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# A UK foresight study of materials in decarbonisation technologies: the case of batteries

Decarbonisation and Resource Management Programme

Open report CR/24/007N

Department for
Business & Trade

British
Geological
Survey

BRITISH GEOLOGICAL SURVEY
DECARBONISATION AND RESOURCE MANAGEMENT PROGRAMME
OPEN REPORT CR/24/007N

# A UK foresight study of materials in decarbonisation technologies: the case of batteries

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Keywords: foresight, critical minerals, decarbonisation, batteries, electric vehicles

Front cover: solarseven. 2021. Charging Up An Electric Car At Night stock photo. iStock.

Bibliographical reference: Petavratzi, E, Josso, P, Shaw, R, Horn, S, and Singh, N. 2024. A UK foresight study of materials in decarbonisation technologies: the case of batteries. British Geological Survey Open report, CR/24/007N. 48pp.

Keyworth, Nottingham British Geological Survey 2024

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# 1 Introduction to battery technology

Batteries are an important enabler for the electrification transition. A battery is a device that produces electrical energy from the conversion of chemical energy (European Union, 2023). They may be non-rechargeable (primary batteries) or rechargeable (secondary batteries or battery accumulators). They are used in numerous applications, such as portable electronic devices, electric vehicles (EVs), medical equipment and power tools. Many types of battery cell are currently used in rechargeable and non-rechargeable batteries according to the specific application (European Union, 2023, Recharge, 2024). Each is manufactured from a range of raw materials.

This study deals only with rechargeable batteries.

## 1.1 PRINCIPLES OF OPERATION

The battery cell represents the basic functional unit in a battery. It consists of a negative (anode) and positive (cathode) electrode, together with a separator that isolates the two electrodes. These are submerged in electrolyte to promote the movement of ions (Battery University, 2021). During the release of energy (discharge), ions move from the anode to the cathode and the ions move back to the anode during a charge. The configuration of a rechargeable battery and its essential parts are illustrated in Figure 1.

The performance of a battery is described in terms of two parameters: the energy density and the power density. The energy density describes the amount of energy a device can store per unit volume or mass (watt hours per litre, Wh/l, or watt hours per kilogram, Wh/kg). Batteries with higher energy density can store more energy in a particular volume and they are therefore suitable for applications where space or weight are at a premium. The power density is a measure of the maximum power that a battery can return based on its mass (watts per kilogram, W/kg). Applications that require rapid charge and discharge, such as electric vehicles and other mobile applications, benefit from high power density (Borah et al., 2020, QuantumScape Corporation, 2023).

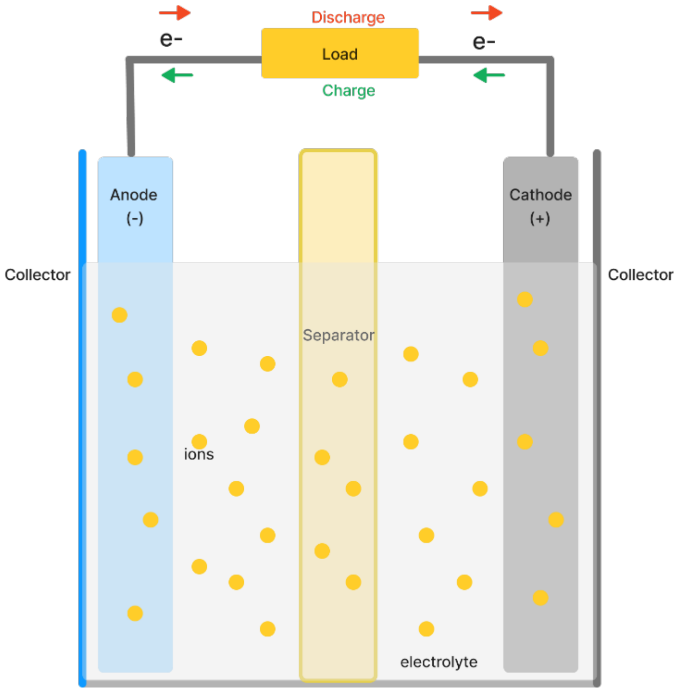


**Figure 1** Simplified structure of a rechargeable battery cell. © UKRI, 2024.

Lithium-ion batteries (LIBs) are now the preferred choice for most applications because of their high level of performance and safety. However, several other types of battery cell, such as nickel-cadmium (Ni-Cd) and nickel metal hydride (NiMH), dominated the market until recently. Several new battery chemistries are in development and are expected to compete against LIBs, including sodium-ion batteries (SIB), lithium-sulfur (Li-S) batteries and solid-state batteries (SSB). This report focuses on rechargeable batteries used by the automotive sector because they are currently the largest market for batteries and demand projections indicate rapid future growth (Neef et al., 2022).

LIBs include a range of different cell chemistries. Lithium (Li) nickel-manganese-cobalt oxide (NMC) cathode cell chemistries currently dominate the EV market, although there have been significant changes in the proportions of the metals used in the last five years. The most notable shift has been a reduction in the proportion of cobalt (Co) used in the cathode. Co, a relatively expensive critical metal, has been increasingly replaced by nickel (Ni) to optimise the performance and reduce the cost of batteries (Gifford, 2022).

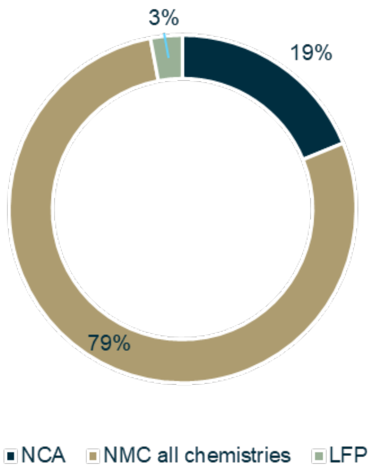


**Figure 2** European market shares of different LIB cell chemistries in 2020 (Gifford, 2022). The market share for SIBs and SSBs are zero. NCA: lithium nickel-cobalt-aluminium oxide; NMC, lithium-nickel-manganese-cobalt oxide; LFP: lithium-iron phosphate. Note: globally, LFP batteries have a much larger share of the market as it is the dominant cell type used in China. BGS © UKRI.

## 1.2 ESSENTIAL COMPONENTS AND MATERIALS

Although a wide range of materials is used in EV batteries, this study focuses on those materials that contribute to the functioning of the two dominant battery types: LIBs and SIBs (Table 1). The cathode and anode active materials are of greatest interest as they represent key constituents of the battery cell, many of which are deemed critical.

**Table 1** Elements used in battery technologies.

| Technology | UK critical elements | Other |
|---|---|---|
| LIB | Cobalt (Co), iron (Fe), lithium (Li), manganese (Mn), niobium (Nb), carbon (graphite), silicon (Si), titanium (Ti), | Aluminium (Al), copper (Cu), fluorine (F), nickel (Ni), phosphorus* (P) |
| SIB | Manganese (Mn), vanadium (V) | Copper (Cu), fluorine (F), sodium (Na), carbon (hard carbon) (C), nickel (Ni), phosphorus* (P) |

Elements in red are excluded from the analysis because they are used in structural components, pr they are not used in the most common configuration of the technology, or there are no data available on their use in batteries.

* Phosphorus is found in the electrolyte and in LFP cathodes, but it is only considered when participating as a cathode active material. See Appendix A for a list of excluded materials.

### 1.2.1 Lithium-ion batteries

Various battery chemistries are used in EVs, each providing particular benefits in terms of:

- vehicle range
- energy output (power)
- charging time
- battery lifetime
- security and safety
- autonomy
- costs
- ethical concerns around material sourcing

(Lusty et al., 2022)

Current LIB technologies for automotive batteries are mainly differentiated by the cathode active materials. Batteries with an NMC cathode accounted for 60 per cent of the global EV battery market in 2022 (International Energy Agency, 2023) and 79 per cent of the European market in 2020 (Figure 2) (Gifford, 2022).

NMC cathodes have varying proportions of No, Co and manganese (Mn) and their proportions to each other are shown in their name. For example, NMC111 has equal proportions of each metal ($LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$), whilst NMC955 has a higher Ni content compared to Co and Mn ($LiNi_{0.9}Mn_{0.05}Co_{0.05}O_2$). The overall trend observed in LIB cathodes is towards lower Co and higher Ni chemistries. The higher Ni content in NMC cathodes increases the energy density of the battery, which in turn increases the vehicle range and energy output (Lusty et al., 2022).

Co allows for a more stable structure and prevents the thermal runaway associated with Ni-rich compositions, which is the main reason why this metal has not yet been fully eliminated from cathodes (Greenwood et al., 2021). In addition, the reduction of Co in NMC cathodes is important to battery manufacturers and original equipment manufacturers because it lessens the cost and price volatility issues related to Co. The association with Co supply from unregulated, unauthorised and unsafe mining in the Democratic Republic of the Congo (DRC), the largest global producer, is also reduced (Borah et al., 2020, Petavratzi et al., 2019).

NCA cathodes had an estimated European market share of about 19 per cent in 2020 (Gifford, 2022). Only the American car maker Tesla currently uses this chemistry. As with NMC, NCA cathodes have a high energy density due to their high Ni content; they also offer long life cycles, but some safety issues have been observed (Lusty et al., 2022). A variant of this technology currently being investigated incorporates Mn to increase thermal stability (NMCA) (Marie and Gifford, 2023).

