickel and other by-products such as cobalt and platinum-group metals. The most widely used method for the recovery of nickel from sulfide ores involves milling and flotation to produce a concentrate (Crundwell et al., 2011). The concentrate is smelted to produce a matte which is sent for refining at another facility that may be located overseas. In the refinery hydrometallurgical techniques involving leaching and solvent extraction are employed to produce nickel metal from the matte (Crundwell et al., 2011).

Most nickel laterite ores are also processed by smelting to produce ferronickel. However, increasingly high-pressure acid leach (HPAL) is being used for the treatment of nickel laterite ores (Ribeiro et al. 2021). This involves leaching a slurry of the milled and screened ore with sulfuric acid in an autoclave at about 250°C and 40–50 bar for approximately one hour. This is followed by neutralisation, washing and separation stages. Further chemical treatment yields either a mixed hydroxide or a mixed sulfide precipitate, intermediate products from which nickel and cobalt can separately be recovered.

The output of primary nickel production is generally divided into two main product categories (Nickel Institute, 2022). Class I nickel or battery-grade nickel describes a group of nickel products comprising electrolytic nickel, powders, briquettes and carbonyl nickel. Class I nickel has a relatively high purity, greater than 99.8 per cent nickel, and is derived from processing sulfide ores and from HPAL treatment of laterite ores. Nickel Class II products comprise nickel pig iron and ferronickel which have a lower nickel content. They are cheaper to produce than Class I and are primarily used in stainless steel. Most Class II nickel is obtained from smelting laterite ores. China and Indonesia currently dominate the global production of refined nickel, accounting for 29 per cent and 25 per cent of the global total in 2020, respectively (Idoine et al., 2022). In the UK the Vale-owned nickel refinery at Clydach in South Wales processes nickel oxide, an intermediate product from Vale's smelters in Canada. It produces nickel pellets for the stainless steel industry and has a nominal annual production capacity of 40 kt (Vale, 2015).

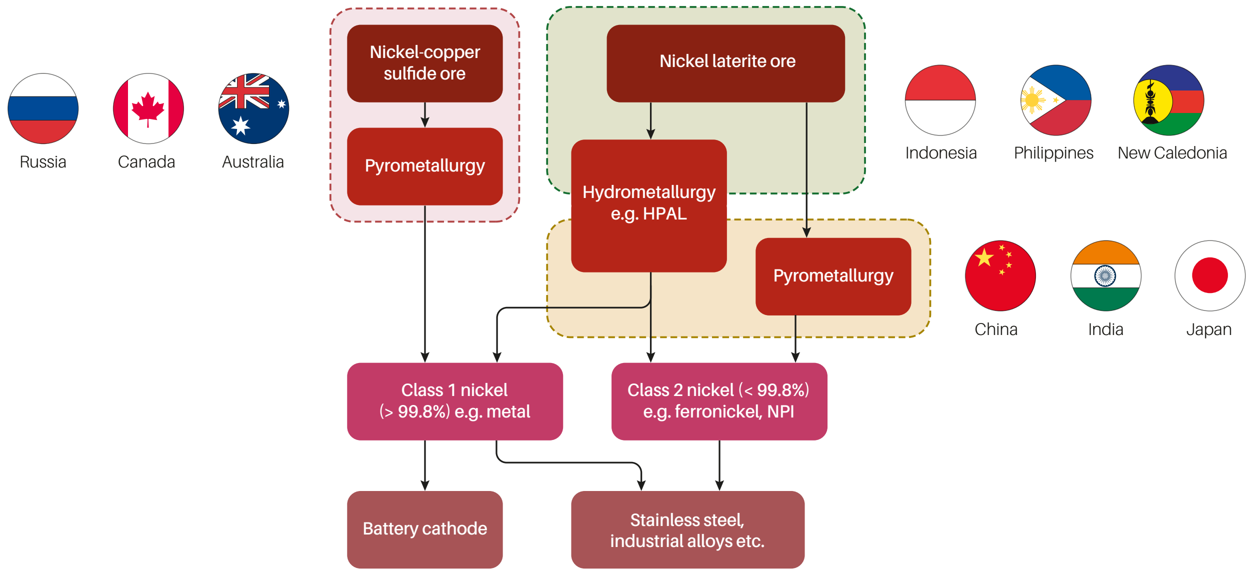


Figure 10 Nickel value chain. The flags denote the principal countries in which selected parts of the valuechain are concentrated. Reproduced with permissions. Source: IEA (2022a) The Role of Critical Minerals in Clean Energy Transitions, World Energy Outlook Special Report. All rights reserved; as modified by the British Geological Survey.

HPAL is technically complex to operate and has high carbon dioxide emissions compared with pyrometallurgical processing of high-grade sulfide ores. Although there has been a long history of failed and delayed HPAL projects in Australia, New Caledonia and elsewhere, there are some recent successes, for example in the Philippines and Cuba, and new projects are being developed in other countries (Ribeiro et al. 2021). The major benefit of HPAL is the ability to quickly produce Class I nickel from laterite ores, which is required for most uses except stainless steel.

On account of its physical and chemical properties, which include high melting point and corrosion resistance as well as the ability to readily form alloys, nickel has numerous applications. The dominant use is in stainless steel which accounts for 72 per cent of total demand. Stainless steel is widely used in engineering, transport, construction, electronics and metal goods. Other important first uses are in plating (7per cent), alloy steels (7per cent), batteries (7per cent) and copper-nickel alloys (6per cent) (Nickel Institute, 2022).

Currently only Class I nickel is suitable for use in LIB cathodes. The provision of adequate, reliable and sustainable supplies of Class I nickel for the growing EV market is challenging because a large proportion of nickel mining is conducted in developing countries, which may have relatively low standards of governance and environmental protection. Furthermore, the production of Class I refined nickel is dominated by China and Russia which together are responsible for about 40 per cent of the global total (Azevedo et al., 2020). Japan, Canada, Australia, Norway and Finland account for approximately 49 per cent of Class I refined nickel production.

Cobalt

Almost all cobalt is a by-product of the mining of copper or nickel (Figure 11). More than 60 per cent is derived from stratiform sediment-hosted copper-cobalt deposits, located mostly in the Democratic Republic of Congo (DRC) and Zambia (Petavratzi et al., 2019). Approximately one third of global production is from the mining of nickel-bearing laterites and magmatic nickel-copper sulfide deposits. Cobalt is extracted from nickel laterites in several countries, notably the Philippines, Cuba, Madagascar and Papua New Guinea, while Australia, Russia and Canada are important

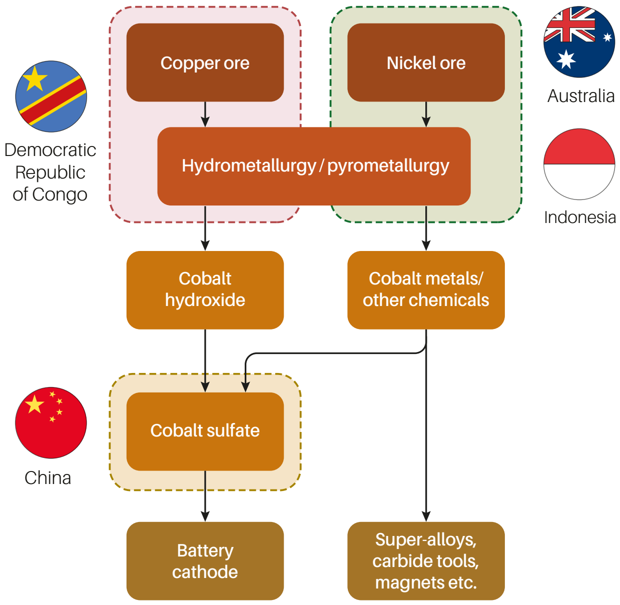


Figure 11 Cobalt value chain. The flags denote the principal countries in which selected parts of the value chain are concentrated. Reproduced with permissions. Source: IEA (2022a) The Role of Critical Minerals in Clean Energy Transitions, World Energy Outlook Special Report. All rights reserved.

producers of cobalt from nickel sulfide deposits. The exact processing route for the extraction of cobalt from the copper ores in central Africa depends on the nature of the ore itself and on the required final product (Roberts and Gunn, 2014). The sulfide ores are generally milled and concentrated by froth flotation. This is followed by roasting and a series of leaching, solvent extraction and purification stages to produce an intermediate cobalt hydroxide product. In contrast, weathered copper-cobalt ores may undergo direct whole ore leach prior to solvent extraction and purification. Nickel-cobalt sulfide ores are generally processed by smelting of a sulfide concentrate to produce a matte from which the cobalt and nickel are extracted in the refinery. Most cobalt is effectively lost in the smelting of nickel laterites to produce ferronickel. As discussed above, HPAL is an alternative process for the recovery of cobalt and nickel from laterites, although the exact processing route that follows leaching to produce pure nickel and cobalt varies according to the nature of the feed material (Petavratzi et al., 2019). However, it is important to note that HPAL of laterite ores is much more energy intensive than smelting and the process has a long history of project failure in several countries, notably Australia.

Cobalt is traded in a wide variety of intermediate forms and in a range of 'metal' products with differing levels of purity. Rather than shipping relatively high volumes of ores and concentrates, most mined material is transformed locally to an impure, partially-processed intermediate product, such as hydroxide, which is shipped to refineries overseas. China dominates global production of refined cobalt with approximately 65 per cent of the global total in 2020 (Idoine et al., 2022), although Europe has significant refining capacity in Finland, Belgium and Norway. There are no cobalt refiners in the UK but the nickel intermediates processed at the Clydach refinery in South Wales processes are likely to contain cobalt. However, cobalt is not recovered during the refining process (Vale, 2015).

Cobalt has numerous applications in manufacturing, notably in cemented carbides, cutting tools and alloys (14 per cent of total), in chemicals for pigments, catalysts, tyres and inks (11 per cent) and in superalloys used chiefly in aerospace (11 per cent). However, the largest end use is in batteries which accounts for 65 per cent of the total, divided between EVs (34 per cent) and other battery applications (31 per cent) (Cobalt Institute, 2022). The battery share has increased markedly in recent years although future demand is uncertain as the EV sector shifts to cathode chemistries with higher nickel contents.

Manganese

Manganese ores are extracted mainly from open-pit mining operations, at some locations linked to the production of iron ore. Dependent on their manganese content, most ores undergo some form of physical beneficiation and/or chemical processing to produce a manganese concentrate. These concentrates are sent to smelters to produce various intermediate products, termed ferroalloys. In exceptional cases, where the manganese grade is particularly high, the ores may be sent directly for smelting.

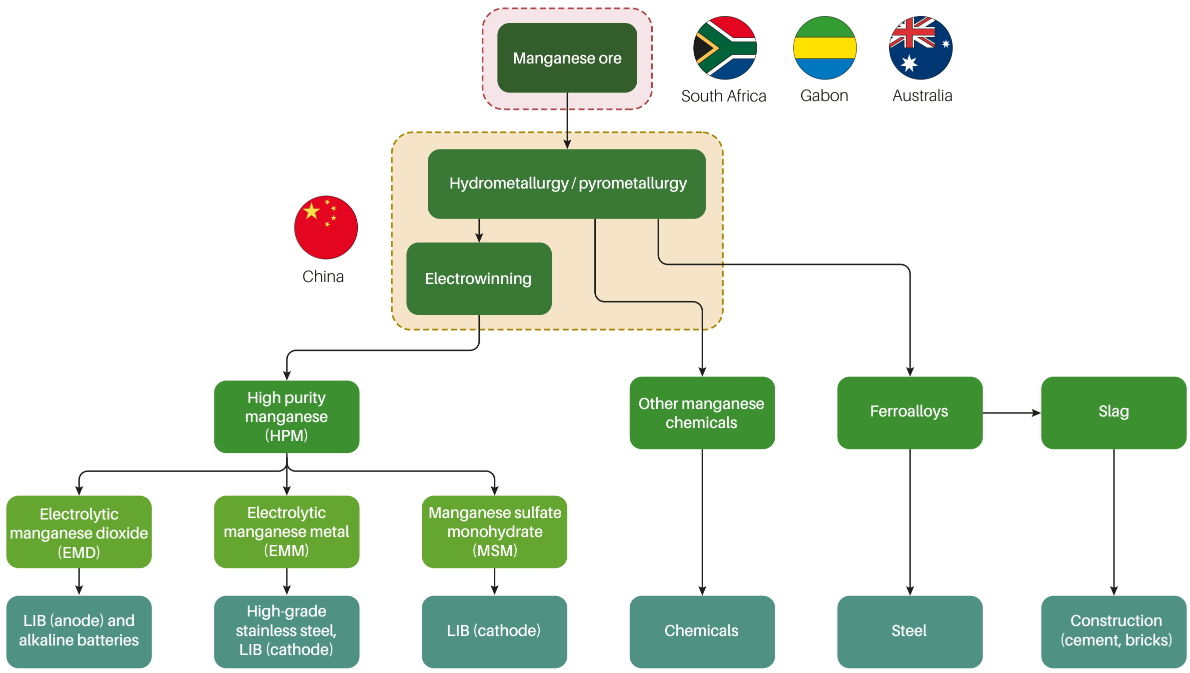


Figure 12 Manganese value chain. The flags denote the principal countries in which selected parts of the value chain are concentrated. BGS © UKRI.

A number of ferroalloys, chiefly varieties of ferromanganese and silicomanganese, are used in making steel of different types (Steenkamp and Basson, 2013). These ferroalloys are produced by smelting the concentrates with a suitable reductant and flux in a blast furnace or, more commonly, in an electric furnace. The use of a closed, energy-efficient submerged arc furnace is now well established in several producing countries such as South Africa. Manganese for applications other than steel-making is used in three main forms derived from high purity manganese metal: electrolytic manganese metal (EMM) and manganese sulphate monohydrate (MSM), which are used for the production of precursor materials for LIB cathodes; and electrolytic manganese dioxide (EMD), which is used for alkaline batteries and in the cathodes for LIBs (MMC, 2021; Zhang and Cheng, 2007) (Figure 12). There are no UK refiners of high purity manganese metal.

Approximately 88 per cent of manganese is used in the manufacture of steel (Sun *et al.*, 2020), as it enhances a number of its physical properties, such as tensile strength and wear resistance. Manganese also combines with sulphur which otherwise would have deleterious effects on the performance of the steel. About 5 per cent of manganese is consumed in non-steel alloys, mostly with aluminium, in drinks cans and food packaging (European Commission, 2020a). A similar amount is used in the manufacture of chemicals such as potassium permanganate for water purification and in fungicides and fertilisers. The balance (c. 2 per cent) is used in batteries, both conventional dry cell types and LIBs (European Commission, 2020a).

Graphite

Graphite, which is a form of carbon, has many physical and chemical properties that make it useful in numerous applications. Its key attributes include high electrical and thermal conductivity, chemical inertness, high lubricity and low weight. Graphite occurs naturally in three principal forms, amorphous, flake and vein (Figure 13). These terms relate to their geological occurrence and to the size and shape of the graphite crystals within the deposits (Mitchell and Deady, 2021).

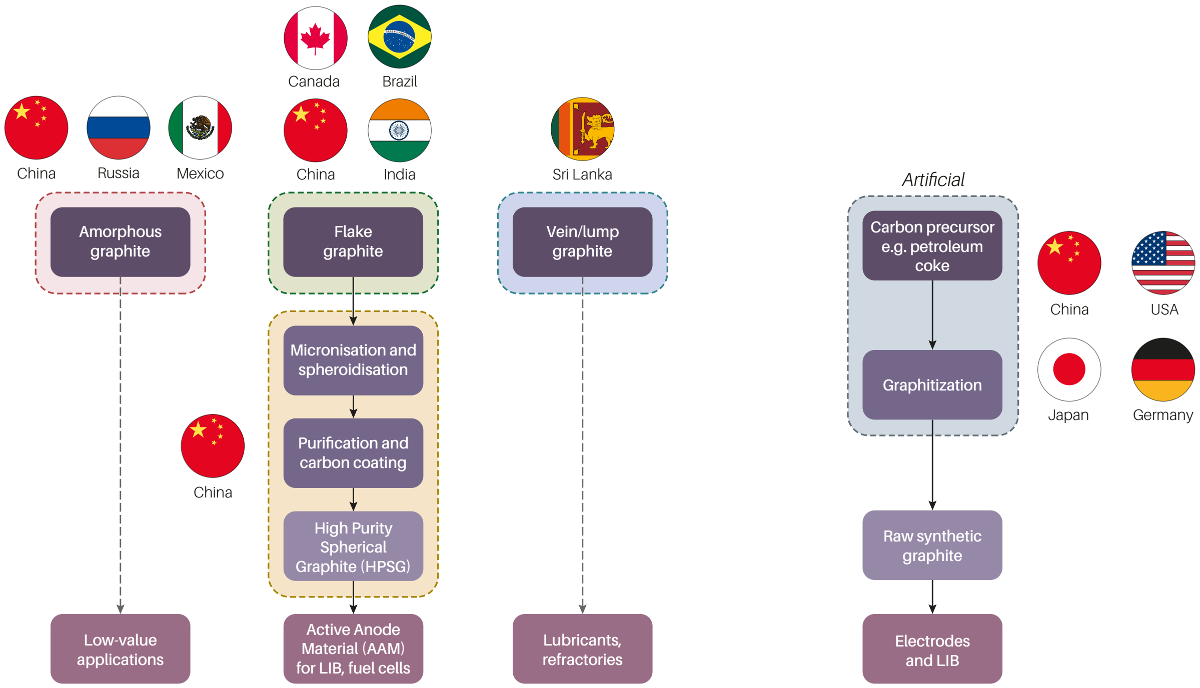


Figure 13 Graphite value chain. The flags denote the principal countries in which selected parts of the value chain are concentrated. BGS © UKRI.