Lithium iron phosphate (LFP) LIB cathodes represented only 3 per cent of the European market in 2020 (Gifford, 2022) but are the dominant battery type in China (International Energy Agency, 2023). Western car makers such as Tesla are now increasingly implementing the use of LFP chemistry due to its cost and safety advantages compared to Ni chemistries (International Energy Agency, 2023). LFP batteries have long life cycles and good thermal stability but have comparably low energy densities, making them less attractive for premium EVs due to shorter driving ranges and smaller power output.

Graphite comprises the dominant anode active material in LIBs and it is likely to remain the preferred material for the time period considered in this study. However, for high-Ni cathode chemistries, the use of a graphite-silicon-doped anode is also possible. Exploration into the potential use of pure silicon (Si) and graphite-Si anodes is under development, for instance by Tesla. Other alternative anode materials, such as lithium titanate oxide (LTO) and niobium (Nb)-based chemistries are also promising for fast-charging batteries, but their market penetration is uncertain and possibly small for the timescales considered in this assessment (Rho Motion, 2023).

### 1.2.2 Sodium-ion batteries

SIBs are an alternative battery technology where sodium (Na) replaces Li and alternative cathode and anode active materials are used. This lowers material costs substantially and enables more sustainable sourcing compared to currently dominant battery materials such as Li, Co and graphite (Degen et al., 2023). The technological similarity with LIBs means that existing battery manufacturing infrastructure could be modified to produce SIBs (Degen et al., 2023).

A variety of cathode-active materials may be used in SIBs. For example, layered oxide cathodes consist of Na-metal oxides where the metal is commonly Ni or Mn, with some variants also using Co or iron (Fe) (Degen et al., 2023). Other popular cathode materials are Prussian blue analogues (PBA) and Prussian white (Sun and You, 2023). Polyanionic materials are also an important group of SIB cathodes, commonly used as a sodium-iron-vanadium phosphate variant (Degen et al., 2023).

Although these cathode types are being trialled in SIBs there is considerable uncertainty over their future commercial development. Only mixed layer oxide cathodes and PBAs have been evaluated in this analysis. Nevertheless, it should be noted that, if PBAs become predominant, Ni and Mn demand will be reduced, while uptake of sodium-vanadium phosphate variants would likely increase demand for vanadium (V).

Unlike LIBs, where the dominant anode material is graphite (crystalline carbon), hard carbon (amorphous carbon) is the main anode material in SIBs. This is relatively easy to manufacture from various biomass materials (Liu et al., 2022). The amorphous structure of hard carbon is also more amenable to the incorporation of Na ions than natural graphite.

There are currently some Na-ion manufacturing plants in operation or under development, chiefly in China, with over 100 GWh capacity planned for 2030. This is less than 1 per cent of current LIB manufacturing capacity (Benchmark Mineral Intelligence, 2023b).

# 2 Supply chain mapping of batteries

Eight raw materials key to the battery supply chain were selected for detailed mapping. The different stages of the battery supply chain are depicted in Figure 3, along with the material transformations that occur at each stage. Some intermediate material transformation steps were excluded in order to focus the analysis on those materials and components with the greatest likelihood of supply disruption (for example, Ni ore and nickel sulfate are included, but the ore is first refined into Ni metal, which was not considered). Raw materials and intermediate products excluded from the analysis are listed in Appendix A.

NMC cathodes require Li as well as various proportions of Ni, Co and Mn (International Energy Agency, 2023). Sulfate chemicals are the preferred form of these metals for the manufacturing of cathode active material, but other forms can also be used.

LFP batteries require Li, Fe and phosphorus (P). P is predominantly used as fertiliser in agriculture, while only three per cent of phosphate is refined into the purified phosphoric acid ($H_3PO_4$) required for the battery industry (Benchmark Mineral Intelligence, 2023a).

NCA cathodes require Ni and Co as well as aluminium (Al). While Al is a key part of NCA cathodes, it was excluded from this analysis due to a lack of material intensity data. Also, the amount of Al in the cathode is negligible compared to Al in the structural components of the battery (for example, foil; casing) which are outside the scope of this analysis. Mn is also used in an NMCA variant, but NCA is the dominant chemistry of this type (Advanced Propulsion Centre UK, 2022a).

Li is required for all but Na-ion batteries. Li is produced from hard rock deposits, in which spodumene is the dominant Li-bearing mineral, and from continental brines. Li brine and spodumene are refined into battery-grade lithium carbonate ($Li_2CO_3$) and lithium hydroxide (LiOH), which are the precursors for cathode active materials.

The main anode material currently in use is graphite, which is produced from natural flake graphite or synthetically from needle coke, a by-product of petroleum and coal refining. There is a trend towards doping the graphite anode with small amounts of Si (up to 8 per cent by weight), to increase the energy and power density of the battery cell. This is already used by several battery makers (Asenbauer et al., 2020, International Energy Agency, 2023). Research into developing Si anodes without graphite is also in development, but has not been commercially used to date (Rho Motion, 2023).

SIBs are an alternative battery technology that is relatively cheap and uses fewer critical materials than LIBs: for example, Na replaces Li and hard carbon replaces graphite (Degen et al., 2023). Na is used in the form of sodium carbonate ($Na_2CO_3$), mainly produced from natural salt resources (sodium chloride) (Degen et al., 2023), but it can also be extracted from natural $Na_2CO_3$ deposits and continental brines.

While there are several cathode materials in development for SIB, this study only considers PBAs and Ni-Mn layered oxides in the supply chain analysis, as these have the greatest commercial potential. CATL, the largest battery manufacturer in China, uses a PBA specifically in the form of Prussian white (Gupta et al., 2022, Sun and You, 2023), while layered oxide cathodes are used by various companies, including the UK-based Faradion (Degen et al., 2023).

Hard carbon is the dominant type of anode material in SIBs and is manufactured from various biomass sources such as cellulose, sugar and resins (Degen et al., 2023).

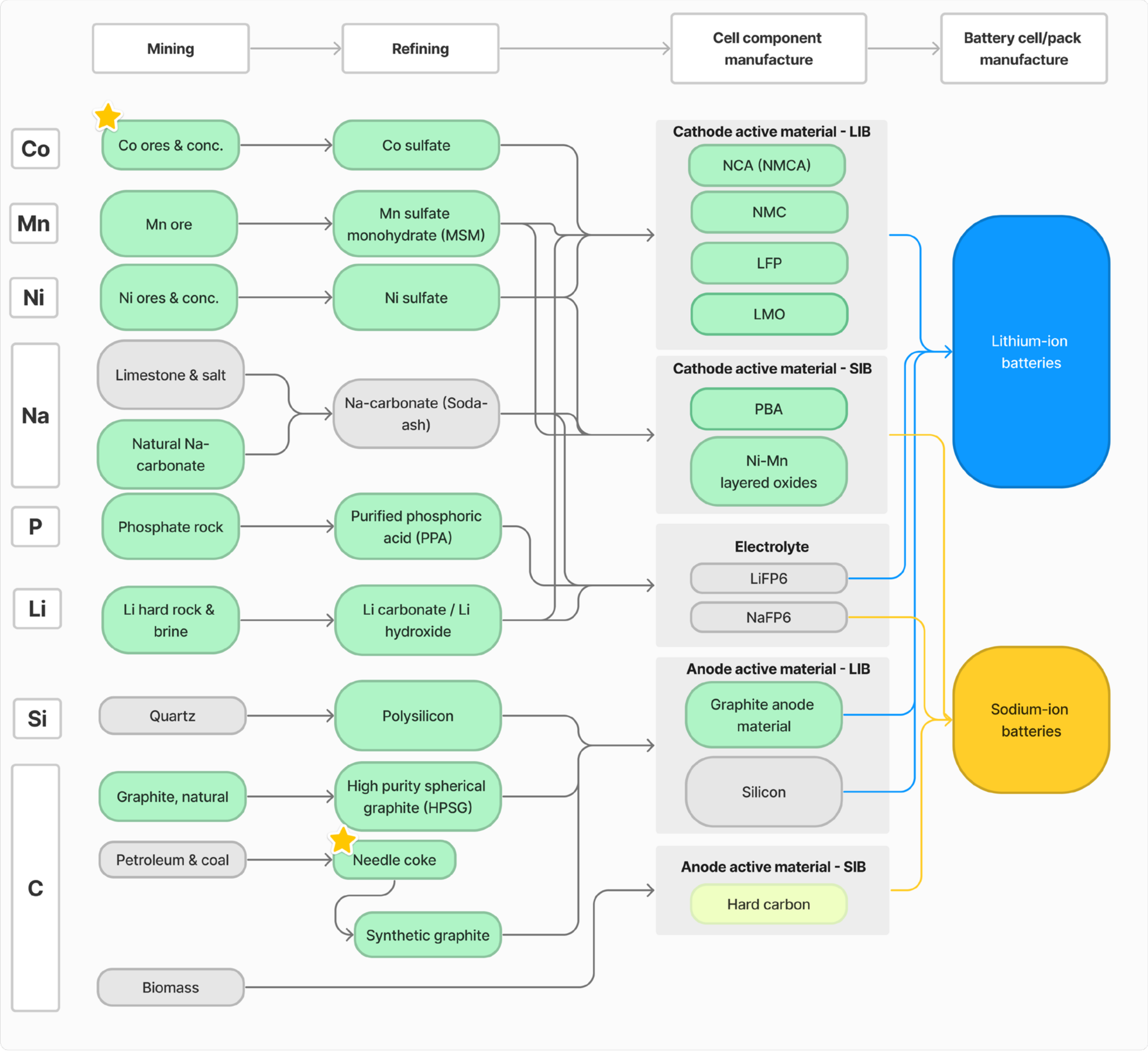


**Figure 3** Supply chain mapping of automotive batteries, key raw materials and components. The green shading indicates materials that have been included in the analysis. A star indicates a material produced as a by-product in the mining or refining stage. The lime green shade indicates a material that was only partially analysed. Co: cobalt; Mn: manganese; Ni: nickel; P: phosphorus; Li: lithium; C: carbon; Si: silicon; Na: sodium; NCA: nickel-cobalt-aluminium oxide; NMCA: nickel-manganese-cobalt=aluminium oxide; NMC: nickel-manganese-cobalt; LFP: lithium-iron phosphate; LMO: lithium-manganese oxide. BGS © UKRI.

# 3 Supply chain bottlenecks

The automotive battery supply chain includes many different raw materials that undergo complex processing and manufacturing stages before they are assembled into battery cells and packs. In many cases, the production of the mined and refined material is concentrated in a few countries, thereby increasing the risk of supply disruption (Figure 4). A similar trend is observed for the midstream and downstream LIB value chain, where the dominance and vertical concentration of Asian countries is apparent (Figure 4).

SIB development is in its very early stages, so it is difficult to predict the dominant nations at present.

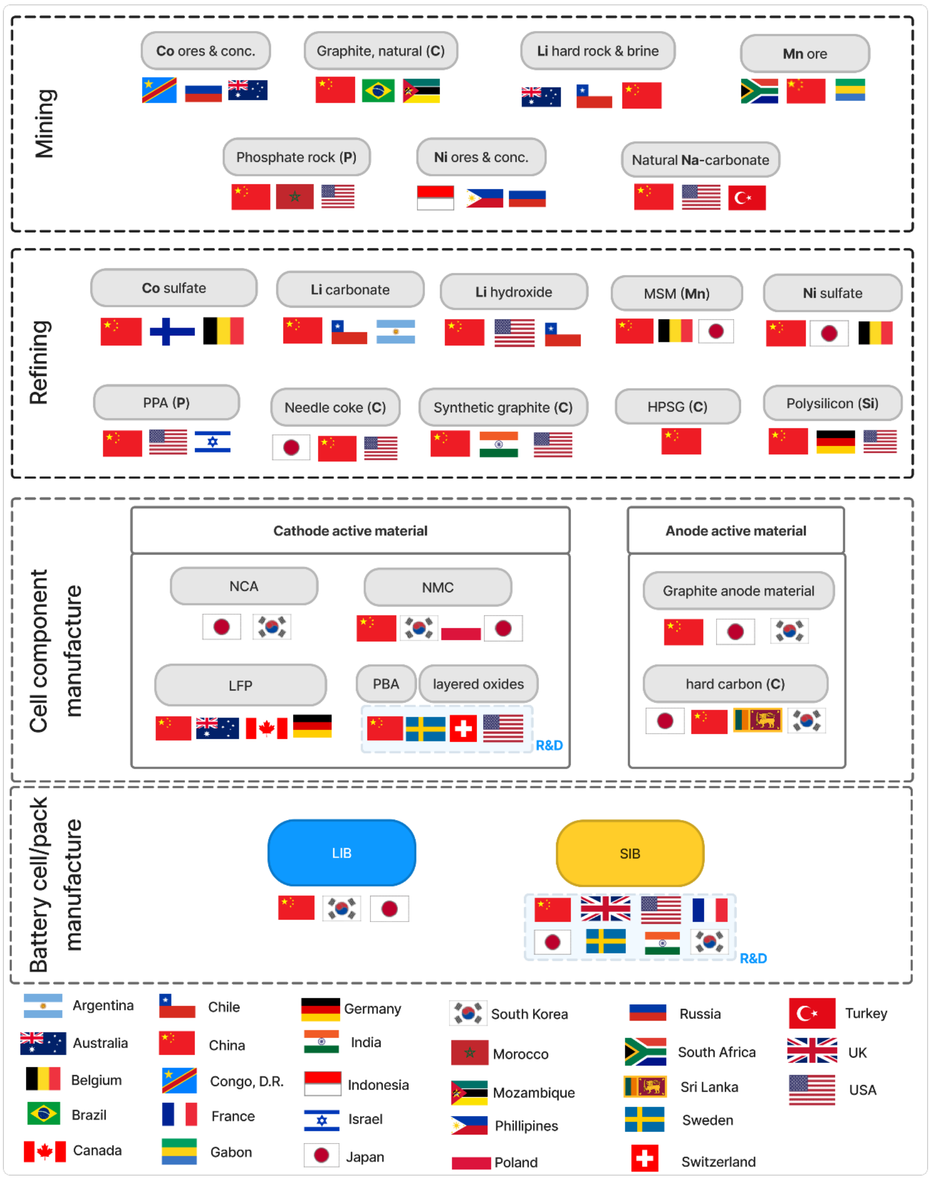


**Figure 4** Geographical production concentration in the automotive battery supply chain. At the mining and refining stages, the national flags show the top three producers, from left to right, based on data from Benchmark Mineral Intelligence (2024) and 2021 production from the BGS World Mineral Statistics Database (BGS, 2023). At the precursor/component production and battery cell/pack manufacturing stages, the flags highlight the location of key producers and players, but their order does not reflect their respective market share. Data compiled and interpreted from Degen et al. (2023), Hampel (2023), International Energy Agency (2022), Liu et al. (2022), Obayashi and Evans (2023), Venditti et al. (2022), Volta Foundation (2023). BGS © UKRI.

## 3.1 MINING AND REFINING

### 3.1.1 Production concentration

The global production share of materials used in the manufacture of LIBs was calculated for the top three producing countries at both the mining and refining stages of the supply chain. Some raw materials have been excluded from this study because of a lack of data of suitable quality and resolution. For example, quartz has been excluded as mine production data for the high-purity feedstock materials (for example, quartzite) required to produce metallurgical Si are unavailable. Likewise, production data for limestone, a feedstock material in the production of synthetic $Na_2CO_3$, are unavailable at the global scale.

At the mining stage, seven materials were considered:

- Co
- Li
- Mn
- Ni
- phosphate rock
- natural graphite
- natural $Na_2CO_3$

Production of all these materials is concentrated, with the top three producing countries accounting for more than 50 per cent of global production in each case. Of these, the production of natural $Na_2CO_3$, Li and natural graphite are extremely concentrated, with the top three producers accounting for more than 75 per cent of the global total (Figure 5). For example, 99 per cent of mine production of natural $Na_2CO_3$ originates from only three countries (China, the USA and Türkiye), with the single largest producer (China) producing more than 60 per cent (Figure 5).

China has a significant presence at the mining stage of all the materials analysed and is the single largest producer of natural graphite (64 per cent), phosphate rock (42 per cent) and natural $Na_2CO_3$ (65 per cent), whereas mine production of Co is dominated by DRC (67 per cent) and mine production of Ni by Indonesia (32 per cent).

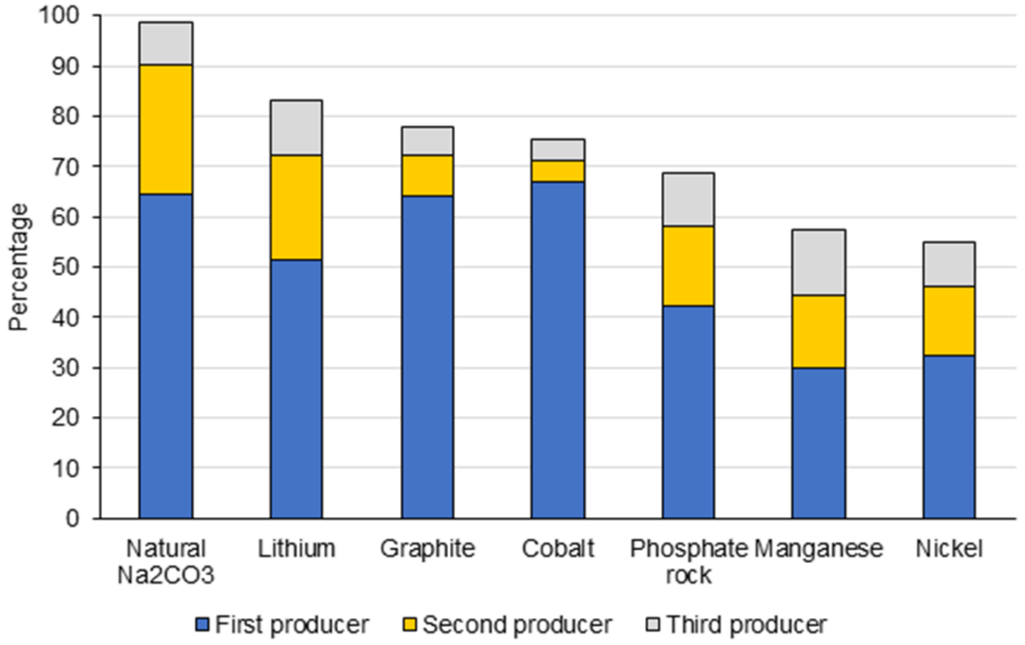


**Figure 5** Global mine production of natural $Na_2CO_3$, Li, natural graphite, Co, phosphate rock, Mn and Ni, showing the production shares of the top three producing countries. Data from the British Geological Survey World Mineral Statistics Database (BGS, 2023). BGS © UKRI.