Most graphite ore is extracted by open-pit mining after which it undergoes beneficiation at the mine site to upgrade the carbon content and remove impurities. This typically involves crushing, screening, grinding, froth flotation, dewatering and drying to yield a concentrate with a carbon content in the range 90–97 per cent. The concentrates are generally shipped elsewhere for further processing. Spheroidisation, where the graphite flakes are transformed into spheres ranging in size from 10–40 microns, is required for certain uses, including the production of anode materials used in LIBs. The spheres are then treated either chemically or thermally to make high purity spherical graphite (HPSG) with a purity of 99.95 per cent carbon. Currently China is the only country which produces HPSG. The final processing stage, which involves coating the HPSG with a single layer of carbon to enhance its conductive properties, is carried out mainly in China, Japan, Korea and Taiwan (Mitchell and Deady, 2021). A number of projects are being assessed elsewhere, including in Europe and the USA, for the spheroidisation and coating of natural graphite (Leading Edge Materials, 2022). Coated spherical purified graphite is the preferred source material for use in the production of LIB cells.

Artificial graphite is a product with many similar properties to natural graphite and an even greater range of applications. It is prepared from various raw materials such as calcined petroleum coke, carbon black, natural graphite and secondary graphite scrap. These are milled and blended with a binder, generally coal tar pitch or petroleum pitch. This mixture is pressed together to produce a solid in the form (e.g. rods, bars, plates, cylinders) required for a particular use. The compacted parts are baked in the absence of air at 1000–1200°C in a process known as carbonisation. The final stage is graphitisation which involves heat treatment excluding oxygen at 2500–3000°C for several weeks. This leads to the production of pure crystalline graphite from the amorphous precursor carbon (Kopeliovich, 2022). Artificial graphite is superior to the natural form in terms of its consistency and its greater longevity in battery applications. However, its production is energy intensive and has a cost profile around double that of natural graphite (Ghilotti and Pan, 2022). Several UK-based companies handle graphite and produce graphite products for various applications. It is notable that the Phillips 66 Company Humber Refinery, in north Lincolnshire, UK has two coking units that upgrade the heavy bottoms and imported feedstocks into speciality graphite and anode grade petroleum coke (Phillips 66 Company, 2022). It is reported that the company is producing the equivalent of 1.3 million vehicles a year of EV battery coke, but this is being shipped to China for LIB manufacture (Laister, 2021).

The largest use of natural graphite in 2021 was in refractories (42 per cent of total) for high-temperature industrial processes, such as the production of metals, alloys, cement, lime and glass. Other major uses were in anode materials for LIBs (24 per cent) and in foundries where it is used for casting products such as in the automotive industry (11 per cent). Other minor uses of natural graphite include friction products, lubricants, steel recarburising (the addition of a surface coating of carbon to low carbon steel to increase its hardness) and pencils (ECGA, 2022).

The predominant use of artificial graphite in 2021 was in electrodes for metallurgical applications, such as steel manufacture, refining ceramics and manufacturing chemicals, which accounted for 52 per cent of the total in 2021. Other major applications of artificial graphite are in batteries (14 per cent) and in recarburising steel (14 per cent) (ECGA, 2022).

7 Battery mineral markets

Production and price trends

Lithium: between 2010–2020, lithium output has increased more than any other battery mineral, from about 22.5 thousand tonnes (kt) in 2010 to 86 kt in 2020, representing a 281 per cent increase over the 10-year period. The majority of this growth has been in the last five years, as lithium production increased rapidly in response to strong demand from the LIB sector. Between 2010–2015, production growth was modest as capacity ramped up from a low base. Since 2016 production has surged, largely accounted for by rapid growth in Australian spodumene output. Between 2016–2017, global supply increased by 85 per cent and Australia's market share almost doubled to 61 per cent. While Australia is still a major producer, it now has a smaller market share (48 per cent in 2020) as growth from Chile and China has increased (27 per cent and 16 per cent market share in 2020, respectively) (Figure 14).

Lithium prices remained largely unchanged until the end of 2015, when rapid growth in the EV market, particularly electric bus demand for LFP battery production in China, saw prices for lithium carbonate increase by more than 300 per cent over a six-month period. Prices remained elevated until the end of 2018, by which point new supply had outpaced mineral/chemical conversion capacity in China and the market moved into surplus. This was marked by a correction in lithium prices, which slipped further in 2019 and 2020 as China scaled back EV subsidies and global EV sales fell short of expectations. Since the start of 2021, prices for lithium carbonate rallied owing to growing demand for LFP battery chemistries. This was compounded by tight supply owing to Covid-related refining bottlenecks in China (Dyatkin and Meng, 2020) (Figure 14).

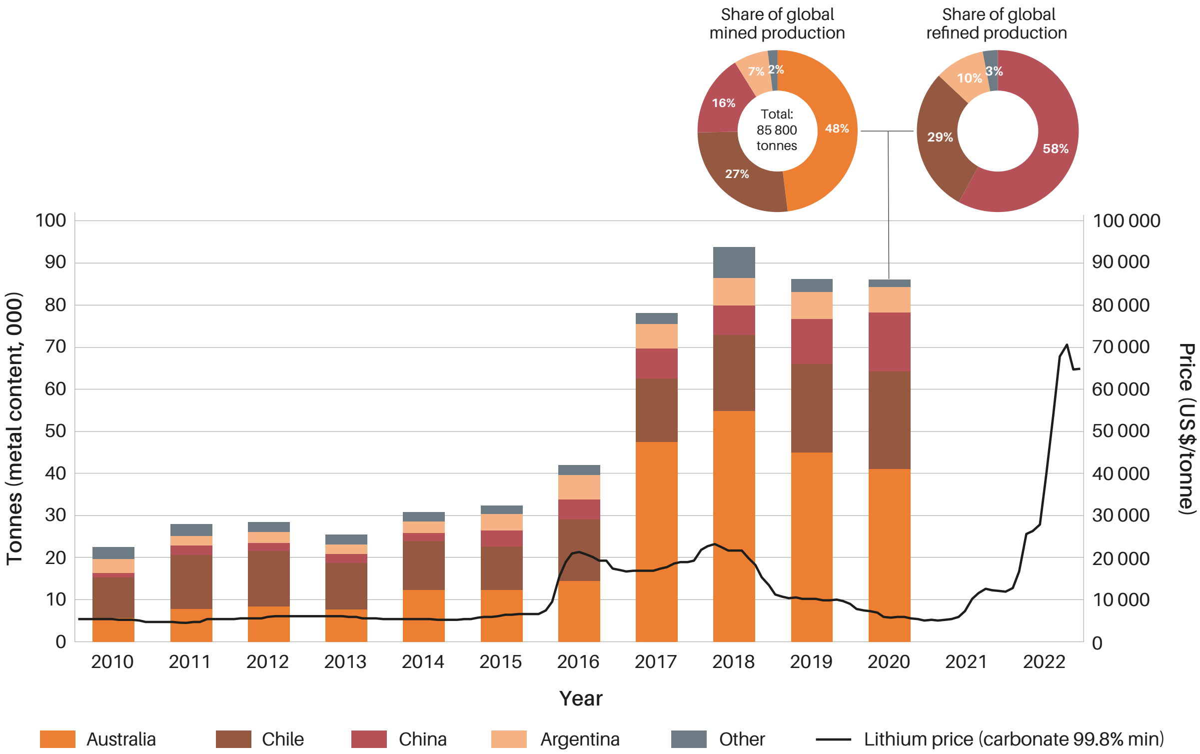


Figure 14 Global production of lithium between 2010–2020, data source: British Geological Survey (2022) and the price of lithium (carbonate, 99 per cent minimum) from 2010–May 2022, data source: Fastmarkets (2022).

Nickel: world mine production of nickel recorded an overall increase of 56 per cent between 2010–2020, from about 1.6 million tonnes (Mt) to 2.5 Mt. Until 2013, mine supply saw strong year-on-year growth as Indonesia and Philippines ramped up production of Class II nickel, but the Indonesian government's ban on unprocessed ore exports in 2014 triggered a steep contraction in supply. In 2014, global mine output fell by more than a third (>1 Mt) and Indonesia's market share fell to just 9 per cent, from 43 per cent a year earlier. Global output was supressed until 2017 when the Indonesian export ban was eased. Three years of growth followed, but the ban was reinstated in 2019. Despite this, over a ten-year period Indonesia's market share has increased from 19 per cent to 33 per cent. The share of mine production from the Philippines and New Caledonia has remained largely the same, while Russia and the rest of the world have reduced (Figure 15).

Between 2010–2020, refined nickel output has been on a clear upward trend, increasing at a rate of 5.8 per cent annually from about 1.5 Mt in 2010 to over 2.5 Mt in 2020, a 75 per cent increase over ten years. Until 2014 this was largely accounted for by growth in China, which increased its market share of refined output from 22 per cent in 2010 to 35 per cent within four years. Since 2014, Chinese growth has slowed, but this has been more than offset by capacity expansion in Indonesia. Between 2010–2020, annual refined output from Indonesia has increased by more than 600 kt, taking its market share from just 1 per cent in 2010 (c. 18.5 kt) to 25 per cent in 2020 (632 kt) (Figure 15).

Between 2010–2016 nickel prices were in long-term decline. There was a temporary reversal in 2014 as the market adjusted to reduced supply from Indonesia, but an overall excess of capacity and stock build-up kept the upside to a minimum. Since 2017, momentum from the EV market has been increasing, as battery manufacturers increased the nickel content in NCM/NCA batteries to reduce the amount of cobalt. In recent years numerous idled facilities and delayed projects have resumed activity in anticipation of growing demand for nickel in EVs, and prices have moved into a bullish trend, particularly for battery-grade nickel (Figure 15).

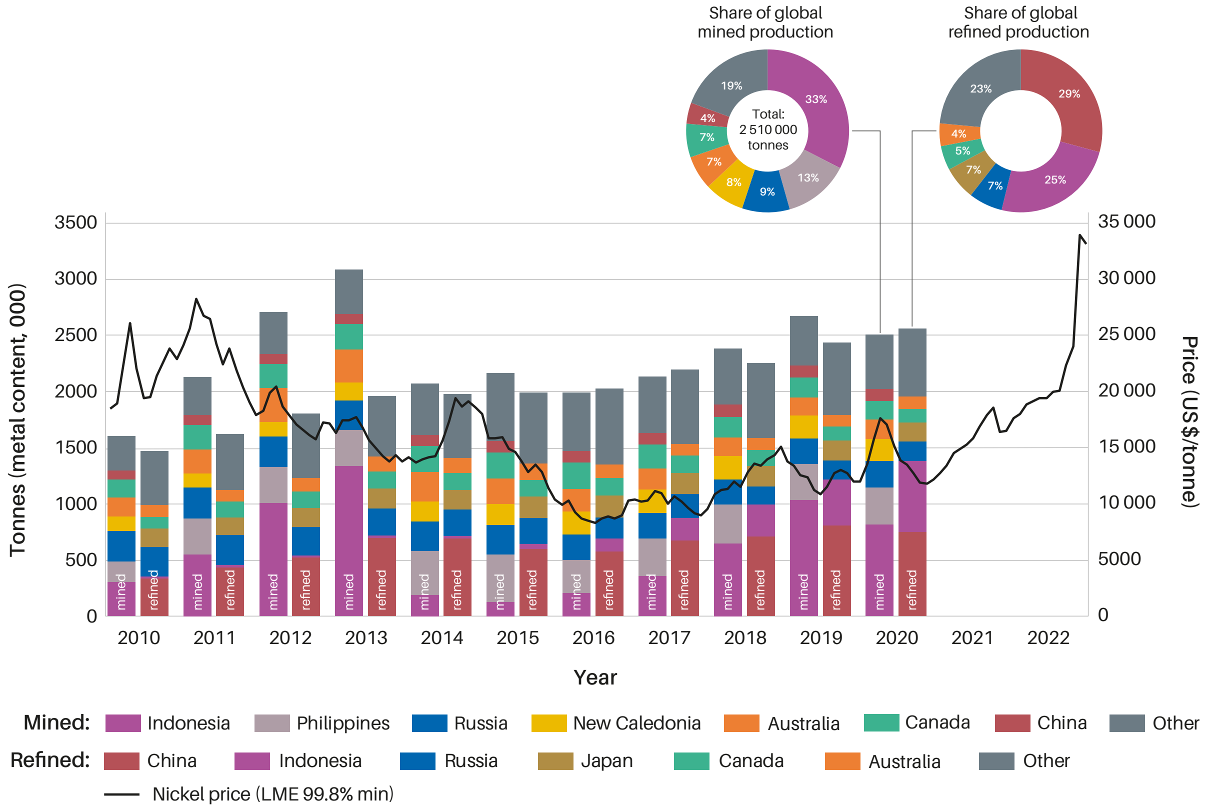


Figure 15 Global production of mined and refined nickel between 2010–2020, data source: British Geological Survey (2022) and the price of nickel metal (LME 99.8% minimum) from 2010–May 2022, data source: Fastmarkets (2022).

Cobalt: world mine production of cobalt has shown a long-term declining trend, from about 138 kt in 2010 to 126 kt in 2020, a fall of almost 9 per cent over the 10-year period. The structure of the market has remained largely the same, and mine supply is still dominated by the DRC, which accounted for 66 per cent of world production in 2020 (down from 71 per cent in 2010). Russia (4 per cent), Australia (4 per cent) and the Philippines (3 per cent) accounted for relatively small shares of global mine production in 2020 (Figure 16).

In contrast to mine production, between 2010–2020, world output of refined of cobalt increased at a rate of more than 5 per cent annually, from about 79.5 kt in 2010 to 131.5 kt in 2020, representing a 65 per cent increase over the 10-year period. This is largely accounted for by growth in China, where capacity expansion has seen the country's share of refined cobalt output increase from 45 per cent in 2010 (c. 36 kt) to 65 per cent in 2020 (estimated at 86 kt). Output from Finland and Belgium have shown modest increases, while Canadian production has remained largely flat and output from the rest of the world has declined (Figure 16).