Ten materials were evaluated at the refining stage:

- needle coke
- cobalt sulfate ($CoSO_4$)
- nickel sulfate ($NiSO_4$)
- $Li_2CO_3$
- LiOH
- synthetic graphite
- spherical graphite
- high-purity manganese sulfate monohydrate (HPMSM)
- high-purity $H_3PO_4$ (HPPA)
- Si metal (a proxy for polysilicon)

BGS does not gather production data for these highly refined materials, except for Si metal. The analysis was therefore conducted using global percentage share data supplied by Benchmark Minerals. Synthetic $Na_2CO_3$ (soda ash) was excluded because of a lack of data. It should also be noted that data for Si metal do not distinguish between low-purity (metallurgical grade, about 98 per cent Si) and high-purity (electronic grade, 99.9999 per cent Si, also referred to as 6N) production. Nevertheless, the inclusion of these data serves to identify the main global sources of Si metal.

The production of seven of the ten materials assessed is highly concentrated, with more than 80 per cent of global supply derived from three countries (Figure 6). Of these, spherical graphite, $CoSO_4$ and HPMSM are the most concentrated, with the top producer (China) accounting for more than 90 per cent of global production in each case. The production of needle coke, HPPA and synthetic graphite are less concentrated, although the top three producing countries in each case still account for more than 70 per cent of global production.

The production of $Li_2CO_3$ and needle coke are both highly concentrated but the share of production held by each of the top three producers is relatively evenly spread: the top three producers of needle coke are Japan (33 per cent of global total), China (22 per cent) and the USA (22 per cent) (Figure 6). In contrast, the top three producers of $CoSO_4$ are China (94 per cent of global total), Finland (5 per cent) and Belgium (2 per cent).

China is the leading producer of nine out of the ten materials assessed at the refining stage:

- spherical graphite (100 per cent of global total)
- $CoSO_4$ (94 per cent)
- HPMSM (91 per cent)
- Si metal (78 per cent)
- LiOH (70 per cent)
- NiSO4 (67 per cent)
- HPPA (63 per cent)
- synthetic graphite (55 per cent)
- $Li_2CO_3$ (46 per cent)

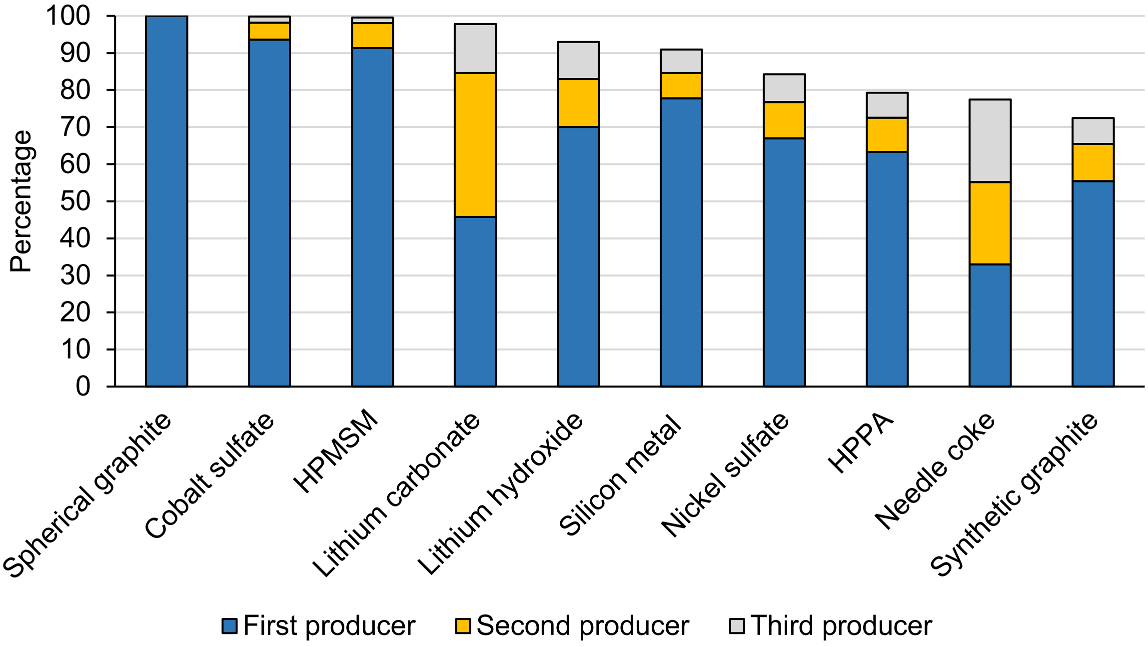


**Figure 6** Global refined production of key materials used in batteries, showing the production shares of the top three producing countries. Except for Si metal (BGS, 2023) all data are from Benchmark Mineral Intelligence (2024). BGS © UKRI.

The production concentration calculation is based on the indicator recommended in the revised methodology for the UK criticality assessment (Josso et al., 2023). This is derived from the production shares of the leading producers modified by a factor that reflects the environmental, social and governance (ESG) performance of those countries.

Generally, production concentration scores for LIB materials are lower at the mining stage than at the refining stage, which is largely a reflection of the lower production shares held by the top producers (production is more diversified). Production concentration scores for refined materials vary widely; some are very high on account of extreme concentration of production and poor ESG scores for the top producers. For example, spherical graphite scores 10.0 because 100 per cent of global production takes place in only one country (China), which has an intermediate ESG score. In contrast, Li ores and concentrates score 2.6 because even though production is highly concentrated (Figure 7), two of the top three producing countries (Australia and Chile) have good ESG scores.

The dominance of China in the upstream battery supply chain is very clear. China is one of the top three global producers of five of the seven materials assessed at the mining stage and, at the refining stage, is the leading producer of nine of the ten materials analysed.

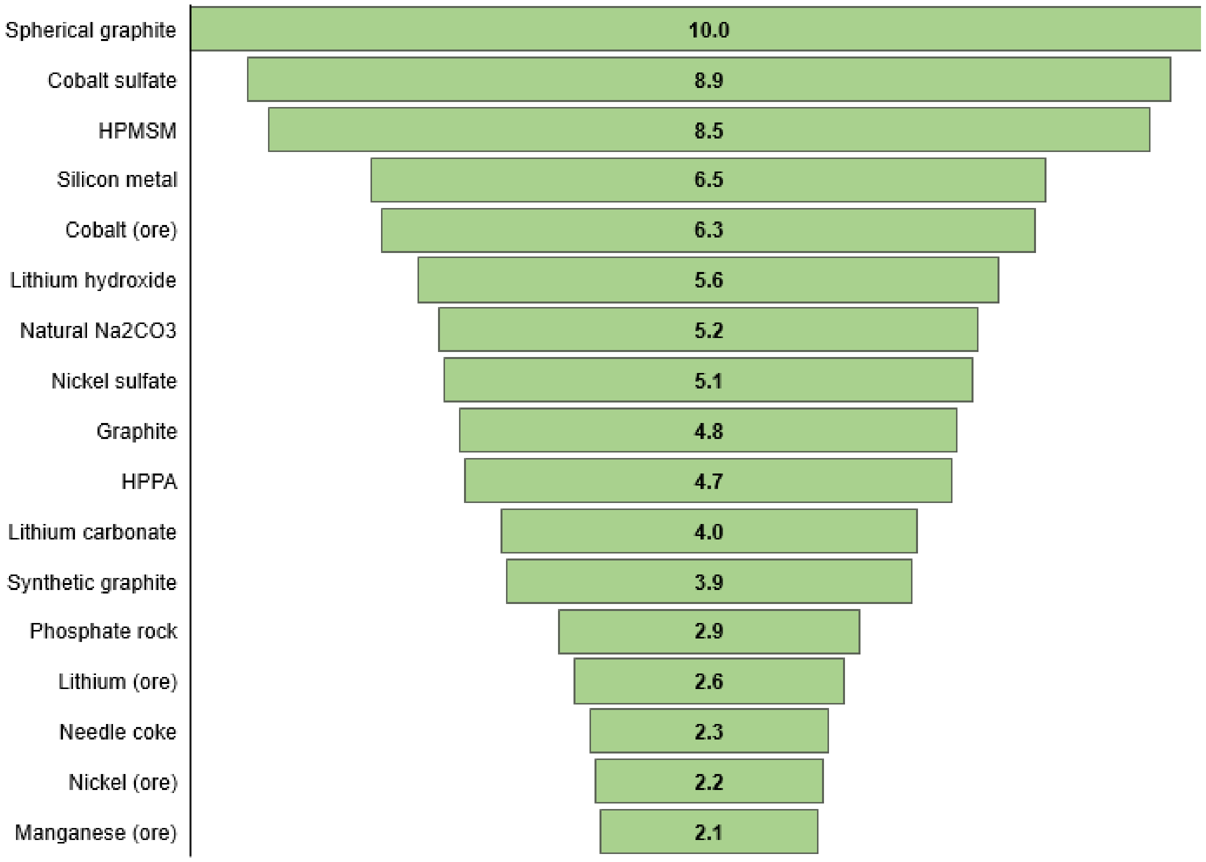


**Figure 7** Ranked production concentration scores for key materials (mined and refined) used in battery technologies based on an ESG-weighted Herfindahl-Hirschman index for each of the top three producing countries. Mined materials (Li, Mn, Ni and phosphate rock) have lower scores on account of their more diverse supply base. Refined metals of greatest concern are those where production is highly concentrated in countries with poor ESG scores. BGS © UKRI.

### 3.1.2 Global trade concentration and trade restrictions

As with the production of mined and refined materials used in the manufacture of LIBs, their trade is geographically concentrated (Figure 4) and may be subject to restrictions imposed by trading nations. It is important to note that the trade data for some of the materials used in LIBs (ores and refined metals) are not available or are reported at too low a resolution to be useful. For example, trade data for some LIB materials are highly aggregated, meaning several commodities are reported under a single Harmonized System (HS) trade code. For example, $CoSO_4$ is reported under a single code along with several other metal sulfates. This makes it impossible to ascertain the amount of $CoSO_4$ that is traded.

A summary of the HS trade codes used to assess trade concentration is given in Table 2.

**Table 2** Six-digit HS trade codes used to assess trade concentration of materials used in the manufacture of batteries.

| HS code | Description | Stage |
|---|---|---|
| 250410 | Natural graphite in powder or in flakes | Mining |
| 251010 | Natural calcium phosphates and natural aluminium calcium phosphates, natural and phosphatic chalk, unground | Mining |
| 260200 | Manganese ores and concentrates, incl. ferruginous manganese ores and concentrates, with a manganese content of >= 20%, calculated on the dry weight | Mining |
| 260400 | Nickel ores and concentrates | Mining |
| 260500 | Cobalt ores and concentrates | Mining |
| 280461 | Silicon containing >= 99,99% by weight of silicon | Refining |
| 280920 | Phosphoric acid; polyphosphoric acids, whether or not chemically defined | Refining |
| 282520 | Lithium oxide and hydroxide | Refining |
| 283324 | Sulphates of nickel | Refining |
| 283620 | Disodium carbonate | Refining |
| 283691 | Lithium carbonates | Refining |
| 750210 | Nickel, not alloyed, unwrought | Refining |

Trade of mined materials in the LIB supply chain has been assessed for Co, Mn, Ni, phosphate rock and natural graphite (Figure 8).

Global exports of Mn ores and concentrates are highly concentrated, with the top three countries accounting for more than 80 per cent of global exports. South Africa is the single largest exporter of Mn ores and concentrates, accounting for 49 per cent of the global total. Imports of Mn ores and concentrates are similarly concentrated, with the top three trading nations accounting for more than 75 per cent and the single largest importer (China) accounting for 50 per cent of the global total. Gabon, the second largest exporter of Mn ores and concentrates, currently applies an export tax (3.5 per cent of the total trade value) and a fiscal tax (up to 5 per cent of the trade value) on its exports of Mn ores and concentrates.

Exports of Co ores and concentrates are extremely concentrated, with the top three trading nations accounting for more than 95 per cent of the global total. DRC dominates exports of Co ores and concentrates, accounting for 91 per cent of the global total. There are many active trade restrictions on exports of Co from DRC in the form of an export tax, a fiscal tax and a licensing agreement. Ninety-six per cent of imports of Co ores and concentrates are shared between three countries (China, Zambia and Morocco), with China being the single largest importing nation, accounting for 55 per cent of the global total.

Global trade of Ni ores and concentrates is also extremely concentrated, with 94 per cent of exports being shared between the top three trading nations (the Philippines, Indonesia and Zimbabwe) and 95 per cent of imports being shared between China (82 per cent), Japan (6 per cent) and South Korea (6 per cent). Two of the top three trading nations have active trade restrictions in place, with the Philippines applying a licensing agreement and fiscal tax (12 per cent of total trade value) to exports, while Indonesia currently applies an export prohibition to trade of Ni ores and concentrates.

Global imports of phosphate rock and graphite are generally less concentrated compared to Ni, Co and Mn. Sixty-four per cent of imports of phosphate rock are shared between India (33 per cent), the USA (19 per cent) and Brazil (12 per cent), while imports of graphite are less concentrated, with the top three nations accounting for 30 per cent of the total. Exports of phosphate rock are concentrated at a similar level to Mn, with the top three nations accounting for 84 per cent of the global total. Morocco is the single largest exporter (51 per cent of total). Exports of graphite are less concentrated, with 55 per cent shared between the top three exporters (China, Madagascar and Mozambique). According to Organisation for Economic Co-operation and Development (2020) there are currently no active trade restrictions on phosphate rock and graphite.

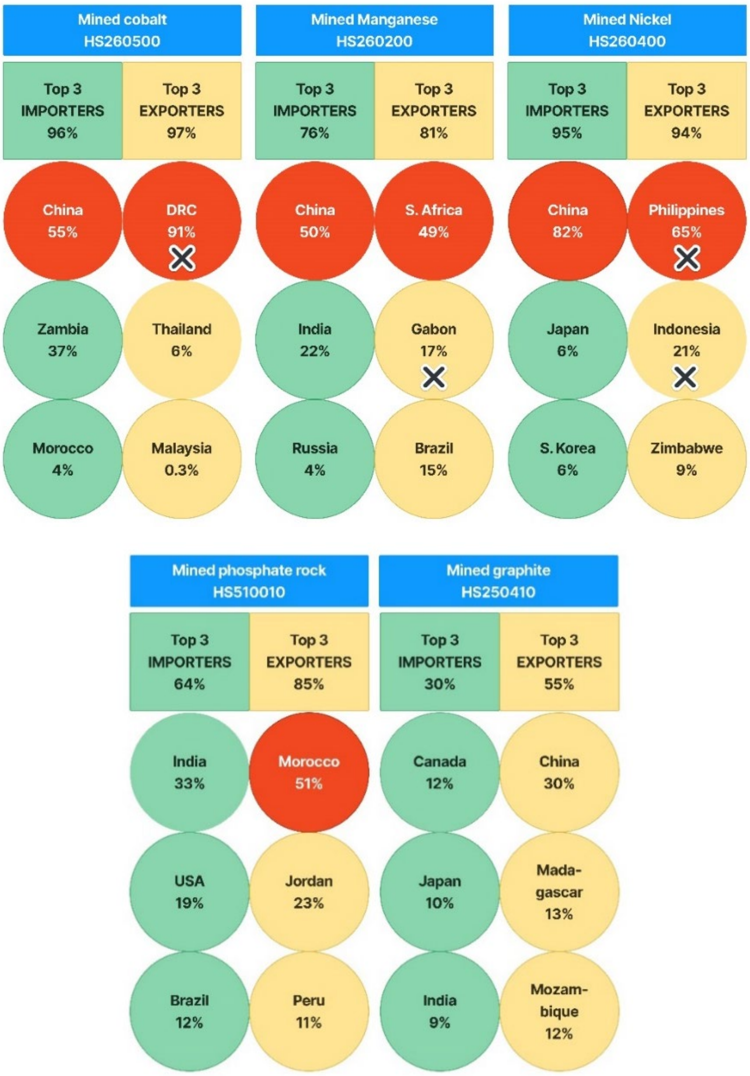


**Figure 8** The top three importing and exporting countries for mined Co, Mn, Ni, phosphate rock and graphite, with the share of global trade flows shown for each country. Countries highlighted in red are dominant exporters or importers (where global share exceeds 40 per cent) while countries with a cross have active trade restrictions. Compiled from UN Comtrade (2023) and Organisation for Economic Co-operation and Development (2020). BGS © UKRI.

Global imports of the refined materials required for LIBs are moderately to highly concentrated, with the top three importers accounting for between 27 per cent ($Na_2CO_3$) and 73 per cent (LiOH) of the global total (Figure 9). Of these, China is the single largest importer of refined Si (54 per cent of the global total), Japan is the single largest importer of $NiSO_4$ (42 per cent) and India is the largest importer of $H_3PO_4$ (52 per cent) (Figure 9). Global exports of these materials are similarly concentrated with the top three exporters accounting for between 48 per cent (Ni) and 90 per cent ($Na_2CO_3$) of the global total (Figure 9).

Chile is the single largest exporter of $Li_2CO_3$, accounting for 64 per cent of the global total, whilst Argentina is the second largest exporter at 14 per cent (Figure 9). Argentina currently applies an export tax (4.5 per cent of the total trade value) to its exports of $Li_2CO_3$. China accounts for

42 per cent of global exports of LiOH, followed by Canada (24 per cent) and Chile (8 per cent). There are currently no active trade restrictions on LiOH.

The USA is the single largest exporter of $Na_2CO_3$ (54 per cent of the global total), followed by Türkiye (24 per cent) and Bulgaria (12 per cent) (Figure 9).

The only other active trade restriction on these materials is a licensing agreement placed on exports of $H_3PO_4$ from Tunisia.

**Figure 9** The top three importing and exporting countries for refined Si, Ni, $Na_2CO_3$, NiSO4, $H_3PO_4$, Li2O and LiOH, and $Li_2CO_3$, with the share of global trade flows shown for each country. Countries highlighted in red are dominant exporters or importers (with a global share exceeding 40 per cent), whilst countries with a cross have active trade restrictions. Compiled from UN Comtrade (2023) and Organisation for Economic Co-operation and Development (2020). BGS © UKRI.

The key points derived from our analysis of the global trade in materials required for battery technologies are:

- China is the largest importer of Ni, Mn and Co ores and concentrates, accounting for more than 50 per cent of global imports in each case
- global exports of Ni and Co (ores and concentrates) are most concentrated, with the single largest exporters (the Philippines and DRC, respectively) accounting for more than 60 per cent of the global total in each case. (Both countries have also placed trade restrictions on exports of these materials)
- trade flows of materials required for LIBs are typically dominated by countries in Africa (DRC; Zambia), Asia (Japan; China) and South America (Brazil; Chile)
- imports and exports of the mined and refined materials required for LIBs are generally similarly concentrated, except for $Na_2CO_3$, where exports are about three times more concentrated (90 per cent) than imports (27 per cent)
- where trade restrictions are imposed, they are almost always applied to exports, with the most common restrictions being licence agreements or export taxes
- it is difficult to assess the direct impact of a particular trade restriction as this will depend on its type, magnitude and duration
    - imposition of a trade embargo or quota is likely to have a greater impact than levying an export tax for a short period
    - the dynamic character of export restrictions also contributes additional uncertainty to the supply chain
- the most significant risk to supply is where global trade is dominated by a few countries (for example, DRC accounts for 91 per cent of global exports of mined Co) and the risk may increase if restrictions are applied to trade
    - for example, China recently applied export licensing to refined gallium (Ga), which led to price increases and some international traders being cut out of the market (Minor Metals Trade Association, 2023).