Between 2010–2016, cobalt prices were in long-term decline owing to an oversupplied market. In 2017 there was a strong uptick in prices as the market shifted into deficit from demand growth in the EV market, as well as lower nickel production (as discussed above, most cobalt is mined as a by-product of copper or nickel). Between 2017–2018 producers were incentivised to increase production by favourable market conditions. However, after reaching a peak of US$89 000 in Quarter 2 2018, an oversupplied market and consumer destocking saw a sharp correction in prices and the world's largest cobalt mine (The Glencore owned Mutanda mine, DRC) was placed on care and maintenance. Cobalt prices have been on a strong upward trend since 2021 as supply fell short of a stronger than expected rebound in demand post-COVID. The decline in

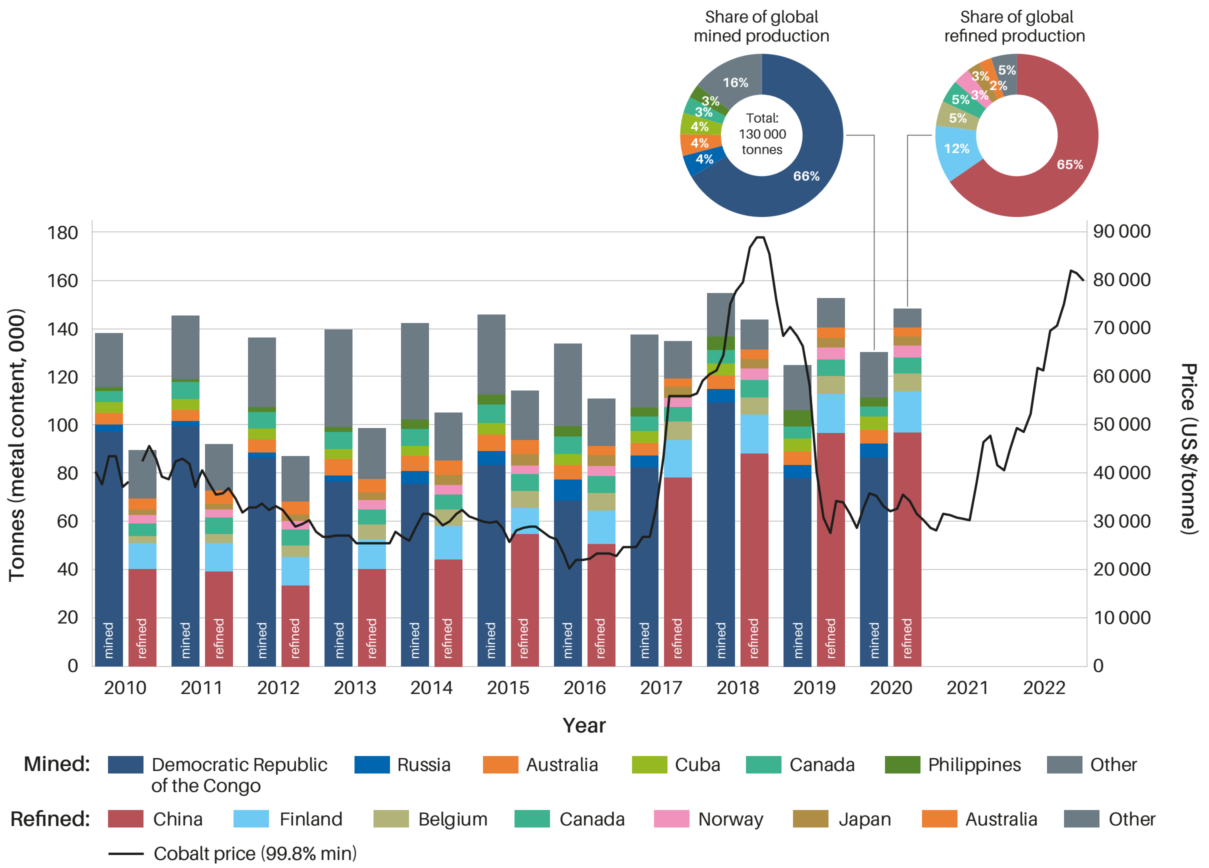


Figure 16 Global production of mined and refined cobalt between 2010–2020, data source: British Geological Survey (2022) and the price of cobalt metal (99.9 per cent minimum) from 2010–May 2022, data source: Fastmarkets (2022).

mine output in 2020, combined with subsequent supply chain bottlenecks and strong demand, led to a tighter market during 2021 and 2022.

Manganese: world mine production has remained relatively stable over the last decade, increasing by just 10 per cent between 2010 and 2020, from about 45 Mt to almost 50 Mt. Expanding production capacity in South Africa has largely offset declining output from China over the last 10 years. South Africa's share of global mine production has more than doubled, from 15 per cent in 2010 to 32 per cent in 2020, while China's has dropped from 28 per cent to 13 per cent in the same period. Output from Gabon and Ghana has also increased in the past five years, while Australian production has declined (Figure 17). Production of refined manganese is dominated by China, which accounted for more than 90 per cent of global production in 2020.

With the majority of demand for manganese accounted for by stable and diversified industrial markets, manganese price movements between 2010–2020 were relatively uneventful. The recent significant price spike is attributed to strong post-COVID demand from both major traditional industrial end-users and the EV sector, which has since corrected as the market balanced out.

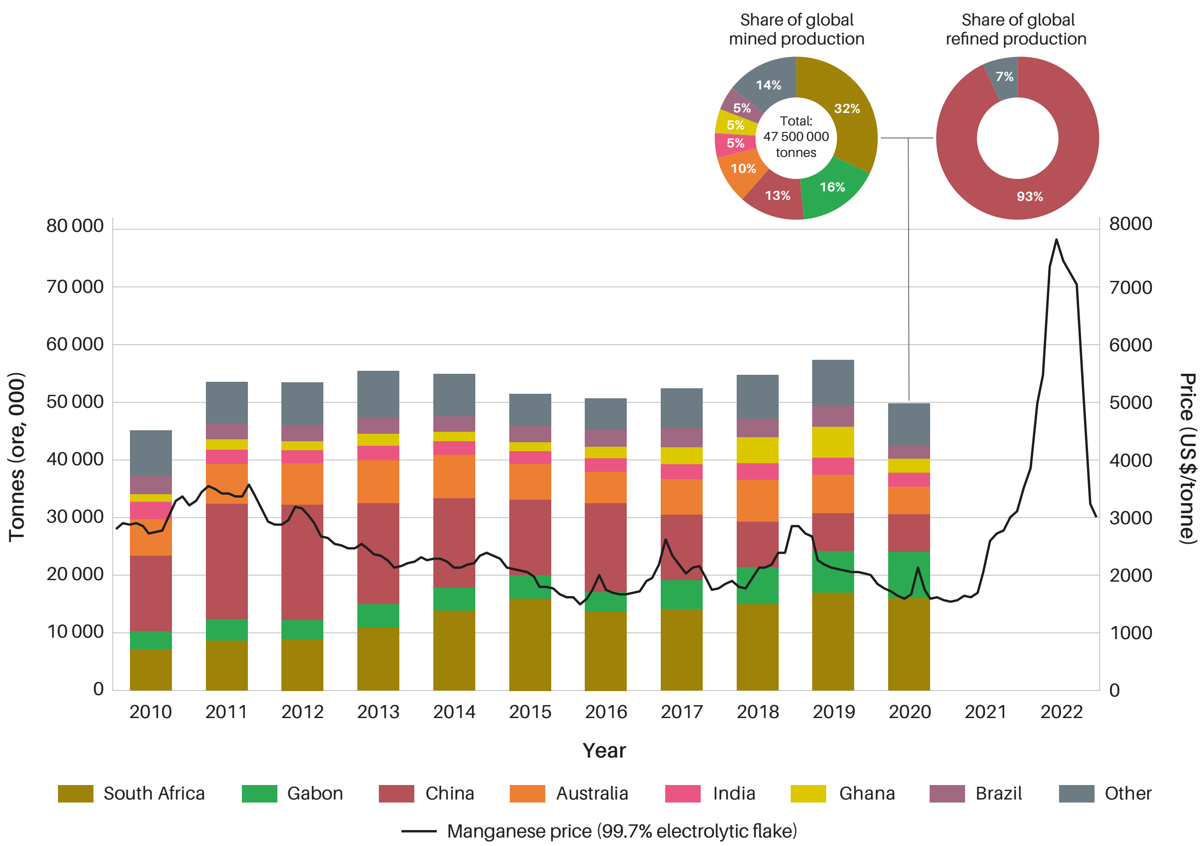


Figure 17 Global production of manganese between 2010–2020, data source: British Geological Survey (2022) and the price of manganese (99.7 per cent electrolytic flake) from 2010–May 2022, data source: Fastmarkets (2022).

Graphite: between 2010–2020 graphite production has markedly declined, from about 2.1 Mt in 2010 to 959 kt in 2020, a 54.9 per cent reduction. This is largely attributed to declining Chinese output. In addition to resource depletion, during this time the Chinese government ordered several of the graphite mines it controlled to close for environmental and resource protection reasons. In 2018, a high-grade mine in Mozambique commenced operations, but was forced to reduce production by the end of 2019 owing to poor market conditions. Madagascar has also been increasing output since 2017, albeit from a very low base. In recent years, increasing demand from both the LIB sector and traditional markets has been incentivising natural graphite production, although it is competing with a growing artificial graphite market. Although its annual output has significantly reduced, China remains the largest producer of natural graphite, accounting for a 68 per cent of world mine production in 2020, down from 85 per cent in 2010. Other important producers in 2020 were Brazil (10 per cent), Madagascar (5 per cent) Korea (3 per cent) and Mozambique (2 per cent) (Figure 18).

Supply has exceeded demand in the graphite market for many years, which has resulted in a long-term decline in prices. With the exception of 2011, when reduced output from China caused a temporary upturn, prices have mostly moved lower year-on-year. In 2021 and 2022 electricity restrictions in China (especially in northern regions where natural graphite mining and processing is concentrated) are expected to have limited output, resulting in higher prices for refined products. However, the graphite market is generally well-supplied, so the price rise has been far less extreme than for certain other battery minerals.

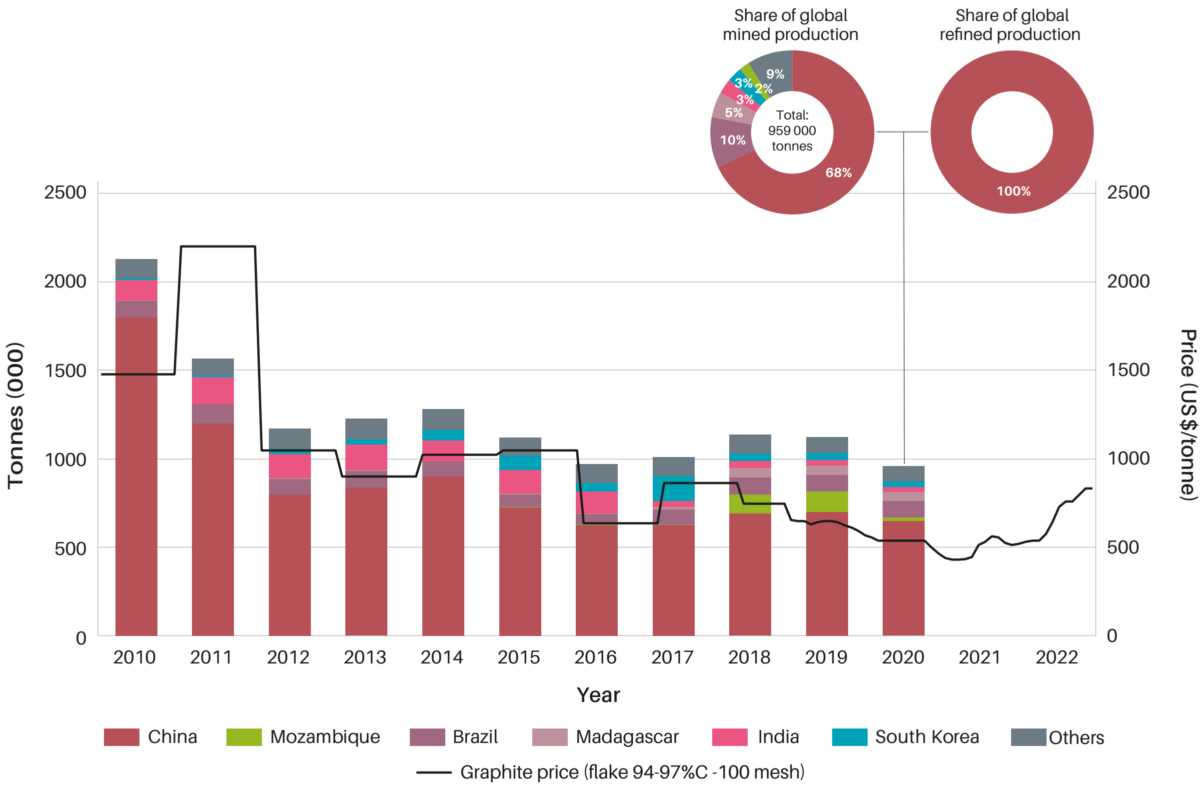


Figure 18 Global production of natural graphite between 2010–2020, data source: British Geological Survey (2022) and the price of graphite (flake 94–97 per cent, -100 mesh) from 2010–May 2022. Annual price data from 2010–2018, data source: USGS, 2022, and monthly price data from August 2018–May 2022, data source: Fastmarkets (2022).

The significance of price movement and volatility

In 2010 average LIB pack prices were US$1200/kWh and they have fallen by 89 per cent in real terms to an average of US$132/kWh in 2021 (BloombergNEF, 2021). This dramatic cost reduction has resulted from new pack designs, improved manufacturing processes and the scaling up of battery production associated with burgeoning EV sales (IEA, 2022b). LIB pack prices continued to decline in 2021, which saw a 6 per cent price reduction over the previous year (average price of US$140/kWh) owing to the increased uptake of lower-cost LFP and the trend towards nickel-rich cathodes that require less cobalt, whcih is the most expensive metal used in LIB cathodes (BloombergNEF, 2021). It is anticipated that this overall price trend will continue, and by 2024 average pack prices could fall below US$100/kWh. At this price point automotive manufactures should be able to produce and sell certain EVs at the same price as similar ICE vehicles (Colthorpe, 2021).

Minerals now represent the majority of total LIB production costs, with cathode and anode materials accounting for about 50 and 12 per cent of the manufactured cost of a cell, respectively (Frith, 2021; IEA, 2022a) (Figure 19). Given the importance of raw material costs in the total manufactured costs of a battery there are concerns that higher prices for certain battery minerals could lead to a short-term increase in LIB pack prices (BloombergNEF, 2021). About 40 per cent of a cell's costs is associated with minerals that have increased in price during the previous two years (Frith, 2021). Whilst LFP cells were about 30 per cent cheaper than NMC cells in 2021, their manufactured costs were also affected by rising lithium carbonate prices (Colthorpe, 2021). Analysis from the IEA estimates that a doubling of lithium or nickel prices would result in a 6 per cent increase in the cost of a battery. It is suggested that this level of price increase for both battery minerals simultaneously would offset all anticipated unit cost savings associated with a doubling of battery manufacturing capacity (IEA, 2022a).

Price volatility is a measure of the day-to-day price fluctuations of a commodity. For many minor metals, especially those produced as by-products, price volatility has historically tended to be high (Renner and Wellmer, 2020). Where the size of the market is small and production highly concentrated, a disruption to supply or an abrupt change in government policy in a key producing country can lead to a price spike. In contrast, a rapid increase in demand for a particular commodity can result in a tighter market and an associated price increase. For example, the rapid growth of the global EV market in the past 5–6 years has resulted in significant price volatility for battery minerals such as lithium and cobalt (Figure 20 and 21). High price volatility can be a serious deterrent to investment in new mining and processing capacity, while also pushing end-users to reduce their exposure and explore alternative materials. For example, there was considerable

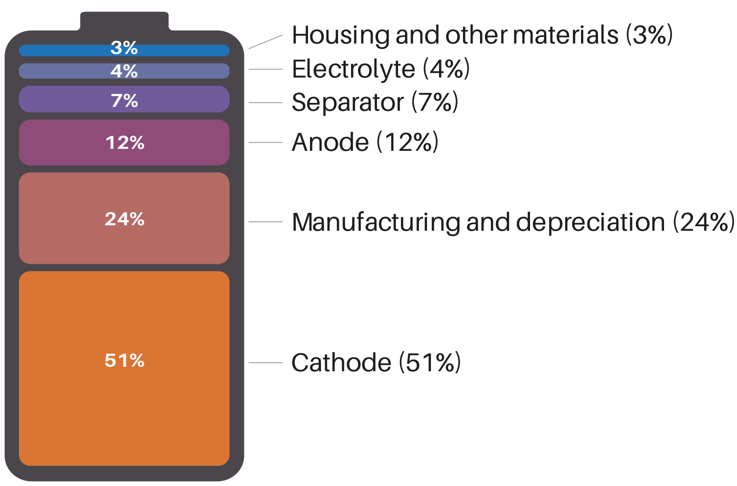


Figure 19 The estimated cost breakdown of a lithium-ion battery cell. Data source: Bloomberg (2021).

substitution of platinum for palladium in autocatalysts in petrol cars during the early 2000s in response to major fluctuations in platinum-group metal prices.

Price volatility was calculated using monthly average price data for the battery minerals and selected other metals (platinum, copper and aluminium) for comparison (Figure 20). Volatility was calculated using the standard deviation of the difference (the 'return') of the logarithmic monthly average prices, which was subsequently annualised (DERA, 2022). Values range between 0–1, where 0 represents no volatility and 1 extreme volatility. For example, a volatility of 0.5 means the standard deviation (or variation) of prices from one month to the next is 50 per cent of the mean value.

Since 2016 battery minerals have experienced price volatility generally in the range of 20–50 per cent. The industrial metals analysed were in the range of 8–22 per cent (Figure 21), only exceeding 20 per cent in 2020, when the COVID pandemic threw market fundamentals into disarray. Lithium has shown the greatest volatility in the past six years, reaching 50 per cent in 2016, closely followed by cobalt, which exceeded 45 per cent in 2019.