## 3.2 COMPONENT AND PRODUCT MANUFACTURE

No quantitative data of battery cell component production was found for this study. However, the dominance of China and other east Asian countries is clear (Figure 4).

- NCA cathode active material is only used by the US company Tesla (International Energy Agency, 2022) and NCA cathode material is dominantly produced by Japanese and South Korean manufacturers (Hampel, 2023, Obayashi and Evans, 2023)
- NMC-based batteries are mainly used in European cars, but production of their precursors is dominated by China, which has approximately 85 per cent of the production capacity (Volta Foundation, 2023)
- Umicore is the only significant NMC producer in Europe with a production plant in Poland and headquarters in Belgium (Umicore, 2024)
- LFP-based batteries are widely distributed in China and LFP cathode active material is also chiefly manufactured in China (more than 90 per cent) (Volta Foundation, 2023)
    - many European and American car manufacturers plan to incorporate more LFP batteries into their future fleets
- graphite anode material is mainly produced in China (more than 80 per cent) while the remainder is manufactured in Japan and South Korea (International Energy Agency, 2022)

Active materials for SIBs are mainly produced in Asia. Cathode active materials for SIBs are not produced in large quantities, but companies in China, Sweden, Switzerland and the USA are expanding their capacity on PBAs and layered oxide cathodes (Degen et al., 2023). There are few hard carbon anode producers and they are mostly located in Japan and China (Figure 4). However, European companies in Sweden and Finland have been developing capacity with pilot-scale production at present (Liu et al., 2022).

# 4 UK supply chain in battery technology

While there are several activities in the UK that contribute towards the development of a domestic battery supply chain, most of these are still in development or are concerned with speciality products manufactured in small quantities. Nevertheless, there is a relatively large number of research activities and start-ups that advance innovation in battery technologies. The Advanced Propulsion Centre (APC) (Advanced Propulsion Centre UK, 2024) and the Faraday Institution (The Faraday Institution, 2024) play an important role in offering funding and networking opportunities between different actors in the automotive battery supply chain.

At the mining stage, there are a few projects aiming to extract Li in the UK. Cornish Lithium has two projects evaluating the recovery of Li from geothermal waters via direct Li extraction (DLE), and from Li-bearing micas in a hard-rock deposit at a former china clay quarry at Trelavour. A pilot DLE plant was commissioned in 2022 to test LiOH production and the company has secured funding for a demonstration plant at Trevalour (Cornish Lithium Plc, 2023).

Imerys British Lithium is also exploring a hard-rock Li deposit in Cornwall and was able to produce battery-grade $Li_2CO_3$ from Li-bearing micas at their pilot plant. The project has an inferred resource estimate of 161 million t at 0.54 per cent lithium oxide ($Li_2O$) (Imerys, 2023).

Northern Lithium is planning to use DLE to extract Li from geothermal waters and has drilled two initial boreholes at their project in County Durham (Northern Lithium, 2024). A similar project is being developed by Weardale Lithium, who have access rights to two geothermal boreholes in Weardale, County Durham, with plans to extract Li (Weardale Lithium, 2024).

At the refining stage, UK activities relating to Li include both operational and development projects. Arcadium Lithium in Bromborough, Merseyside (previously known as Livent) is the largest UK Li production site. Although their UK focus is on the production of butyllithium and organometallic compounds required for the polymer and pharmaceutical markets, their vertically integrated international operations make them an important UK player. They have interests ranging from Li mining, including full and part ownership of several salt flats in South America, to refining and product manufacture (Arcadium Lithium, 2024, Livent, 2024).

Leverton Lithium is the only current UK producer of battery-grade LiOH and $Li_2CO_3$, with facilities located in Basingstoke, Hampshire (Green Finance Institute, 2023, Leverton Lithium, 2024). Another two Li refineries are planned at the Teesside freeport in north-east England: Tees Valley Lithium, with a planned capacity of 96 000 t per annum LiOH and Green Lithium, with a capacity of 50 000 t per annum LiOH (Green Lithium Ltd., 2024, Tees Valley Lithium, 2022).

There is limited refining of Co in the UK. ICoNiChem, located in Widnes, Cheshire, produces various Co chemicals and nickel carbonate ($NiCO_3$) from feedstock imported from Türkiye. They also produce $CoSO_4$ that can be used in the battery industry, but the company mainly supplies other Co markets (for example, catalysts and tyres) (ICoNiChem, 2024a).

At Clydach, South Wales, the Brazilian mining company Vale operates a Ni refinery, transforming nickel oxide (NiO) into high-purity Ni powders and pellets. These products are dominantly used for Ni alloys, stainless steel and plating applications due to their high purity, but they can also be used as a battery component precursor (SFA Oxford, 2023, Vale, 2024).

These activities reflect progress towards the development of a UK battery supply chain. However, most are early-stage mine exploration and refining projects; additional investment is required in the upstream Li supply chain to contribute to supply in a timely manner.

The only producer of precursor battery raw material on a large scale in the UK is Phillips 66. Its petroleum refinery at the Humber estuary in Lincolnshire produces needle coke that can be used as a precursor of synthetic graphite (Phillips 66, 2024). However, this coke is exported overseas so there is no synthetic graphite production in the UK (Green Finance Institute, 2023).

$Na_2CO_3$ as a refined product for SIBs is currently produced by Tata Chemicals Europe in Northwich, Cheshire, chiefly for the glass industry (Tata Chemicals Europe, 2024), but a similar product could be used for precursors in the Na-ion supply chain.

There is a lack of capacity and investment in cathode and anode active material production in the UK, which is detrimental to the development of a domestic battery supply chain. Equally, cell manufacture is not available in the UK (Green Finance Institute, 2023). Nevertheless, there are a few companies that are working on next-generation active materials. These include the development of Nb anodes by two companies, Echion Technologies and Nyobolt, both based in Cambridgeshire, which show improvement in charging time and cycle life (Echion Technologies, 2024, Nyobolt, 2024) as well as the development of Si anodes by Nexeon in Oxfordshire, who have recently partnered with Panasonic (Lienert, 2023). Phillips 66 has partnered with the UK-based SIB start-up Faradion to develop hard carbon anode material (Fallas, 2021) and Deregallera, based in Caerphilly, Wales, has also developed a hard carbon anode and is working on developing a SIB cell for energy storage (Deregallera, 2024, Fallas, 2021).

The UK is better positioned in Li electrolyte production; Mitsubishi Chemical Group in Billingham, County Durham, is one of only two significant producers in Europe (Advanced Propulsion Centre UK, 2022b). Mitsubishi Chemical Group is strategically well positioned in the vicinity of the Teesside freeport, where two new Li refineries are planned (Tees Valley Lithium and Green Lithium) (Mitsubishi Chemical Group UK, 2024).

Several planned UK gigafactories will ramp up battery supply to the UK and overseas car manufacturers. However, Envision Automotive Energy Supply Corporation (AESC) is currently the only operational large-scale facility. Their factory in Sunderland, Tyne and Wear, has a battery capacity of 2 GWh (Mckelvie and Bennett, 2023).

In addition:

- AESC plans to expand its production and build another gigafactory in Sunderland with an 11 GWh capacity
- Tata Motors Jaguar Land Rover Automotive Plc (JLR) announced in 2023 that it will build a 40 GWh plant in Bridgewater, Somerset, with plans to start production in 2026 (Tata Sons, 2023)
- Another gigafactory is planned in Coventry, West Midlands, with a planned capacity of 60 GWh; this West Midlands gigafactory is currently seeking investment from Asian battery manufacturers (West Midlands Gigafactory, 2023)

Other projects have not been successful, notably the gigafactory planned by Britishvolt, which filed for bankruptcy after failing to secure investment for their project in Northumberland (Mckelvie and Bennett, 2023).

Various smaller, UK-based companies are aiming to develop next-generation battery cells. These include Faradion and Amte Power, both evaluating SIBs, and Ilika, which is working on solid-state Li-ion batteries (Green Finance Institute, 2023).

With an increasing stock of electric vehicles in the UK, there will be an increasing number of end-of-life (EoL) batteries available that can be either re-used or recycled to support future supply of battery materials. The APC estimates that 28 000 t battery cell waste could be recycled from manufacturing scrap and EoL batteries by 2030 (Advanced Propulsion Centre UK, 2022c). However, most EoL batteries are currently recycled in mainland Europe as the quantities are too low for industrial-scale operations to be feasible in the UK (Green Finance Institute, 2023). Nevertheless, there are various companies and research projects in the UK that are looking into the re-use and recycling of batteries. Several companies such as Zenobe and Powervault are already taking on EoL batteries to be re-used in energy storage systems, while JLR also partnered recently with Wykes Engineering to re-use EoL Jaguar batteries (Jaguar Land Rover, 2023, Mason-Cottrell, 2022, Zenobe, 2024).

Recycling of EV batteries on an industrial scale only recently commenced. Recyclus in Wolverhampton, West Midlands, started operating in July 2023 and aims to process 8300 t LIBs per year (Dawkins, 2023), while Veolia operates a battery recycling plant in Minworth, West Midlands, currently with a capacity of 5000 t per year (Jersey Evening Post, 2023).

Other LIB recycling companies are:

- Altilium Clean Technology, Devon
- Cawleys, Milton Keynes
- RSBruce, Sheffield

The LIB recycling sector in the UK collects, dismantles and shreds the batteries to produce ‘black mass’, a mixed material containing the most valuable metals including Li, Co, Ni and Mn (Donnelly et al., 2023). There is currently very limited black mass recycling in the UK. Altilium Clean Technology has plans to secure a production site at Teeside as an expansion to its current pilot plant in Devon and aims to process 50 000 t black mass per year, but they have not yet secured the required permits (Jolly, 2023). ICoNiChem has trialled the addition of black mass to their feedstock to produce Co chemicals (ICoNiChem, 2024b), although this process is still in development.

# 5 UK future demand

## 5.1 MARKET SHARE SCENARIOS AND MODELLING CONDITIONS

Understanding technology transformation is critical for projecting embedded material demand, as the bill of materials and the market penetration of new and improved technologies is likely to shift in the future. The technological evolution of the battery chemistry for automobiles has previously been modelled for a range of scenarios up to 2050 and geographical extents (Europe; global) (Racu, 2023, Rho Motion, 2023, Xu et al., 2020).

In this analysis, estimates of future material requirements are based on:

- demand for projected UK EV sales and proposed UK gigafactories that plan to manufacture batteries in the UK (Benchmark Mineral Intelligence, 2024, National Grid, 2023)
    - as the UK fleet does not solely consist of UK-manufactured vehicles (roughly 80 per cent of the vehicles manufactured in the UK are exported) the two demand estimations are presented separately
- assumption of a gradual transition of battery chemistries from 2020 onwards, based on an extension of recent trends and developments of current chemistries (Figure 10) (Marie and Gifford, 2023)
- material intensity data for battery chemistries (kg/kWh), collated from a range of sources (International Energy Agency, 2023, Racu, 2023)
- material intensities used in the UK battery manufacture demand estimation, which fall into two different chemistry categories: mid-Ni (NMC 532/622) and high-Ni (NMC 811/955) (Benchmark Mineral Intelligence, 2024)
    - Figure 11 shows the market evolution of these battery chemistries up to 2050
- the assumption that graphite is the only anode material across all chemistries, except for Li and Mn-rich NMC (LMR-NMC) and SIBs (in the absence of detailed material intensity data for anode active materials in LIBs)
    - a graphite-Si (80/20 per cent weight share) anode has been evaluated (Rho Motion, 2023) for LMR-NMC and SIBs
- two different cathode chemistries for SIBs: PBA and Ni-Mn layered oxides
    - due to the lack of data on the market evolution of these two SIB cathodes and considering that each utilises a different material matrix, demand estimations have been based on a 100 per cent market share for each cathode chemistry
- SIBs commonly use hard carbon as the main anode material; however, due to the lack of data on the intensity of hard carbon usage in anodes, it has been excluded from the demand estimation

In the modelled UK fleet scenario, the NMC (all chemistries) and LFP (including LMFP) Li-based cathode chemistries dominate the EV market over the next 20 years. Next-generation technologies (LMR-NMC, Na-ion and Li-S cells) are assumed to attain a modest market share of about 20 per cent from 2030 onwards.

Currently, NMC types dominate the market, with a 75 per cent share in 2020, and are expected to remain market leaders until 2040. By 2040, the NMC chemistries are likely to decline to around 32 per cent as the use of the cheaper LFP chemistry becomes more widespread. By this time, LFP chemistries will account for a 32 per cent market share, and lithium-manganese oxide and next-generation chemistries for the remainder. It should be noted that the global market share of LFP cathode chemistries was about 42 per cent in 2023 due to the high penetration of LFP in China and the relative importance of the Chinese market, which accounts for 74 per cent of batteries manufactured globally (Marie and Gifford, 2023).

In this scenario, the development of next-generation technology is expected to grow gradually with a market share smaller than existing chemistries (between 10 and 15 per cent by 2035). The outlook for next-generation batteries is highly uncertain as new battery chemistries remain in the research and development stages. These uncertainties, together with long lead times of five to ten years for commercial development, make reliable estimation of market penetration for these technologies very difficult (Marie and Gifford, 2023).

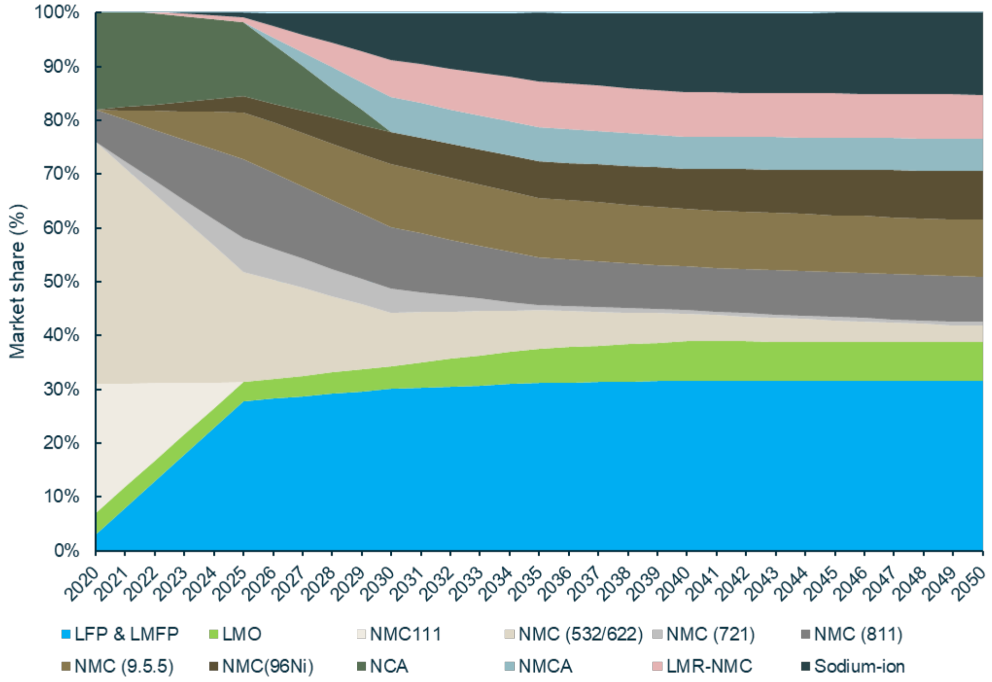


**Figure 10** Evolution of the battery market between 2020 and 2050 showing the technology transformation that is likely to take place (Marie and Gifford, 2023). The market shares for the different cathode chemistries are used to estimate material demand of the UK fleet. BGS © UKRI.

**Figure 11** Evolution of the battery market between 2020 and 2050 showing the change in NMC cathode chemistry that is likely to take place in UK battery manufacturing (Benchmark Mineral Intelligence, 2024). BGS © UKRI.

In the modelling scenario of the UK battery manufacturing sector, mid-Ni cathode chemistries are replaced by high-Ni cathodes over the next six years. From 2030 onwards, high-Ni cathodes become the dominant chemistry of choice in UK battery manufacturing (Figure 11).

## 5.2 FUTURE UK RAW MATERIAL NEEDS FOR BATTERIES

The number of EVs (including vans) in the UK from 2010 to 2020 (Figure 12A) is based on vehicle license data reported by the Department for Transport (2022). Data on EVs for 2021 to 2050 are derived from the National Grid's Future Energy Scenarios (FES) (National Grid, 2023). The FES match the UK Government's proposed 2030 zero-emission vehicle mandate. However, it is noted that EV manufacture could start to face increasing challenges due to recent pressures with raw material supply and consumer spending power caused by the cost-of-living crisis and high levels of inflation (National Grid, 2023). For all the net zero FES — for example, 'Leading the way' — a consumer behaviour switch post-2035 towards mobility as a service, such as using autonomous vehicles or reducing vehicle ownership, is assumed (National Grid, 2023).

The forecast models represent the number of fully electric vehicles as passenger vehicles and vans that are expected to be in use at a specific point in time. However, the average lifespan of an EV is assumed to be 14 years. This means that an EV will be obsolete after this period and it will need to be replaced with a new vehicle. Therefore, the overall stock of EVs will be bigger than in Figure 12B to account for obsolete vehicles. The number of obsolete vehicles per year is included in the demand forecast.

Plug-in hybrid and hybrid vehicles are excluded from this analysis.