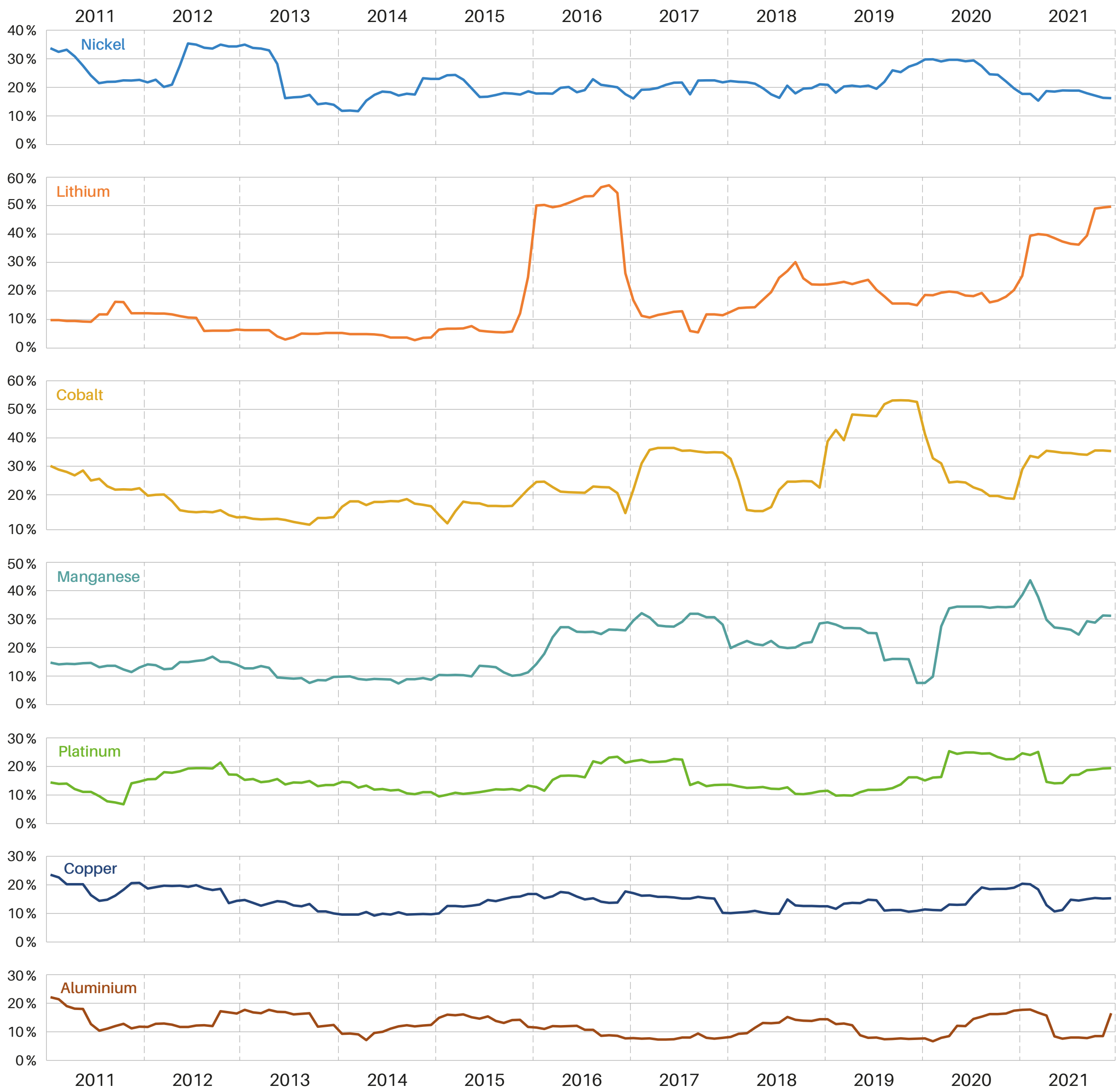


Figure 20 Monthly price volatility for the battery minerals and selected other metals for comparison (platinum, copper, aluminium). Prior to August 2018 only annual data is available for graphite. Data source: Fastmarkets (2022).

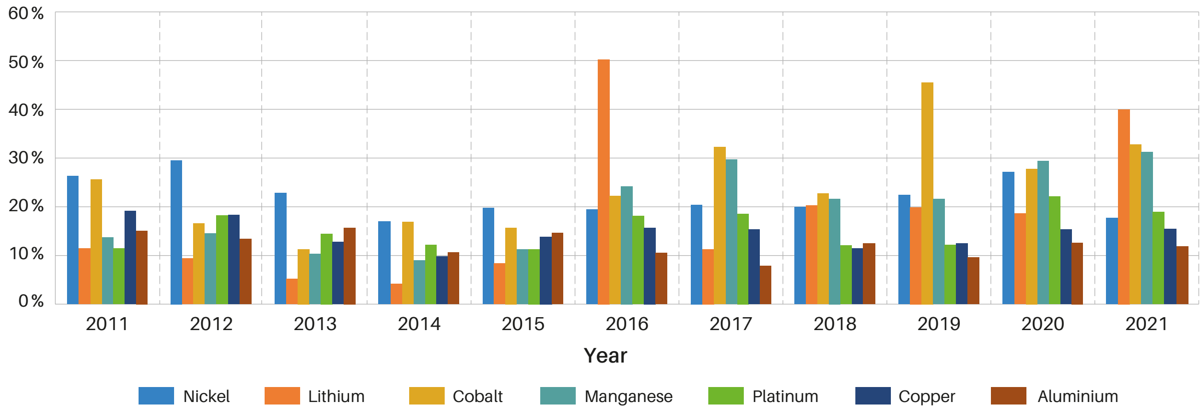


Figure 21 Average annual price volatility for the battery minerals and selected other metals for comparison (platinum, copper, aluminium). Prior to August 2018 only annual data is available for graphite. Data source: Fastmarkets (2022).

For cobalt, nickel and lithium, a degree of price correction is expected in the near term after recent meteoric price increases. However, prices for all five battery minerals are forecast to remain elevated above long-term averages until 2025, as constrained supply is compounded by double-digit demand growth from LIBs for EVs.

Certain raw material markets are characterised by vulnerabilities that lead to greater price volatility:

- Geographical concentration: today's extraction and processing operations for battery minerals are highly concentrated in a small number of countries (Figures 9 to 13) making their supply chains vulnerable to political instability, geopolitical risks and export restrictions. For example, in 2014 and 2019 the government of Indonesia implemented a ban on direct-shipping nickel ore, which as the leading producer, resulted in sharp price spikes on both occasions.
- By-product status: prices of by-product metals are often volatile owing to supply inelasticity, whereby production is unable to respond to rapid changes in demand. By-product supply is governed by the recovery of the main product ore, which can cause the by-product supply curve to shift and amplify price volatility (Redlinger and Eggert, 2016). Cobalt, for example, is predominantly mined as a by-product of copper (55 per cent of global total in 2020) and nickel (29 per cent in 2020) (Cobalt Institute, 2021) and is, therefore, almost entirely dependent on demand for, and production of, these base metals.
- Availability of secondary supply: metals with large secondary markets (i.e. recycling) tend to be more stable, as there is additional material available if demand requires. Recycling rates are heavily influenced by prices, and secondary producers are often able to respond more quickly than primary producers to increased demand. The secondary supply of battery raw materials is largely non-existent, which contributes to greater price volatility for these commodities.
- Project development lead times: long project lead times are a risk for investors, as there is a greater likelihood of projected market fundamentals changing in that period. Analysis of mines that came online between 2010–2019 shows that it took 16.9 years on average to develop projects from discovery to first production (IEA, 2021a). Development throughout the value chain must also be coordinated; the recent rise in lithium carbonate prices amid ample mine supply is an indication of a bottleneck elsewhere in the value chain (in this case, refining capacity).
- Resource quality: in recent years, ore quality across many commodities has declined as higher-grade parts of deposits are exploited earlier. Extracting metal from the lower grade ore that remains often requires more energy and generates larger amounts of rock waste and

tailings that require careful treatment, meaning that over time, greater efforts are needed to offset underlying upward pressure on production costs.

- Environmental, social and governance issues (ESG): the mining industry faces growing pressure from stakeholders to address its emissions and other issues related to social and environmental performance. Tightening scrutiny of ESG could have an impact on costs and supply prospects.
- Climate risks: in recent years, the high water intensity of ore processing has brought the vital importance of sustainable water sourcing to attention. Lithium is particularly vulnerable to water stress, owing to the highly arid environments that many continental brine deposits are found in, for example the Lithium Triangle region in the south-west corner of South America, spanning the borders of Argentina, Bolivia and Chile. The groundwater system that underlies these deposits is complex, featuring high-salinity brines in contact with fresh water, which is used for potable water supply, as well as supporting the process of lithium extraction.

Trade flows

Data sources

The data used in this analysis were extracted from the UN Comtrade database, which provides open access to official international trade statistics (DESA/UNSD, 2022) UN Comtrade store trade data based on Harmonized System (HS) codes pertaining to a variety of different classification systems. For this assessment, the HS codes relevant to the raw materials required for manufacturing LIBs for LDVs were selected. These are: Lithium oxide and hydroxide (282520); Lithium carbonate, carbonates (283691); Sulphates of nickel (283324); Cobalt oxides and hydroxides, commercial cobalt oxides (282200); Cobalt, mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders (810520); Manganese dioxide (282010); Natural graphite (2504), and Artificial graphite, colloidal or semi-colloidal graphite, preparations based on graphite or other carbon in the form of pastes, blocks, plates or other semi-manufactures (3801). Retrieved data were cross-verified by reconstructing the search inputs between the reporting and partner countries to ensure the accuracy of the data that might be reported incorrectly due to unit differences between countries or for other reasons.

The selected HS codes represent the early stages of the raw material value chains for manufacturing LIBs, comprising processed forms that include lithium, cobalt, nickel, manganese and graphite. Trade codes for those forms of these materials processed beyond their potential use in battery applications were not included in the analysis. Data were collected on global and UK trade flows (import and export) of the selected commodities to each of the reporting and partner countries (Figures 22 to 28). 2019 was selected as the reference year because complete global reporting of the data are available for that year. Reporting for subsequent years was interrupted by the COVID pandemic. The trade data presented and discussed below illustrates the global dominance of the countries exporting the major share of the selected commodities and the UK's dependency on the chief exporting partner countries.

Limitations

The use of UN Comtrade data carries inherent limitations. Most importantly, the data is only accurate so far as countries accurately report their trade. Some countries may not report detailed commodity trade flows for reasons of confidentiality and may not report data annually. Furthermore, countries may also differ due to the trade reporting classification systems they employ (DESA/UNSD, 2022). Differences in unit systems, valuations and currency exchange rates can lead to mismatched volume and value reporting. Further detailed information can be found on the UN Comtrade website (DESA/UNSD, 2022).

There are significant differences in the import and export totals of the selected commodities (Figures 22 to 28). Ideally, the reported imports for country A from country B would match with the stated exports from country B to country A. However, this is not the case in the UN Comtrade dataset because the imports are recorded cost insurance and freight (cif)[4] while exports are free on board (fob)[5]. This may represent a difference of about 10–20 per cent. The trade balance differences may also be due to several other factors including: i) classification concepts and detail; ii) date of recording; iii) valuation; iv) coverage; and vi) processing errors.

Global and UK trade patterns

Lithium oxide and hydroxide: China and Canada were the largest exporters of lithium oxide and hydroxide, which together accounted for about 90 kt, or more than 70 per cent of the global total, with about 39 per cent and 32 per cent shares, respectively (Figure 22). Japan and Korea are the major global importers of lithium oxide and hydroxide, accounting for about 61 kt, or more than 72 per cent overall, comprising about 45 per cent and 28 per cent, respectively. The UK's imports of lithium oxide and hydroxide were mostly from the Netherlands (445 tonnes) and Belgium (323 tonnes) accounting for about 75 per cent of the total. Given that the Netherlands and Belgium are not primary producers of these materials, it is clear that these countries also depend on other sources that are primary producers and refiners of lithium oxide and hydroxide.

Lithium carbonate; carbonates (referred to as lithium carbonate): Chile dominated the global export of lithium carbonate, accounting for about 82 kt, representing about 71 per cent of the total, followed by China, Belgium and the Netherlands, which accounted for about 11 per cent, 6 per cent and 5 per cent, respectively (Figure 23). Korea, China, Japan and Russia dominated the global imports of lithium carbonate, representing about 80 per cent of the total. As with lithium oxide and hydroxide, the UK's imports were largely from Germany and Belgium which are not the primary producers or refiners of lithium carbonate. The UK imports more lithium carbonate (c. 1.7 kt) than lithium oxide and hydroxide (c. 1 kt).

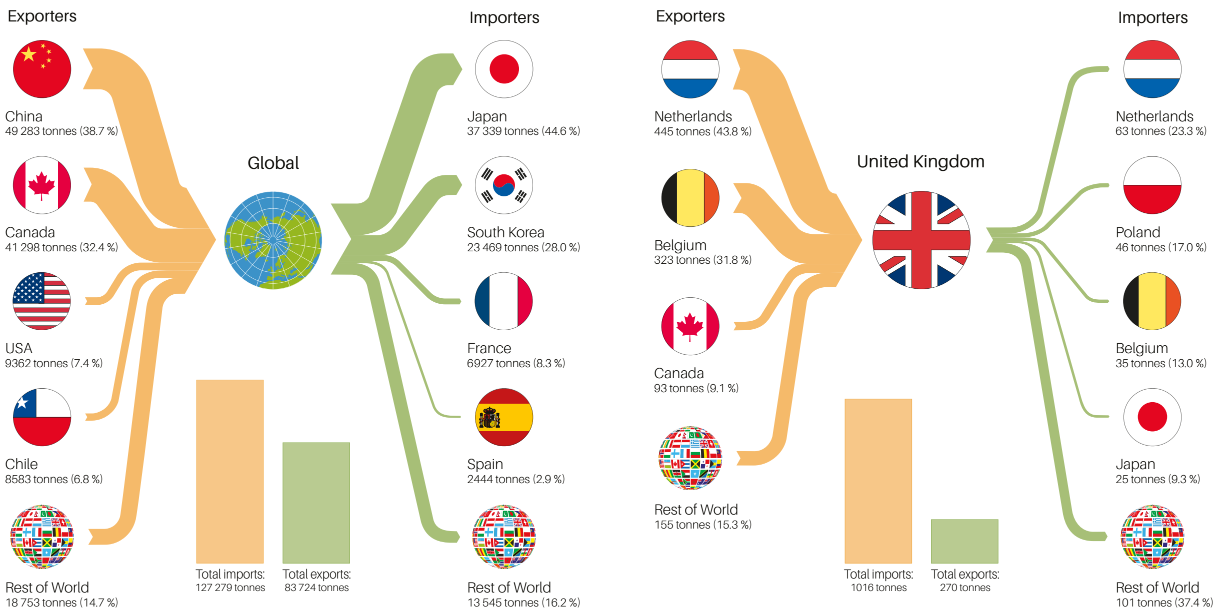


Figure 22 Global and UK trade of lithium oxide and hydroxide in 2019. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 282520; USA = United States of America; South Korea = Rep. of Korea.

[4] An international shipping agreement, which represents the charges paid by a seller to cover the costs, insurance, and freight of a buyer's order while the cargo is in transit.

[5] A shipment term used to indicate whether the seller or the buyer is liable for goods that are damaged or destroyed during shipping.

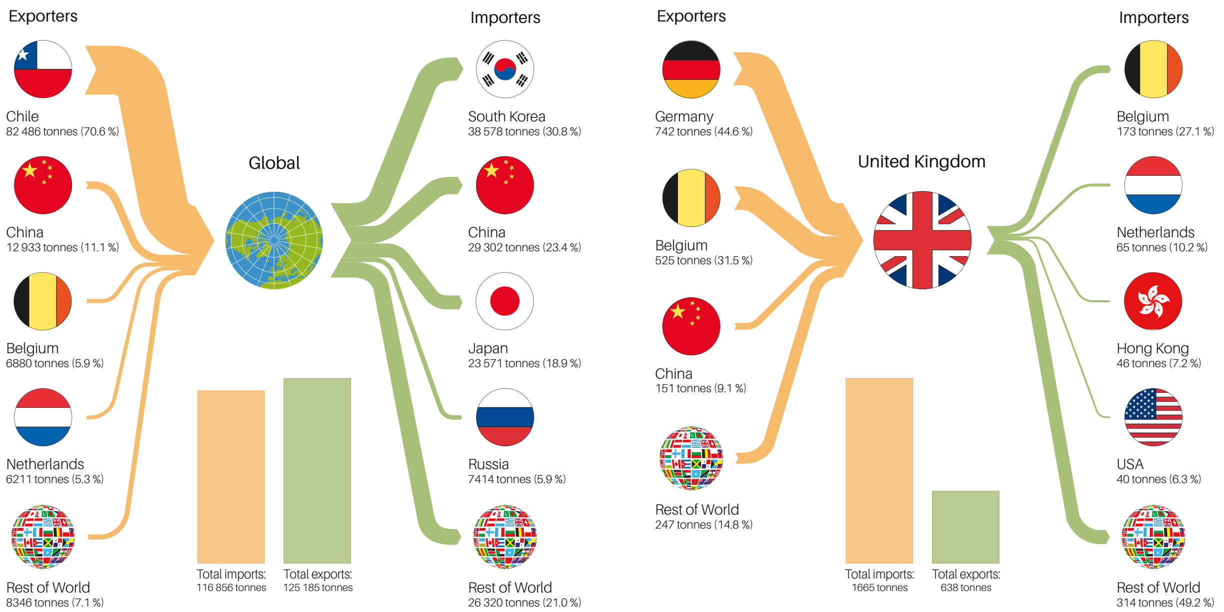


Figure 23 Global and UK trade of lithium carbonate in 2019. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 283691; USA = United States of America; South Korea = Rep. of Korea.

Sulphates of nickel: Taiwan, Belgium, Korea and Germany were the major global exporters of sulphates of nickel, accounting for about 46 per cent (c. 73 kt), 19 per cent, 11 per cent and 5 per cent of the total, respectively (Figure 24). Japan, Belgium, Korea and Canada were the major importers, accounting for about 70 per cent of global imports. Japan represented more the 95 kt of imports, or 49 per cent of the total. The UK's imports of sulphates of nickel were some 7.5 kt, chiefly from Belgium, which accounted for about 90 per cent of the total.

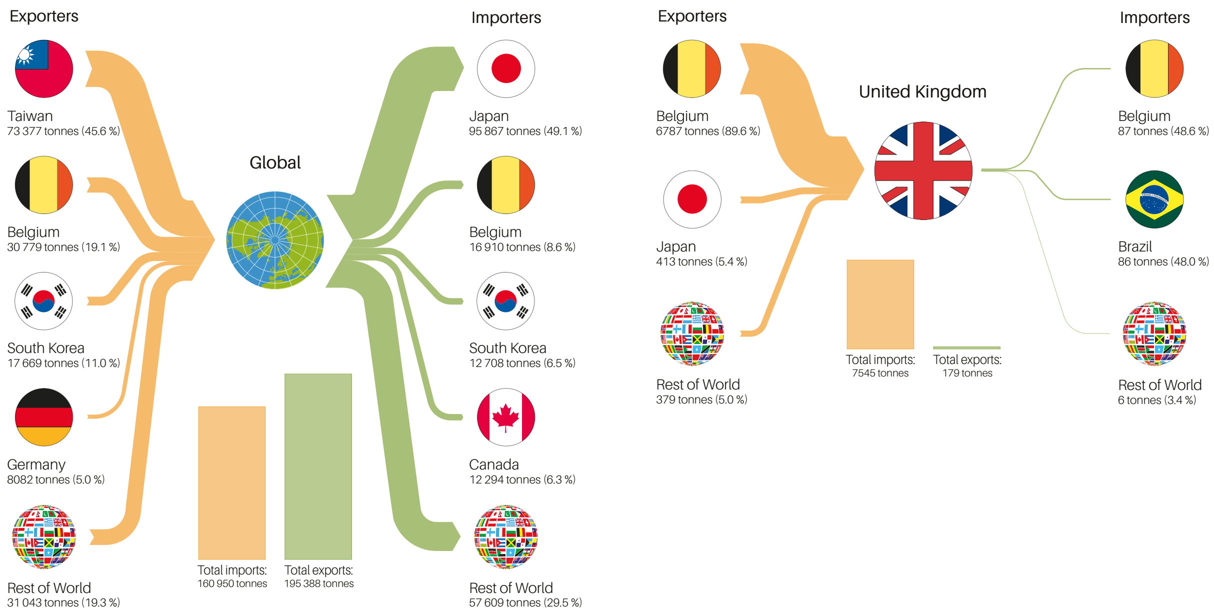
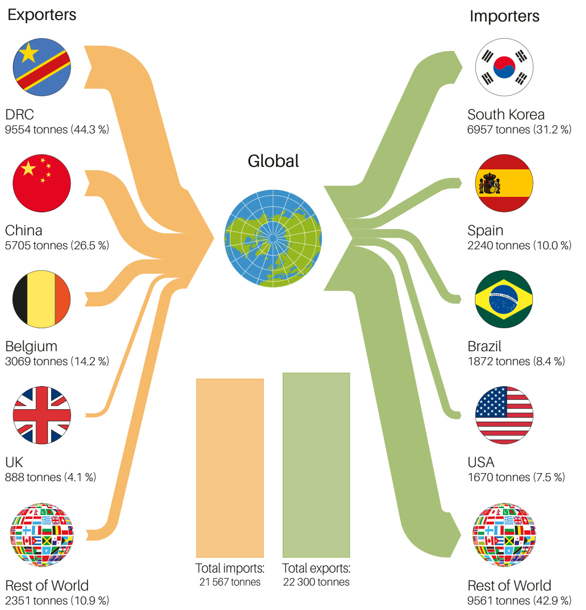


Figure 24 Global and UK trade of sulphates of nickel in 2019. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 283324; Taiwan = Other Asia, nes; South Korea = Rep. of Korea.

Cobalt oxides and hydroxides; commercial cobalt oxides (referred to as cobalt oxides and hydroxides): the DRC and China were the major exporters of cobalt oxides and hydroxides with about 44 per cent and 27 per cent of the global total, respectively (Figure 25). Belgium and the UK are the third- and fourth-ranked exporters, accounting for about 14 per cent and 4 per cent of the global total, respectively. Korea, Spain, Brazil and the USA were the major global importers, together accounting for about 57 per cent of overall imports. Total UK imports were about 130 tonnes, and Finland (88 tonnes) and Belgium (32 tonnes) were the major exporters to the UK, accounting for about 92 per cent of the total UK imports of cobalt oxides and hydroxides.

Cobalt; mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders (referred to as cobalt; mattes and other intermediate products): the export share of cobalt; mattes and other intermediate products to the world is relatively diversified with significant shares from Malaysia (26 per cent of the total), Canada (13 per cent of the total), Russia (13 per cent of the total) and Belgium, which together account for about 58 per cent of the total (Figure 26). However, China dominates global imports with about 80 per cent of the total, or some 300 kt. Furthermore, China was also the dominant source of UK imports, accounting for about 75 per cent of the total (3.5 kt). Global exports of cobalt; mattes and other intermediate products are almost 17-fold greater than for cobalt oxides and hydroxides. The UK also reflects this pattern, importing about 3.5 kt of cobalt mattes and other intermediate products compared to 131 tonnes of cobalt; mattes and other intermediate products.



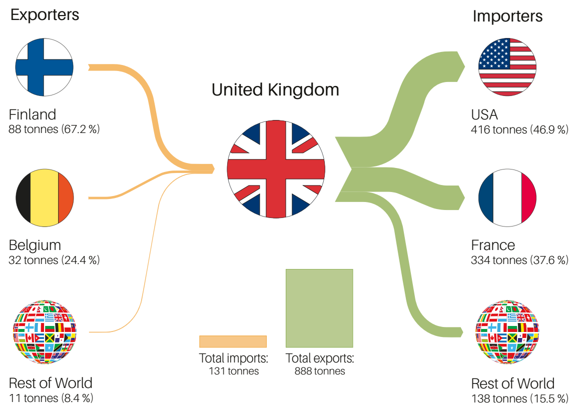


Figure 25 Global and UK trade of cobalt oxides and hydroxides; commercial cobalt oxides in 2019. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 282200; USA = United States of America; South Korea = Rep. of Korea; DRC = Democratic Republic of the Congo.

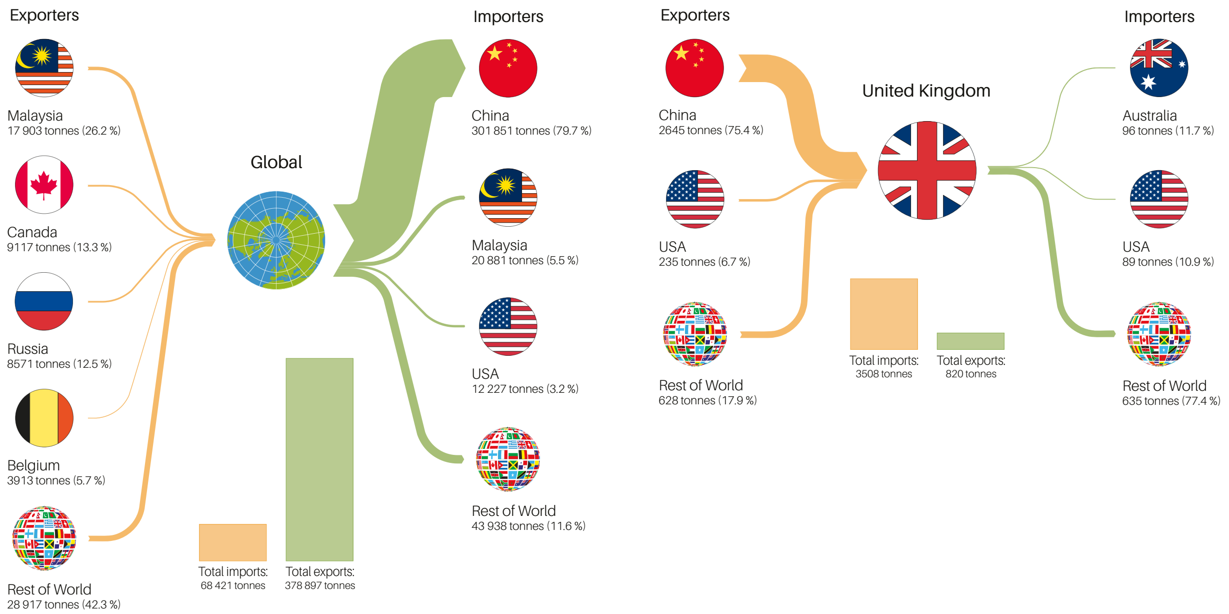


Figure 26 Global and UK trade of cobalt; mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders in 2019. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 810520; USA = United States of America.

Manganese dioxide: Myanmar and China were the major exporters of manganese dioxide globally, together responsible for some 119 kt, or about 63 per cent of the total. There is no predominant importer of manganese dioxide with several countries importing broadly similar amounts (Figure 27). The UK's imports of manganese dioxide were chiefly sourced from the Netherlands, the USA and India, with the Netherlands accounting for 790 tonnes, or about 65 per cent of total UK imports (c. 1.2 kt).

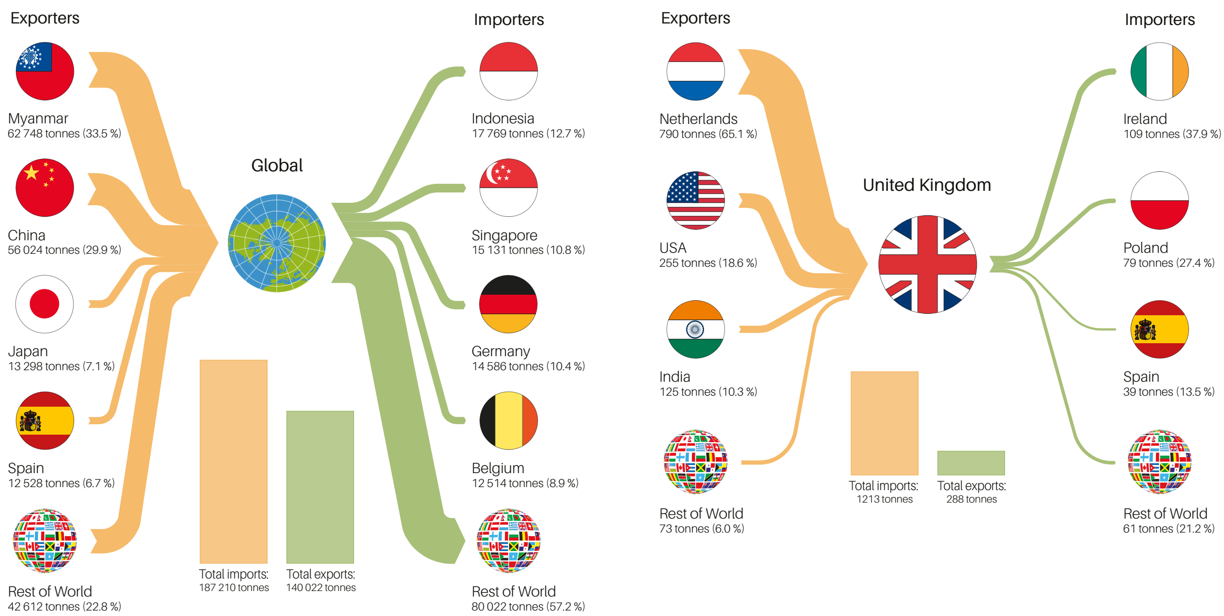


Figure 27 Global and UK trade of manganese dioxide in 2019. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 282010; USA = United States of America.

Graphite: China dominates the global trade in graphite. It accounts for exports of about 289 kt of natural graphite, or 47 per cent of the global total (Figure 28), and 462 kt of artificial graphite[6], or 42 per cent of the global total (Figure 29). The distribution of global imports of natural graphite is spread among several countries, although China imported about 30 per cent of the total. Malaysia was the principal importer of artificial graphite, accounting for about 383 kt, or 28 per cent of the total. China is the main source of graphite to the UK, accounting for more than 35 per cent of natural graphite imports (c. 2.1 kt), and more than 44 per cent of artificial graphite imports (c. 7.5 kt). UK trade in graphite is dominated by artificial material, at about 17 kt, or 74 per cent of the UK's total graphite imports.

Evaluation

Despite the limitations and potential inaccuracy of the data used in this evaluation, overall trade patterns are clear at both the global and UK scales. The importance of China as the leading source for cobalt and graphite is inline with expectation given its global dominance in the production of refined cobalt and graphite. However, the UK's reliance on imports of nickel, manganese and lithium from Belgium, Germany and the Netherlands (Table 6) does not reflect the original source of these materials given the absence of significant production capacity in these countries. The trade data actually reflect the location of the ports from which the intermediate products were shipped. It

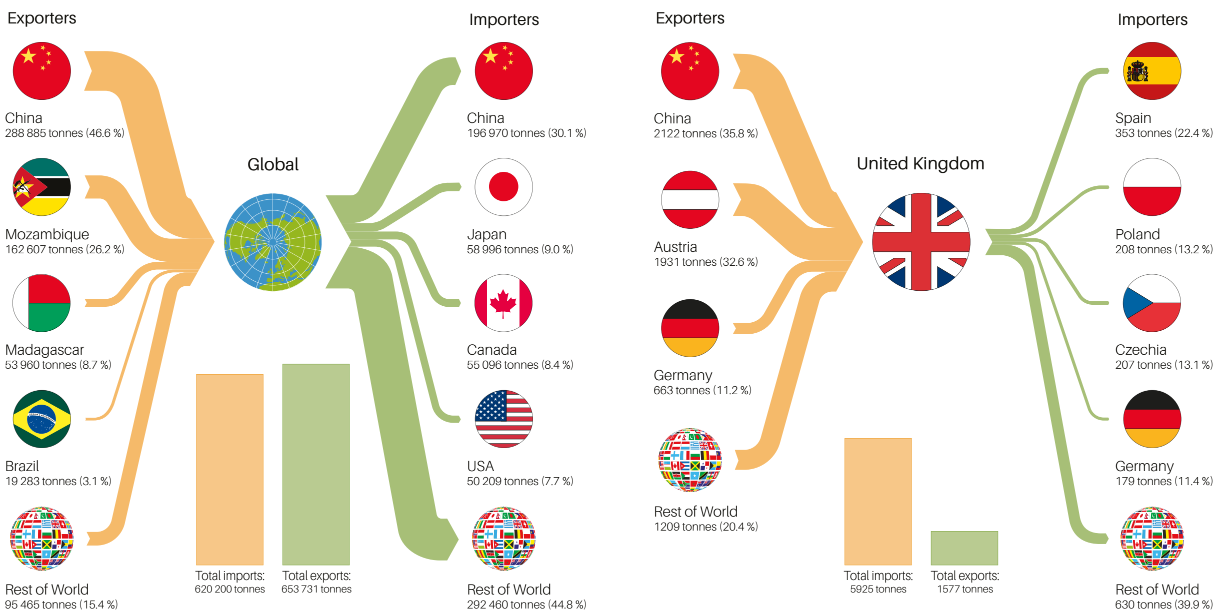


Figure 28 Global and UK trade of natural graphite in 2019. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 2504; USA = United States of America.

6 Artificial graphite; colloidal or semi-colloidal graphite; preparations based on graphite or other carbon in the form of pastes, blocks, plates or other semi-manufactures.

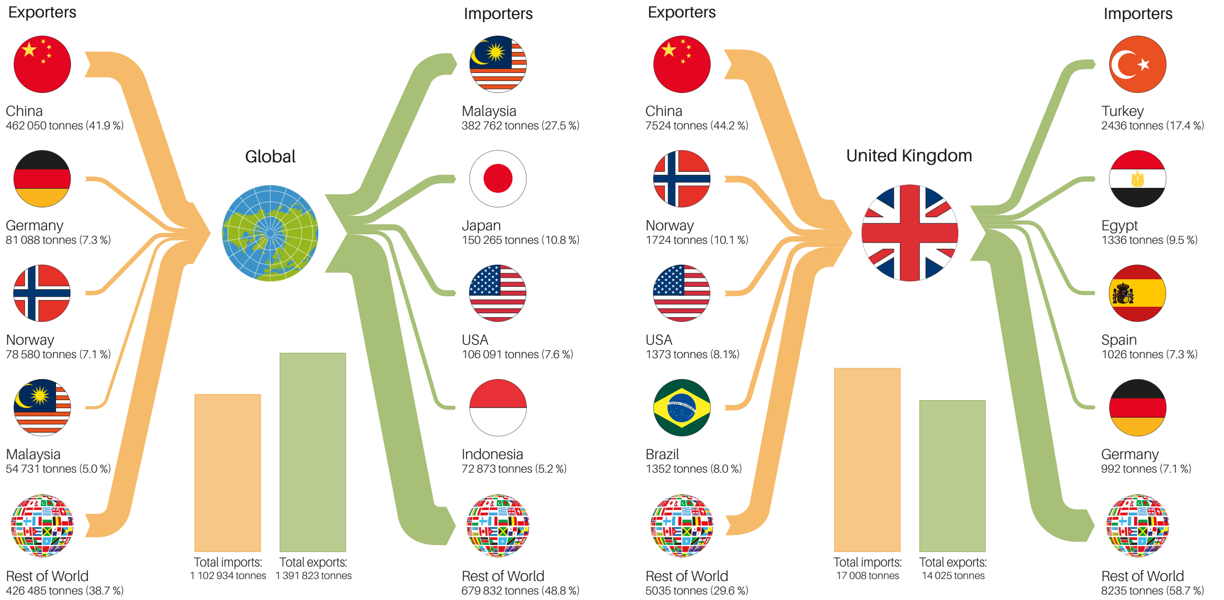


Figure 29 Global and UK trade of artificial graphite; colloidal or semi-colloidal graphite; preparations based on graphite or other carbon in the form of pastes, blocks, plates or other semi-manufactures in 2019. Data source: DESA/UNSD (2022), United Nations Comtrade database; HS code: 3801; USA = United States of America.

is necessary to look further back along the value chains of these materials to identify the location of the extraction and processing stages which led to the production of these materials. This would initially involve interrogation of the trade data for those European countries on which the UK is apparently dependent and require consultation with industrial consumers in the UK.

Table 7 Summary of the principal countries from which the UK was importing battery minerals in 2019.

	Lithium oxide and hydroxide (282520)	Carbonates; lithium carbonate (283691)	Sulphates of nickel (283324)	Cobalt oxides and hydroxides; commercial cobalt oxides (282200)	Cobalt mattes and other intermediate products (810520)	Manganese dioxide (282010)	Natural graphite (2504)	Artificial graphite6 (3801)
Belgium	2nd (32%)	2nd (32%)	1st (90%)	2nd (24%)				
Germany		1st (45%)						
Netherlands	1st (44%)					1st (64%)		
China					1st (75%)		1st (36%)	1st (44%)
Finland				1st (67%)				
USA					2nd (7%)	2nd (21%)		
Austria							2nd (33%)	
Norway								2nd (10%)
Japan			2nd (5%)					

8 The future supply-demand balance of battery minerals

Primary supply of battery minerals and projected demand

The global production of lithium, nickel and refined cobalt has increased significantly over the past decade. However, there is growing concern over the future availability of adequate and sustainable supplies of some of these materials at the scale and pace required to supported projected global EV uptake and associated battery manufacture. This is reflected in recent assessments undertaken by national governments in which lithium, cobalt and graphite are considered to be 'critical' on account of the likelihood of their supply disruption and the economic vulnerability to such a disruption (European Commission, 2020b; Lusty et al., 2021). These three materials are also present in the latest list of minerals critical to the United States economy, which also includes manganese and, for the first time, nickel (USGS, 2022b).

The availability of adequate geological resources and reserves has been suggested by some authors as a factor potentially limiting future supply of some raw materials (Bardi and Pagani, 2007; Cohen, 2007; Royal Society of Chemistry, 2019; Sverdrup and Ragnarsdóttir, 2014). Some studies have calculated depletion times for mineral reserves and thus suggest that supplies will be exhausted over short timescales, ranging from a few years to several decades. However, these calculations are fundamentally flawed because they are based on incorrect understanding of what mineral reserves represent (Crowson, 2011). In fact, reserves are a dynamic entity that measures what is available to exploit today under present market conditions and with current technology. They are just a small part of a mineral resource, which is a natural concentration of minerals that is of potential economic interest for the future extraction of those minerals. Reserves are not static and are never actually depleted; rather they are continually replenished by exploration which converts resources to reserves. Under appropriate market conditions these reserves may then be extracted. Otherwise, they will revert to resources to await a change in circumstances which will render them viable to work in the future. As a result, global reserves are not well known and are not reliable indicators of future mineral availability and the concept of reserve depletion times is invalid (Lusty and Gunn, 2015; Lusty et al., 2020; Worstall, 2015). Published mineral reserve data should be regarded as a working inventory of what is currently available to mine and by no means reflects all that exists in the Earth's crust.

Although geological availability is not an issue there are numerous factors that affect the accessibility of a mineral resource and may, therefore, lead to supply disruption. The significance of each varies between individual commodities and key producing countries. They are dynamic in character and a change in any one of them can have serious consequences for supply at any time. Such factors include: production concentration; protectionist tendencies, such as resource nationalism, geopolitics and trade wars; the political and economic conditions in producing countries; investment availability for new mining and processing projects; lack of exploration and underpinning geoscience research; competing demand; the by-product status of many critical metals (such as cobalt); environmental performance and regulation in producing countries; and the social acceptability of extraction and processing activities.

It is also very difficult to forecast future supply given the uncertainties in the scale and timing of new production capacity. Consequently, it is particularly challenging to build robust and resilient supply chains for battery minerals over a short timescale.

One way of assessing the likely adequacy and reliability of the future supply of battery minerals is to monitor the global pipeline of new mining and processing projects. Assessment of the economic viability of these projects in the context of current and future market conditions allows conclusions to be drawn about supply potential and associated risks. The development of robust investment strategies is critically underpinned by an in-depth understanding of these complex and rapidly changing markets. Proprietary data, software tools and expert advice for assessing future raw material supply are available from several commercial companies, although these are not in the public domain. An analysis of this type could not be undertaken in the time available for this study. The International Energy Agency (IEA) presents data on projected production levels for lithium and cobalt to 2030. These are based on current mining operations and those in the development pipeline. Comparison with projected global demand for these minerals under the IEA STEPS and SDS shows when potential supply deficits can be expected based on the underlying assumptions (IEA, 2022a, p 119). This suggests that under the IEA STEPS near-term supply should meet the expanding raw material needs for the energy transition, but the next decade will require strong investment in expansion of production and firm commitments to new exploration and development projects to sustain adequate battery mineral supply beyond 2030.

Given a lack of access to proprietary data and the future uncertainty about projects currently under development, an alternative approach to the assessment of future supply was used. This involved analysis of the compound annual growth rate (CAGR) of past mine production. Other studies have also used CAGR calculated for different time periods and compared them with projected demand (IEA, 2022a; KU Leuven, 2022; Watari et al., 2020; World Bank Group, 2020).

The changes in global production for the five battery minerals over the period 2010–2019 were examined (Figure 14 to Figure 18) using data from the BGS World Mineral Statistics database (British Geological Survey, 2022). Where available, data for both mine production (chiefly ores and concentrates) and refinery production (metal) were considered. Data for 2020 were excluded to avoid any influence from the COVID pandemic. The CAGRs for production were calculated for a 5- and 10-year period (Table 8).

Table 8 Compound annual growth rates (CAGR) for the global production of battery minerals over two time periods, global battery mineral production in 2019, and projected global production in 2030 based on the 10-year CAGR rate. Data source: British Geological Survey (2022).

Commodity	CAGR 2015–2019 (%)	CAGR 2010–2019 (%)	Global production in 2019 (tonnes)	Projected global production in 2030, based on applying the 10-year CAGR (tonnes)	Projected global production increase in 2030 relative to 2019 (%)
Lithium (metal content)	28	16	86 259	441 411	412
Nickel (mine)	5	6	2 673 570	5 075 234	90
Nickel (refined metal)	5	6	2 442 211	4 636 046	90
Cobalt (mine)	-4	-1	124 753	-	-
Cobalt (refined metal)	7	6	135 324	256 885	90
Manganese (mine)	3	3	57 408 993	79 467 473	38
Graphite (mine)	0	-7	1 123 733	-	-

For certain battery minerals, such as nickel and cobalt metal, the calculated CAGR is relatively high at 6 per cent, leading to a projected increase in the global production total of 90 per cent in 2030 relative to total production in 2019. For lithium the CAGR is much higher at 16 per cent over the same ten-year period, and would translate into a production increase of 412 per cent in 2030. If the CAGR for the five-years 2015–2019 for lithium (28 per cent) is projected forward that leads to an increase of 1411 per cent in 2030 relative to total production in 2019. For manganese the CAGR is 3 per cent, which, projected to 2030, leads to a 38 per cent increase in global manganese production relative to 2019. The relatively low rate of growth in manganese production since 2010 reflects the much larger scale of its production compared with other battery minerals. Over the ten-year period 2010–2019 graphite production has declined significantly, leading to the negative CAGR calculated. This is largely in response to China rationalising its graphite extraction sector with the imposition of new environmental guidelines and the closure of some extractive operations (Yang et al., 2017).

The negative CAGR for mined cobalt is a result of the generally decreasing price over the last ten years, with the exception of the 2017–2018 price hikes (Figure 16), combined with cobalt stockpiling and its dependency on the copper and nickel markets (Campbell, 2020). This decline is in marked contrast to the 6 per cent increase in CAGR for refined cobalt metal. This growth was sustained by the improving recoveries of cobalt from nickel laterites and DRC sourced ores in China, as well as the availability of stockpiled cobalt ores and concentrates (Campbell, 2020). Given its by-product status and dependency on the market of other major commodities, with a major centre of production in a politically unstable country, significant uncertainty remains over primary cobalt production in the next decade. Improvements in the technology for the recovery of cobalt from base metal ores, and the addition of new capacity in politically-stable producing countries that rank high in term of environmental and social performance would help to overcome decreasing primary production and enhance future global supply security (Campbell, 2020). Despite the market moving towards lower cobalt content in batteries, the supply risk remains important due to the sheer scale of the expanding battery market.

Although the calculated CAGRs indicate the production growth rates that have been achieved in mining and/or refining in the past, it is by no means certain that these rates can be maintained in the future on the scale, and at the required pace, to meet the rapidly increasing global demand for battery minerals. Recent criticality assessments by United States Geological Survey and the British Geological Survey have considered high growth rates to indicate a high level of industry vulnerability to supply disruption (Lusty et al., 2021; McCullough, 2017). However, given the many varied influences that determine production levels from individual deposits and which, therefore, influence national and global production totals, the use of CAGRs from the past is not considered a reliable way to forecast future supply. Furthermore, past production data does not reflect the additional future demand from the energy transition. It is very likely that future production will need to be much greater than that projected based on 2019 production. In order to better appreciate the scale of future battery mineral production that will be required it is more instructive to compare 2019 global production with demand projections for the world and UK in 2030 (Table 9).

Depending on the scenario (Table 5) it is estimated that in 2030 the UK battery manufacturing sector would require between about 12–17 per cent of total global lithium production levels in 2019. UK graphite demand for anodes in 2030 is also very significant as a proportion (between 8–12 per cent) of total world graphite production in 2019. Under the UK-NMC scenario in 2030, the UK gigafactories would require up to 9 per cent of 2019 global production levels of mined cobalt. The UK share of mine nickel production in 2030, as a proportion of total global production levels in 2019 ranges from about 3–4 per cent under the NMC-dominated scenarios. Manganese is the only battery mineral with a notably smaller relative demand increase in 2030, as the increased demand associated with LIBs is small compared with its total production in 2019.

Global demand projections for battery minerals and the UK-specific estimates indicate that major increases in supply will be required by 2030 compared with 2019 global production. The

Table 9 Global battery mineral production in 2019 and the UK share in 2030 as a percentage of total global production levels in 2019 based on three demand assessments (Table 5). Global production data is from British Geological Survey (2022). The UK-NMC scenario is based on the various battery chemistries that the announced UK gigafactories plan to produce (Table 3). The UK-NMC/LFP scenario assumes that 50 per cent of the announced UK capacity is used to make LFP batteries. The third demand assessment (APC-NMC-811) is based on forecasts of UK light duty electric vehicle production and assumes all cells use NMC-811 (Advanced Propulsion Centre, 2022a).

	Global production in 2019 (tonnes)	UK share (%) in 2030 of total global production in 2019		
Scenario		*UK-NMC*	*UK-NMC/LFP*	*APC-NMC-811*
Lithium (metal content)	86 259	17.3	16.5	12.4
Nickel (mine)	2 383 865	3.8	2.1	3.0
Nickel (refined metal)	2 673 570	3.4	1.9	2.7
Cobalt (mine)	124 753	9.0	4.7	7.3
Cobalt (refined metal)	135 324	8.3	4.4	6.7
Manganese (mine)	57 40 8993	0.02	0.01	0.01
Graphite (mine)	1 123 733	12.0	12.0	8.5

UK shares of the global production totals are all significantly larger than at present.

Although high production growth rates have been achieved in the past as a result of increased mining and/or refining, it is uncertain if such rates can be maintained in the future, particularly when ESG performance is now, and will continue to be, the foremost consideration (Eheliyagoda and Zeng, 2020). Not only is increasing supply dependent on the continual identification of new resources of these minerals, but it is also necessary to overcome the many, varied barriers (environmental, social, economic, political, etc.) that determine whether these resources can be converted into reserves and actually mined. Average lead times from initial deposit discovery to the start of mining in the period 2010–2019 were 16.5 years, although this varied between individual countries and locations and commonly exceeded 20 years (IEA, 2022a). In rare cases, where exceptionally favourable conditions prevail, this period can be shortened considerably, although it is much more common for projects to fail at some stage in their evaluation and never actually enter production. These projects may be abandoned indefinitely or may be re-evaluated at a later date in response to a change in market conditions, such as higher commodity prices, improved processing technology or infrastructure availability, or changes in government policy.

A comparison of the development of the lithium extraction industry in Australia and Chile serves to illustrate the global variation in the timescale for exploration and mine development. Although both countries have plans to increase production from their known reserves, since 2014 Chilean companies have only raised their production marginally and no new permissions have been granted (Sherwood, 2019). In contrast, production in Australia increased fivefold between 2014–2018 (Champion, 2018). This was achieved by expanding existing projects and by opening new mines. Production of lithium from the major deposit at Pilgangoora in Western Australia began in 2018, only 2 years after completion of a definitive feasibility study (Pilbara Minerals, 2018).

Although geological availability is not an issue, bringing adequate new supply on stream within a short timescale may be problematic (CRM4EV, 2022). Heijlen et al. (2021) analysed the global mine development pipeline for nickel and cobalt in the light of future demand scenarios and project lead times. They showed that the time taken to demonstrate the feasibility of a nickel or cobalt project has significantly increased during the last two decades to a median of 12 years. They concluded that there needs to be a major increase in the capacity of land-based mining and indicated a possible role for seafloor resources, as well as measures aimed at reducing raw material demand.

The growth in the relative share of the UK consumption in 2030 relative to world production is an indication of the required growth in primary production for which several other nations will be competing at the same time. In the context of the global energy transition it is important to note: (i) the EV market is in a nascent stage and raw material demand from its development will be in competition with resources for well-established and growing markets such as construction, steel and electrical networks; and (ii) the development of electromobility is only one part of the energy transition along with wind, nuclear and solar, which are also rapidly expanding. These developments in green and renewable power generation will also add considerably to the demand for raw materials. Of relevance to the LIB sector, is significant projected and potentially competing demand for nickel and manganese for wind energy and, to a lesser extent in the nuclear sector (IEA, 2022a), whilst cobalt, graphite and lithium remain largely exclusive to battery technologies. Relative to the shares in 2020, estimated demand from clean energy technologies in 2040 is expected to increase from 28 per cent to 75 per cent for lithium, from 15 to 40 per cent cobalt, and from 8 to 33 per cent for nickel, under the IEA STEPS (Figure 30). Significantly larger increases are predicted under the IEA SDS (IEA, 2022a).

Secondary supply of battery raw materials

The Circular Economy (CE) is a revolutionary alternative to a traditional linear, make-use-dispose economy. It is based on maintaining continuous flows of resources at their highest value for the longest time period and then recovering, cascading and regenerating products and materials at the end of each life cycle (Ellen Macarthur Foundation, 2016; Global Battery Alliance World Economic Forum, 2019). Application of CE principles is expected to alleviate pressure on primary supply requirements by optimising use and reuse of batteries whilst providing a secondary supply of raw material through recycling batteries that have reached their end-of-life (EOL).

Sustainability requirements and regulations for batteries

There is no standard global policy framework governing the EOL management of LIBs. In

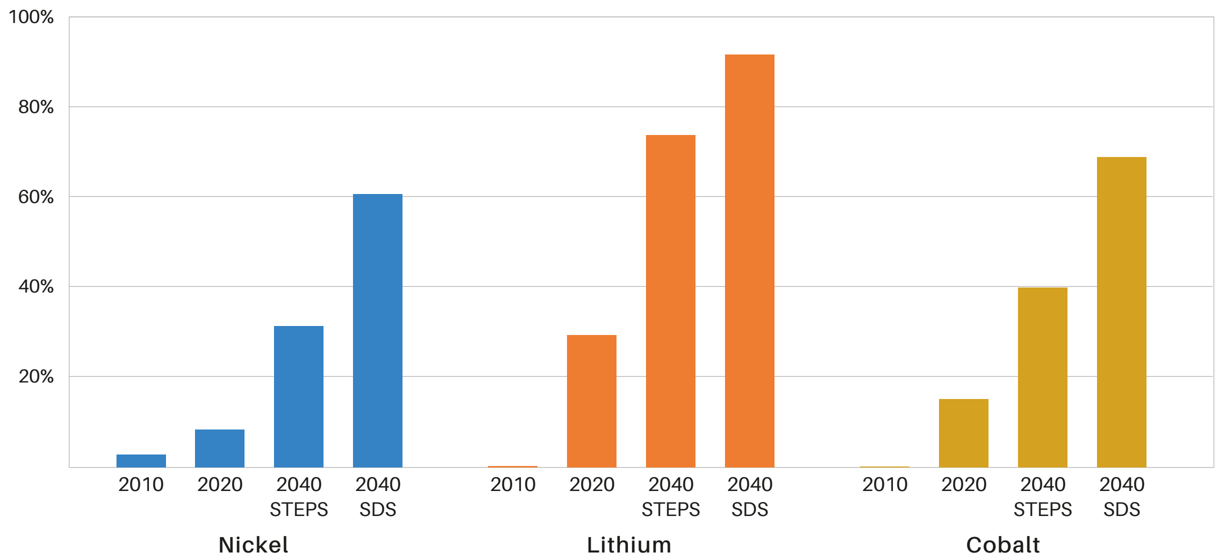


Figure 30 Share of clean energy technologies in total demand for lithium, cobalt and nickel under the IEA STEPS and SDS. Adapted from IEA (2022a). Reproduced with permissions. Source: IEA (2022b) The Role of Critical Minerals in Clean Energy Transitions, World Energy Outlook Special Report. All rights reserved; as modified by the British Geological Survey.

Asia, particularly China and Japan, a variety of regulations have been developed and institutions established to recycle LIBs. In Europe, a comprehensive regulatory framework is likely to be enacted to manage battery manufacture, labelling, reuse and recycling, and to stimulate technology development. However, in other countries, such as the United States and India, there has been little regulatory development, although battery recycling in the United States is receiving increased attention from the federal government (Bird et al., 2022; IEA, 2022a). Clear guidance, policy incentives and regulations on collection, sorting, transport, storage and recycling of EOL LIBs are crucial to increasing material supply from this source. Developments at the product engineering and design phase to enable efficient recycling processes are also critical. Specific guidelines or regulations for storing spent batteries or technical guidance for skilled personnel to discharge and dismantle spent batteries are also lacking in most countries. China is one of the few countries with some technical guidelines on dismantling and restoring spent EV batteries and retraining of staff at car manufacturers (IEA, 2022a). Future bottlenecks at the recycling and reuse stage of the UK EV CE should also be anticipated due the lack of trained workers and an absence of specific technical guidelines and regulations pertaining to battery handling at the end of the first life cycle (Harper et al., 2019; Sun et al., 2018).

The CE was a key driving force behind the European Commission proposal in 2020 for a Sustainable Batteries Regulation, which indicated that batteries entering the EU market should become sustainable, high-performing and safe along their entire life cycle (European Commission, 2020c). It has been indicated that the UK will also undertake a consultation on revising its battery regulations in late 2022, which will consider three key areas: portable batteries; changes in industrial and automotive batteries; and the EU batteries regulation (Langley, 2022). From January 2027, the proposed EU regulatory framework for batteries would introduce a mandatory declaration of recycled content for industrial batteries, EV batteries and automotive batteries containing cobalt, lithium or nickel, amongst other metals. Mandatory minimum levels of recycled content would be established for 2030 and 2035 (i.e. 12 per cent cobalt, 85 per cent lead, 4 per cent lithium and 4 per cent nickel as of January 2030, increasing to 20 per cent cobalt, 10 per cent lithium and 12 per cent nickel from January 2035) (European Commission, 2020c).

Global battery recycling

The number of EVs (BEVs + PHEVs) retired around the world is expected to rise from 540 000 in 2025 to more than 46 million in 2040. Battery waste from these electric vehicles is projected to increase more than 80 times, from 42 GWh in 2025 to 3 455 GWh in 2040. The global battery recycling market is expected to grow in response, from 26 GWh in 2025 to 1 606 GWh in 2040 (Herh, 2022; SNE Research, 2022).

As of late 2021, the global capacity for LIB recycling was about 322 kt, with a further 70 kt of planned capacity (Baum et al., 2022). China accounts for 58 per cent of current capacity (188 kt), followed by Europe (28 per cent; 92 kt), Japan (7 per cent; 21.5 kt) and the USA (3 per cent; 11 kt tonnes). Current global planned recycling facilities are estimated to add nearly 400 kt, led by East Asia (219.5 kt) and Europe (110 kt) (Baum et al., 2022).

Between 2015–2019 Chinese EV production had a compound growth rate of about 33 per cent, reaching 1.18 million units in 2019. Owing to this huge increase in demand, Chinese production of LIBs in 2019 reached 71 GWh, representing a compound growth rate of about 43 per cent between 2015–2019. This increased demand for LIBs in China has resulted in more EOL LIBs, which were reported to amount to 355 kt in 2019. It is indicated that a total of 129 kt of EOL LIBs were recycled in China in 2019, of which 96 kt were derived from digital electronics (Gaogong Lithium Battery, 2020).

Analysis by the IEA indicates that in 2030 under both the STEPS and SDS the share of recycled lithium and nickel as a proportion of total demand will be about 1 per cent or less. The contribution that recycling will make to total demand for cobalt in 2030 is estimated to be slightly greater, representing 2 per cent of total demand under both the IEA STEPS and SDS. Under the IEA STEPS, secondary production of lithium, cobalt and nickel in 2030 is estimated to be about 1.5 kt, 6.3 kt and 23 kt, respectively. Under the IEA SDS the secondary production volumes in 2030 are slightly greater, at 2 kt for lithium, about 8 kt for cobalt, and about 31 kt for nickel (IEA, 2022a).

It is not until 2040 that recycling starts to make a more significant contribution to total supply. At this time the share of recycled lithium as a proportion of total global demand under the IEA STEPS and SDS is estimated to be about 7 per cent (c. 27 kt) and 5 per cent (c. 61 kt), respectively. In 2040 the share of recycled nickel as a proportion of total demand under the IEA STEPS and SDS is estimated to be 5 per cent (c. 230 kt) and 7 per cent (c. 515 kt), respectively. The share of recycled cobalt as a proportion of total global demand in 2040 under the IEA STEPS and SDS is estimated to be 11 per cent (45 kt) and 12 per cent (c. 95 kt), respectively (IEA, 2022a).

UK electric vehicle battery recycling

Until recently the UK had no domestic EV battery recycling capacity. This changed when the Sheffield-based company, RSBruce, launched its in-house LIB battery recycling facility in November 2021 (RSBruce, 2021). Recent announcements on the development of pilot-scale recycling plants and other planned facilities in the UK, including information on their expected GW equivalent recycling capacity, provide an indication of the potential scale of the future domestic LIB recycling sector. Altilitech Ltd, based in Plymouth, plans to expand its laboratory-scale LIB recycling to the pilot plant-scale. The pilot plant completion is expected to trigger investment in the first large-scale plant in the UK, processing battery waste from 20 000 EVs per year. The company's ambition is to have a recycling plant at each of the UK gigafactories by 2040 (Altilium Metals, 2020). In January 2022, Veolia announced its first EV battery recycling facility in Minworth, West Midlands, which will have the "capacity to process 20 per cent of the UK's EOL EV batteries by 2024" (Veolia, 2022). Britishvolt and Glencore released a joint statement in February 2022 concerning plans to develop a world-leading ecosystem for battery recycling in the UK via a new recycling plant at the Britannia Refined Metals operation in Northfleet. The plant will have an expected processing capacity of a minimum of 10 000 tonnes of LIBs annually, including, but not limited to, battery manufacturing scrap, portable electronics batteries and full EV packs. The facility will also process all Britishvolt's battery manufacturing scrap from its gigafactory in Blyth (Glencore, 2022).

Ongoing research supported by the Faraday Battery Challenge aims to support innovative laboratory-scale battery technological developments and enable the capability to expand new battery technologies developed within the UK to a commercial scale. The Challenge is focused on developing cost-effective, high-performance, durable, safe and recyclable batteries to capture a growing market (The Faraday Institution, 2022b). This research is very unlikely to impact on UK secondary supply of recycled battery metals before 2030, but will improve the development of circular economy strategies for batteries, including recycling and reuse within the UK over the longer term.

The potential for UK supplies of recycled battery raw materials

The secondary supply of metals from LIBs is limited by the quantity of material available from scrap or EOL sources, as well as the effectiveness of collection and recycling (KU Leuven, 2022). EV batteries degrade over time and are designed to last for about 10–12 years in most vehicles. Once their usable capacity falls below about 80 per cent they do not meet the performance standards required for an EV (Gilmore, 2021; Engel, 2019). However, these batteries are still suitable for stationary energy storage applications, for example, storing and managing renewable electricity. The lifespan of batteries in 'second life' energy storage applications depends on their use, ranging between about 6–30 years (Casals et al., 2019). Accordingly, second life applications for batteries can potentially result in significant delays in them becoming available for EOL recycling. This factor, combined with the relatively recent adoption of EVs in the UK and the average EV battery lasting more than a decade, constrains the amount of recycled metals available from EOL vehicles alone up to 2035 (Advanced Propulsion Centre, 2022b). Owing to the EU Sustainable Batteries Regulation, it is important to recognise that a lack of recycled battery raw materials derived from EOL vehicles in the UK economy could have implications for the ability of

UK-based battery manufacturers to meet mandatory minimum levels of recycled metal content in batteries.

Manufacturing scrap, derived from the planned UK gigafactories (Table 3), is a more important potential near-term source of recycled battery materials. Assuming UK battery production capacity reaches 90 GWh by 2030, the APC estimates that this could create up to 20 kt of reusable cathode active materials for the UK market. This would be sufficient to produce 7 GWh of new batteries. When combined with vehicles that have reached their EOL it is estimated that 28 kt of battery waste could be available for reuse in the UK by 2030. Furthermore, it is suggested that this material may make the minimum recycled content levels for batteries achievable, if the regulations permit battery production scrap as a source of recycled content alongside EOL batteries. The APC estimates that by 2040 a total of 235 kt of waste battery materials will be available for recycling and reuse in the UK, comprising about 204 kt from EOL vehicles (now the principal feedstock for recycling), 24 kt from production scrap and 8 kt associated with warranty returns. This represents sufficient cathode active materials to produce 60 GWh of new batteries (Advanced Propulsion Centre, 2022b). Furthermore, National Grid modelling indicates that after 2033, the quantity of EV batteries reaching their first EOL will largely surpass the yearly increase in UK storage capacity required (National Grid ESO, 2021), suggesting a more significant flow of batteries into the recycling sector.

9 Future UK supplies of battery minerals, solutions, and bottlenecks

Potential for domestic production of battery minerals

Although a range of different types of lithium-bearing minerals are known to occur in the UK, many of them, with the exception of lithium-bearing micas, are exceedingly rare and are only found in minor quantities at a few localities. The amount of academic research and commercial exploration for lithium in the UK has increased significantly in recent years (British Geological Survey, 2020a). In south-west England Cornish Lithium Ltd is currently producing small amounts of lithium chloride from their DLE pilot plant in Cornwall (Cornish Lithium, 2022). They also have a JORC-compliant indicated resource estimate for their hard-rock project at Trelavour. The resource currently stands at 51.7 million tonnes at 0.24 per cent lithium oxide (Cornish Lithium, 2021). British Lithium Ltd, also in Cornwall, are developing a hard-rock project in the St Austell area. The company has a JORC-compliant resource, although this is not currently publicly available. British Lithium Ltd has recently built a pilot plant in Cornwall, which has successfully produced battery-grade lithium carbonate from lithium-bearing micas (British Lithium, 2022).

In the UK the most important occurrences of nickel are chiefly located in Aberdeenshire in north-east Scotland. Minor occurrences of nickel are known in mid-Wales, south-west England and the North Pennine Ore Field, where nickel is found alongside lead, copper, zinc, silver, bismuth and cobalt. There are no records of significant production of nickel at any of these locations. However, since the 1980s there has been considerable academic research on nickel and associated mineralisation in the UK and some commercial exploration on a relatively small scale, especially in north-east Scotland (British Geological Survey, 2020b).

Minor cobalt occurrences are widespread in the UK, particularly in south-west England, the Lake District and mid-Wales. At these locations the cobalt is generally a minor constituent in ores of other metals such as copper, lead, zinc and nickel, some of which may have been mined on a small scale in the past. There may be some potential for undiscovered cobalt resources although it should be stressed that there has been no systematic exploration for cobalt in any of these areas nor has there been any modern research to understand the abundance and distribution of cobalt in the known occurrences (British Geological Survey, 2020c)

Manganese was exploited in the past in the UK, mainly in south-west England, and north and north-west Wales. Minor deposits are found elsewhere in England and Scotland. Much of the manganese production of south-west England was a by-product of iron-ore mining. There has been no systematic or modern exploration for manganese in the UK, with domestic interest and investigations peaking during the two World Wars.

Several graphite occurrences are documented in the UK, but there has been no systematic exploration to define resources or reserves. It is also unlikely that any of the known historic graphite occurrences would be of sufficient size and/ or quality to be commercially exploited (British Geological Survey, 2020d).

Although the potential for significant production of battery minerals in the UK is limited there is a good case for undertaking systematic exploration using modern techniques in some areas. This is already underway in south-west England, but other areas, notably north-east Scotland, merit further investigation for nickel and cobalt resources.

Potential overseas sources of battery minerals

In many countries, considerable attention is being paid to identifying new resources of battery minerals and bringing them into production. In some regions, particularly the USA and EU, national governments are actively promoting exploration and related research aimed at identifying new resources and thus increasing supply security for their domestic industries (European Commission, 2020e; The White House, 2022). Elsewhere there are growing levels of exploration activity and project development for battery minerals in countries seeking to supply overseas markets (S&P Global, 2022). These include countries with long-established mining industries such as Canada and Australia, both of which are already important producers of nickel. In addition, exploration for lithium in Western Australia, already a major producer, is continuing at pace and a number of new targets are being evaluated. Several developing countries are also seeking to benefit from the extraction of indigenous resources of battery minerals. In Africa, for example, Mozambique and Madagascar are already important producers of graphite, much of which is shipped to China for further processing. Advanced graphite projects are also present elsewhere, notably in Tanzania and Malawi, while exploration is also underway in Uganda, Namibia, Guinea, Ghana and Botswana (Bide et al., 2022).

Despite the high level of exploration and project assessment that is underway in many countries, there are no guarantees that new production will be brought on stream at the scale and pace required to meet the demands of the clean energy transition. As discussed previously most new projects will fail at some stage in their evaluation for a variety of reasons. The availability of adequate resources is not the main challenge, but rather whether other barriers, social, environmental, political and economic, can be overcome to allow secure and sustainable access to these resources. A good example is provided by the Jadar lithium project in Serbia where Rio Tinto identified one of the largest greenfield lithium resources in the world, with planned production of 58 000 tonnes of lithium carbonate (55 000 tonnes of which is battery-grade) annually (Rio Tinto, 2022). Rio Tinto committed US$450 million in pre-feasibility, feasibility and other studies in Jadar to understand the nature of the deposit, with a further US$2.4 billion earmarked for mine construction, subject to necessary approvals, permits and licences. However, according to press reports the project faced strong opposition from local stakeholders over the potential environmental impact of a mine, and in January 2022, the Serbian government withdrew the spatial plan and revoked Rio Tinto's licence to operate.

Trade restrictions

Potential trade restrictions are an important consideration when seeking to secure supplies of battery minerals from overseas. Various restrictions may be placed on the trade of a given commodity; these include, but are not limited to, export taxes, licensing, export quotas and export prohibitions. These may be imposed by governments for a variety of reasons including conservation of natural resources, environmental protection, income generation and promoting domestic value addition by undertaking further processing of ores and concentrates prior to export. For example, in 2020 an export prohibition was placed on cobalt from the DRC to add greater value in country and increase associated income generation. Although trade restrictions may benefit the country implementing them, as in the case of DRC, such restrictions can represent a barrier to trade. This is particularly problematic, where the production of a commodity is concentrated in a few countries. Trade restrictions can also be used as a geopolitical tool. For example, the restriction on exports of rare earth elements (REE) from China to Japan in 2010, was a result of a territorial dispute over ownership of the Diaoyu/

Senkaku islands in the East China Sea (Feldhaus et al., 2020). This had serious global repercussions, giving rise to concerns about supply disruption and leading to a rapid, although short-lived, escalation of REE prices. Similarly, economic sanctions placed on a country in response to conflict or political instability can have a negative impact on both the country being sanctioned and the countries implementing the sanctions. For instance, the recent sanctions against Russia in response to the conflict in Ukraine have had a significant impact on the global supply of Class I nickel (Finley, 2022). Conversely, trade agreements can be a valuable tool for improving security of supply as trade between countries generally happens according to a well-defined set of procedures (Grossman, 2016). However, even where an agreement is in place that does not guarantee access to material, particularly if a trade partner country has its own aspirations to achieve net-zero.

When considering where the UK might source battery minerals in the future it is important to look at countries where trade agreements are currently in place or are being actively negotiated. In 2020 the UK had signed 38 separate trade agreements with

Table 10 Major producers (>50 per cent of global total) of mined battery minerals (ores and concentrates) showing current trade agreements with the UK and existing trade restrictions. Rows highlighted in green indicate countries where the UK has a current trade agreement in place; rows highlighted in orange indicate countries where a trade agreement is currently being negotiated by the UK. 'NONE' indicates there are currently (2020) no trade restrictions, whereas 'UNKNOWN' indicates that the trade restriction status is not known.

	Ore and concentrates of battery minerals				
	Lithium	Nickel	Cobalt	Manganese	Graphite
Australia	NONE	NONE	NONE	NONE	
China	NONE			Non-automatic licensing	NONE
Chile	NONE				
Russia		Non-automatic licensing	NONE		
Cuba			UNKNOWN		
DRC			Export prohibition		
Indonesia		Export prohibition			
Philippines		Non-automatic licensing			
New Caledonia		NONE			
Canada		NONE			
India				Non-automatic licensing	Other measure
Gabon				Export tax	
South Africa				Non-automatic licensing	
Brazil					NONE
Madagascar					UNKNOWN
Korea					UNKNOWN

various overseas territories (WTO, 2022), some of which are important producers of battery minerals (e.g. Australia, Chile, Canada) (Table 10 and 11). It is also important to note where restrictions are in place and may, therefore, be a barrier to trade (e.g. licensing on the trade of manganese from South Africa) (Table 9). However, it should be noted that trade restrictions can be effective over varying timescales and that the status of a particular trade restriction can change at short notice. Furthermore, it is important to identify restrictions that have been imposed in the past but are no longer currently active. If a particular country has a track record of imposing trade restrictions then the possibility of it imposing similar restrictions in the future should be considered as part of any risk assessment. It is notable that, as of 2020, there are very few restrictions in place on the trade of lithium and graphite. However, there are various restrictions on the trade of nickel, manganese and cobalt at the extraction (i.e. mining) and processing stages (Table 10 and 11).

Table 11 Major producers (>50 per cent of global total) of processed battery raw materials (mainly intermediate products and metal) showing current trade agreements with the UK and existing trade restrictions. Rows highlighted in green indicate countries where the UK has a current trade agreement in place; rows highlighted in orange indicate countries where a trade agreement is currently being negotiated by the UK. 'NONE' indicates there are currently (2020) no trade restrictions, whereas 'UNKNOWN' indicates that the trade restriction status is not known.

	Processed battery minerals				
	Lithium	Nickel	Cobalt	Manganese	Graphite
Australia		NONE			
China	NONE	Export tax	Non-automatic licensing	Non-automatic licensing	NONE
Chile	NONE				
Argentina	Export tax				
Japan		UNKNOWN	UNKNOWN		
Belgium			UNKNOWN		
Finland			NONE		
Canada		NONE			
Russia		Non-automatic licensing			
Indonesia		Export prohibition			

Conclusion

The challenge: to meet legally-binding targets to achieve net zero emissions by 2050 and interim targets to reduce emissions significantly by 2035, the UK has to rapidly decarbonise road transport. To address this and support the UK automotive industry, which is a major part of the export economy, the Government plans to build an internationally-competitive EV supply chain at pace and scale in the UK. Domestic battery manufacturing plants or 'gigafactories' are an essential part of this commitment. Agreed UK-EU electric vehicle trade rules of origin mean that from 2024, the cathode-active materials required by these gigafactories must be made locally to allow continued tariff-free trade with the EU. Domestic production would also reduce reliance on imports of high-value cathode-active materials, particularly from the Asia-Pacific Region. UK battery manufactures will require lithium, nickel, cobalt and manganese to synthesise cathode active materials (CAM), together with natural or artificial graphite for the production of graphite-based anode materials.

Estimated UK demand for battery minerals: several companies have announced plans to expand existing facilities or establish new gigafactories in the UK that will ramp up production to 2030. If these manufacturing plans are fully realised, they equate to an estimated cumulative UK annual battery production capacity in 2030 of 135 GWh. The associated demand for individual battery minerals is dependent on the types of batteries that make up this production and the efficiency of the production processes. Based on current information on the most likely battery chemistries that will make up this production (principally nickel, manganese, cobalt: NMC), our study estimates that in 2030 the UK will have an annual requirement for about 15 kt of lithium, 90 kt of nickel, 11 kt of cobalt and 10 kt of manganese to synthesise CAM. At the same time the UK will also require 135 kt of graphite annually to produce anodes. An Advanced Propulsion Centre (APC) study based on the battery demand (96 GWh) associated with the forecast size of the UK light duty EV fleet in 2030 and assuming that all cells are NMC811 chemistry estimates that UK demand for lithium, nickel, cobalt, manganese and graphite will be 10.7 kt, 72 kt, 9.1 kt, 8.5 kt and 96 kt, respectively (APC, 2022a). The estimates produced by the two scenarios result in a different in demand in excess of 30 per cent for certain minerals. This highlights the influence of underlying assumptions in any scenario-based projections of mineral demand. A further scenario developed for our study explored the mineral demand implications of a significant shift in future UK manufacturing output to lithium iron phosphate (LPF) batteries (already very important in some markets such as China). This latter scenario illustrates how the adoption of this battery type can contribute to reducing domestic demand for nickel, cobalt and manganese. Energy storage technologies are evolving rapidly and in order to make UK battery mineral demand projections beyond 2030, it is necessary to consider a range of additional scenarios. These additional scenarios should be based on varying market shares of different combinations of battery chemistries.

What these demand levels mean for the UK? the UK is currently dependent on imports and therefore the global market for its battery mineral needs. As a result it is important to consider UK-specific battery mineral demand estimates in 2030 in the context of future global demand for these minerals. Many other countries are building gigafactories at pace to support their automotive sectors (more than 300 are planned or being developed worldwide). These actors are already competing to access supplies of battery minerals. Even under the more conservative International Energy Agency (IEA) Stated Policies Scenario (STEPS), global demand projections indicate that all of the battery minerals will experience triple digit percentage demand growth increases up to 2030 and beyond, due to the burgeoning market for EVs. This is the projected situation prior to considering other, potentially competing, industrial sectors that will also consume battery minerals. To assess the scale of the challenge the UK faces in fulfilling its battery mineral demand requirements in 2030, it is revealing to compare these estimates with existing total world production levels for battery minerals and with the volumes currently imported by the UK.

The UK is set to become a major consumer of battery minerals: depending on the UK battery demand scenario chosen, it is estimated that in 2030 the UK would consume 12–17 per cent of the lithium produced globally in 2019. UK graphite demand for anodes in 2030 is also very significant as a proportion (between 8–12 per cent) of total world graphite production in 2019. In the longer term, the estimated UK demand for cobalt may be moderated by a continuing trend towards nickel-rich cathodes. However, based on the battery chemistries that the UK gigafactories are currently planning to manufacture, in 2030 the UK could require up to 9 per cent of 2019 global production levels of mined cobalt. The UK share of mine nickel production in 2030, as a proportion of total global production levels in 2019 is about 3–4 per cent under the NMC-dominated scenarios examined in this study. Despite the scale of these estimated UK demand levels, by 2030 global production of all the battery minerals is likely to have increased significantly. As a result, in reality UK demand will account for a smaller share of global production in 2030 than is outlined above.

Increasing import dependency: the UK currently has no commercial-scale production of primary (mined) battery minerals and limited refining capacity. It is therefore reliant on imports from resource-rich nations, or from those with established mineral processing and refining capacity. Despite the limitations and potential inaccuracy of trade data, it is clear that the UK currently imports a range of battery minerals and derived products for use in a range of industrial applications. It is also apparent that the estimated UK battery mineral demand requirements in 2030 far exceed current UK import levels for all of the battery minerals. For example, to meet estimated UK demand for nickel, manganese and graphite in 2030, based on the battery chemistries that UK gigafactories currently plan to manufacture, would require a 12-, 8- and 6-fold respective increase in current imports of sulphates of nickel, manganese dioxide and graphite. Import data on battery raw materials highlights the UK's high dependence on China for cobalt and related products, as well as for natural and artificial graphite. Where the trade data indicate a European source of UK imports, these materials are likely to have originated in another country via large entrepôts such as Antwerp or Rotterdam. However in this study, this level of detailed analysis of battery mineral supply chains has not been undertaken. A major factor that the UK needs to consider when assessing the risks associated with its import dependence are the potential trade barriers that could disrupt existing global supply chains.

Global competition for battery minerals: analysis of the key global importers of the battery minerals highlights major consuming countries with which the UK will potentially be competing for supplies. Major consumers of lithium are South Korea, China and Japan. Japan also accounts for almost half of the global imports of sulphates of nickel. Global imports of cobalt are overwhelmingly dominated by China, although South Korea is the world's largest importer of cobalt oxides and hydroxides. China and Malaysia are respectively the world's largest importers of natural and artificial graphite. The dominance of certain countries in the Asia-Pacific Region as consumers of battery minerals is clear.

Can primary supply match the projected levels of demand for battery minerals? A significant ramping-up of primary production of battery minerals is required to meet projected UK and global demand in 2030 and beyond. Although long-term geological availability is not an issue, bringing adequate new supply on-stream in the near term may be problematic. High production growth rates for certain battery minerals have been achieved over the last 5–10 years as a result of increased mining and/or refining. However, it is uncertain if such rates can be maintained in the future, particularly when Environmental, Social and Governance (ESG) performance is now, and will continue to be, a key consideration for western consumer-facing OEMs.

Faced with this rapid increase in demand for batteries, thus far there has been inadequate investment in developing capacity for the extraction and refining of new battery minerals, with the majority of global mineral exploration and development investment remaining focussed on other commodities such as gold and copper. In addition, there has been a disproportionate focus on research, innovation and investment in the downstream parts of the battery value chain (e.g. on battery design, recycling and developing manufacturing capacity). The development of new mining projects is subject to a wide range of vulnerabilities and risk, leading to a very high rate of failure. As with many other mineral commodities, long lead times for many battery mineral mining projects exacerbate the risk of a mismatch in timing between projected demand and the mining industry's ability to bring new supply online.

The International Energy Agency (IEA) presents data on projected production levels for lithium and cobalt to 2030. These are based on current mining operations and those in the development pipeline. Comparison with projected global demand for these minerals under the IEA STEPS and Sustainable Development Scenario (SDS) provides an indication of when potential supply deficits can be expected based on the underlying assumptions. Time constraints mean that our study has not been able to assess the global pipeline of new battery mineral mining and processing projects and their economic viability. Such an analysis would permit a quantitative assessment of the supply¬-demand balance and potential deficits.

The role of recycling: several companies have announced plans to establish battery material recycling facilities in the UK. Significant capacity could be in place as early as 2024, and by 2040 the UK is expected to have a well-established battery recycling ecosystem. However, several factors (such as that the average EV battery lasts more than a decade and these batteries can then go on for use in 'second life' applications) constrain the amount of recycled metals available solely from end-of-life (EOL) vehicles up to 2035. Manufacturing scrap, derived from the UK's planned gigafactories, represents a much more important near-term source of supply. The APC estimate that this type of scrap could generate up to 20 kt of reusable cathode active materials for the UK market in 2030 (sufficient to produce 7 GWh of new batteries). In common with global assessments, it is not until 2040 that recycling makes a significant contribution to total supply. At this time it is estimated that 235 kt of waste battery materials will be available in the UK (sufficient cathode active materials to produce 60 GWh of new batteries) (APC, 2022b). Irrespective of the recognised benefits that recycling brings from an environmental and security of supply perspective, it will become an imperative for the battery manufacturing sector, owing to extended producer responsibility regulations, and the EU Battery Regulations that proposes from 2030 that new batteries must contain mandatory minimum levels of recycled content of cobalt, lithium and nickel.

Supply chain risk: the international supply chains, on which the UK is currently dependent for its supplies of battery minerals, are complex, dynamic, and generally have poor end-to-end visibility. As a consequence, the UK is vulnerable to supply disruptions arising from geopolitical, economic, environmental and social issues. The principal areas of supply chain risk include:

i. *Geopolitical factors*: global mining and refining of lithium, nickel, cobalt, manganese and graphite is typically concentrated in three countries or fewer. For example, more than 60 per cent of world mine production of cobalt is from the DRC, a country with a history of political and economic instability and civil unrest; China accounts for 65 per cent of global refined cobalt output. The Indonesian government's ban on unprocessed nickel ore exports in 2014 resulted in a significant reduction in supply of this metal.
ii. *ESG*: battery mineral production has environmental and social impacts, which may influence the development of new projects and existing supply. For example, there are concerns about the potential impacts of lithium brine extraction on water stress in some arid regions; and artisanal and small-scale mining is an important contributor to cobalt supply from the DRC, but has been linked to reports of human rights abuses. Concerns about the environmental impact of minerals extraction in some countries have led to short-term reductions in the production of certain minerals.

iii. *By-product status*: certain battery metals are mostly by-products of the mining of other minerals. For example, cobalt is predominantly mined as a by-product of copper and nickel production.
iv. *Price volatility*: several factors, including those summarised above, contribute to relatively high levels of price volatility for most battery minerals: lithium has displayed the greatest price volatility in the past six years, reaching 50 per cent in 2016; closely followed by cobalt, which exceeded 45 per cent in 2019. Price volatility represents one of the greatest risks for UK battery manufactures, given that minerals represent the majority of total LIB production costs.

Domestic production capacity and international trade: there has been no systematic exploration for battery minerals in the UK, and the scale of potential resources is highly uncertain. Based on current knowledge and recent developments the greatest potential for domestic production appears to be associated with lithium and nickel, with possible by-product cobalt.

Battery mineral resource development is most advanced in south-west England, where companies are actively exploring and have commissioned pilot-scale plants to produce battery-grade lithium. However, future commercial production levels and the timescales for realising these remain uncertain. If it is of sufficient scale, domestic production would bring significant security of supply benefits. The emphasis that UK developers are placing on sustainable and environmentally responsible extraction processes will greatly enhance the environmental performance of UK battery mineral supply chains. This is significant as the rising importance of ESG issues will place increasing pressure on OEMs and their mineral suppliers to improve their performance. Plans to establish significant lithium refining capacity in the UK would also contribute to reducing security of supply risk. However, the announced large-scale facilities are predicated on imported feedstocks with their own supply vulnerabilities. It is notable that the UK produces a significant quantity of specialty graphite and anode grade petroleum coke. Although currently most of this is exported, this material could potentially support domestic battery supply chains.

Despite the potential for commercial-scale domestic production of certain battery minerals, the scale of local demand and the variety of minerals required means that UK will remain heavily-dependent on international trade for the majority of its battery mineral needs, particularly in the period up to 2030. As such, it will be vital to develop new strategic trade links with established mineral producing countries that have significant undeveloped battery mineral resources and strong ESG credentials. It is very likely that these countries will be seeking to capitalise on growing global demand for critical minerals to support their own economies (for example, Canada and Australia). It is also important to explore opportunities in low- and middle-income countries with which the UK has strong existing links. Countries that are well-endowed with resources of battery minerals, and are seeking to develop these resources in a sustainable way would be favoured trading partners with the UK.

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