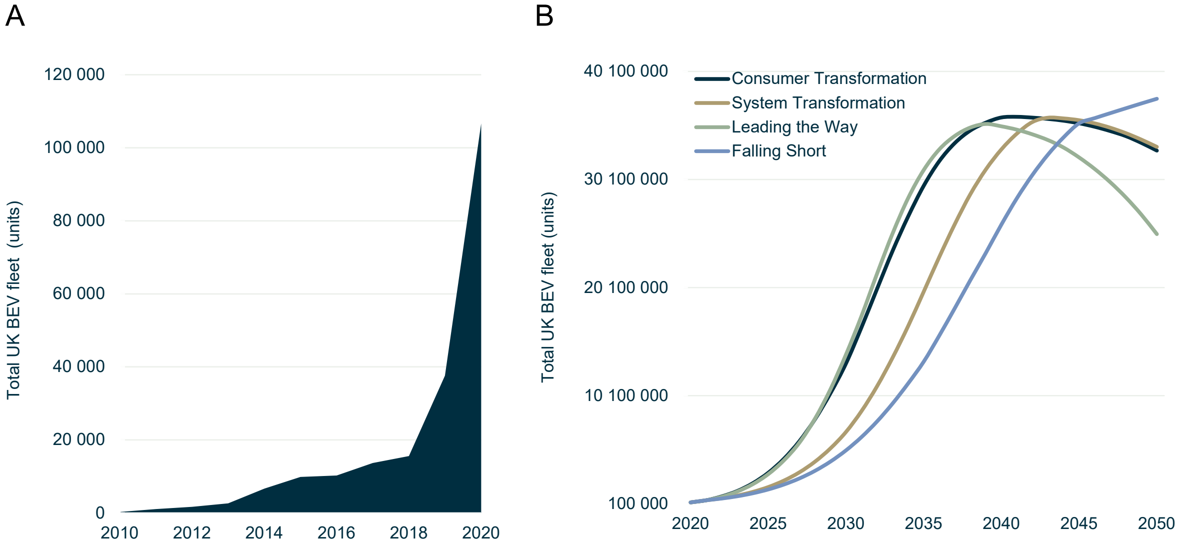


**Figure 12** A: Total number of fully electric vehicles (passenger vehicles and vans) in the UK up to 2020 (Department for Transport, 2022); B: Future cumulative number of fully electric vehicles in the UK under four different scenarios (Department for Transport, 2022, National Grid, 2023).

The future UK demand for the selected elements embedded in the EV battery is presented in two ways:

- as the quantity (in tonnes) required between 2020 to 2050 for each of the National Grid FES and for the UK battery manufacturing sector
- as the percentage of current global metal production (based on average production between 2017 and 2021) (Table 3)

**Table 3** Global metal production (five-year average, 2017 to 2021) for the elements assessed in this analysis. Data from BGS World Mineral Statistics Database (BGS, 2023).

| Element | Global production (tonnes) |
|---|---:|
| Li | 94 570 |
| Co (refined) | 132 017 |
| Carbon (graphite) | 1 125 388 |
| Ni (smelter + refined) | 2 423 024 |
| Si (metal) | 3 035 036 |
| Na ($Na_2CO_3$) | 44 058 697 |
| Mn | 54 566 982 |
| P (phosphate rock) | 231 398 414 |

The forecasts in Figure 13 and Figure 14 show the cumulative UK demand between 2020 and 2050 for the UK fleet and the UK battery manufacture, respectively. Figure 15 presents the annual demand as a percentage of current global metal production between 2020 and 2050 for the UK fleet and the UK battery manufacture. Annual demand for each element has also been quantified to illustrate temporal fluctuations (Appendix B).

The cumulative demand for all the elements evaluated, except for Na and Si, increases rapidly between 2020 and 2030. This is because demand prior to 2020 for automotive batteries is negligible. The initial rapid increase in demand equates to a few hundred kilotonnes (kt) for most elements with the exception of graphite, for which the cumulative demand by 2030 is slightly over 1000 kt. Between 2030 and 2040, although the rate of demand growth falls, the level of demand increases two-fold for Co, three-fold for Li, Ni, P and graphite, and by four times for Mn. Commercial use of Si and Na in EV batteries only starts in 2030. Consequently, the rate of increase in demand up to 2040 for these elements is higher than for the other materials.

The material quantities required for P, Mn and graphite between 2030 and 2040 are in the range of 300 kt, whilst the quantities required for Ni and Li are about 250 kt. For the other elements, the quantities are in the range of 100 to 150 kt, except for Si, for which demand in this decade is predicted to be about 40 kt. Between 2040 and 2050, only a slight increase in demand is forecast compared to the previous decade.

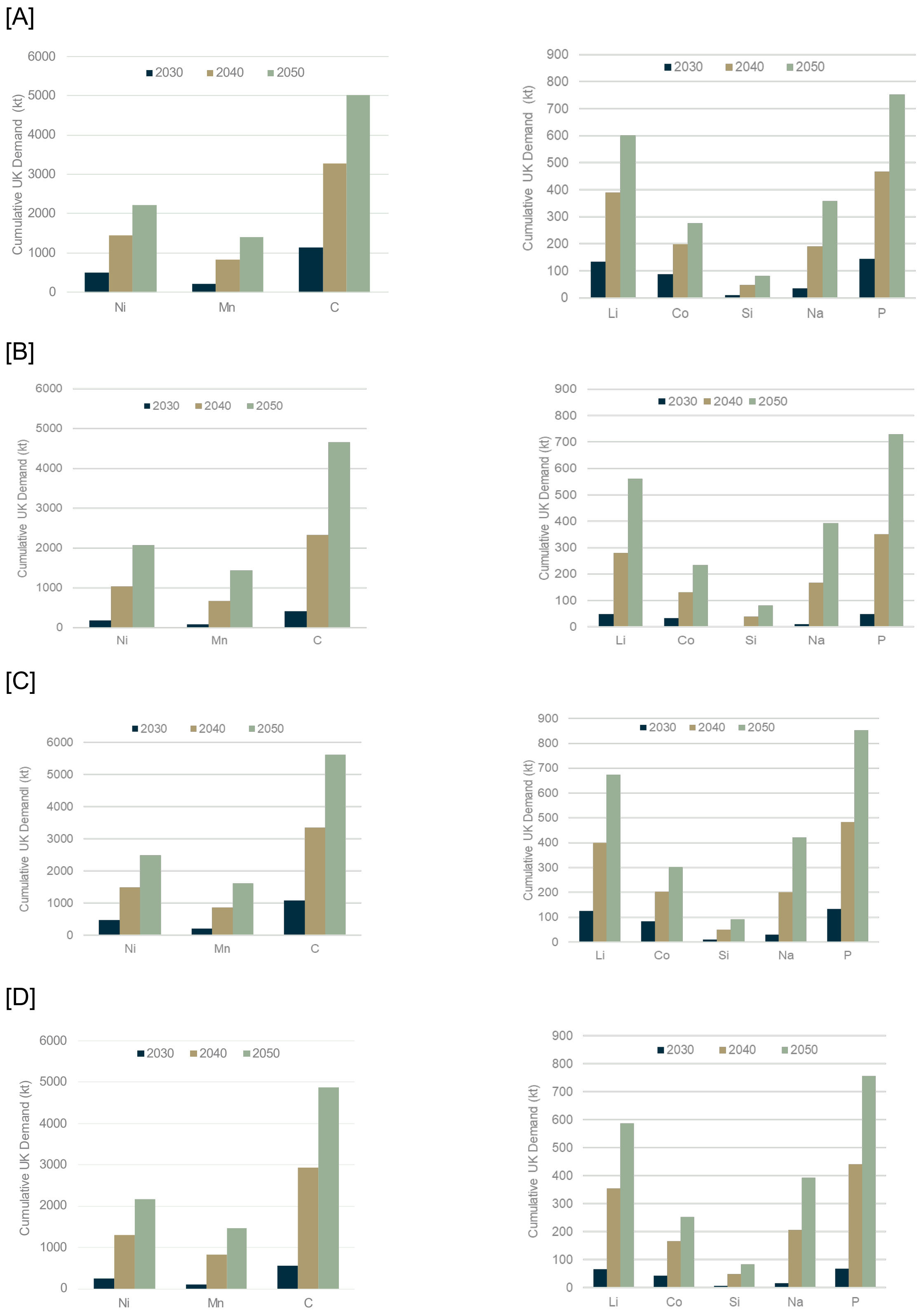


**Figure 13** Cumulative forecast UK demand (kilotonnes) for the battery elements considered in this study between 2020 and 2050 under four different FES: [A] 'Leading the way'; [B] 'Falling short'; [C] 'Consumer transformation'; [D] 'System transformation'. C = graphite. BGS © UKRI.

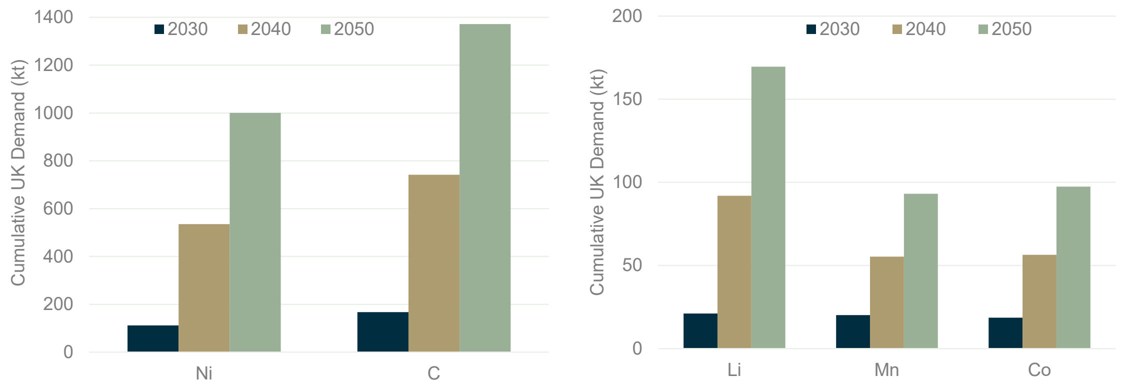


**Figure 14** Cumulative forecast UK demand (tonnes) for the elements required in battery manufacture between 2020 and 2050, based on planned UK gigafactory capacity. C = graphite. BGS © UKRI.

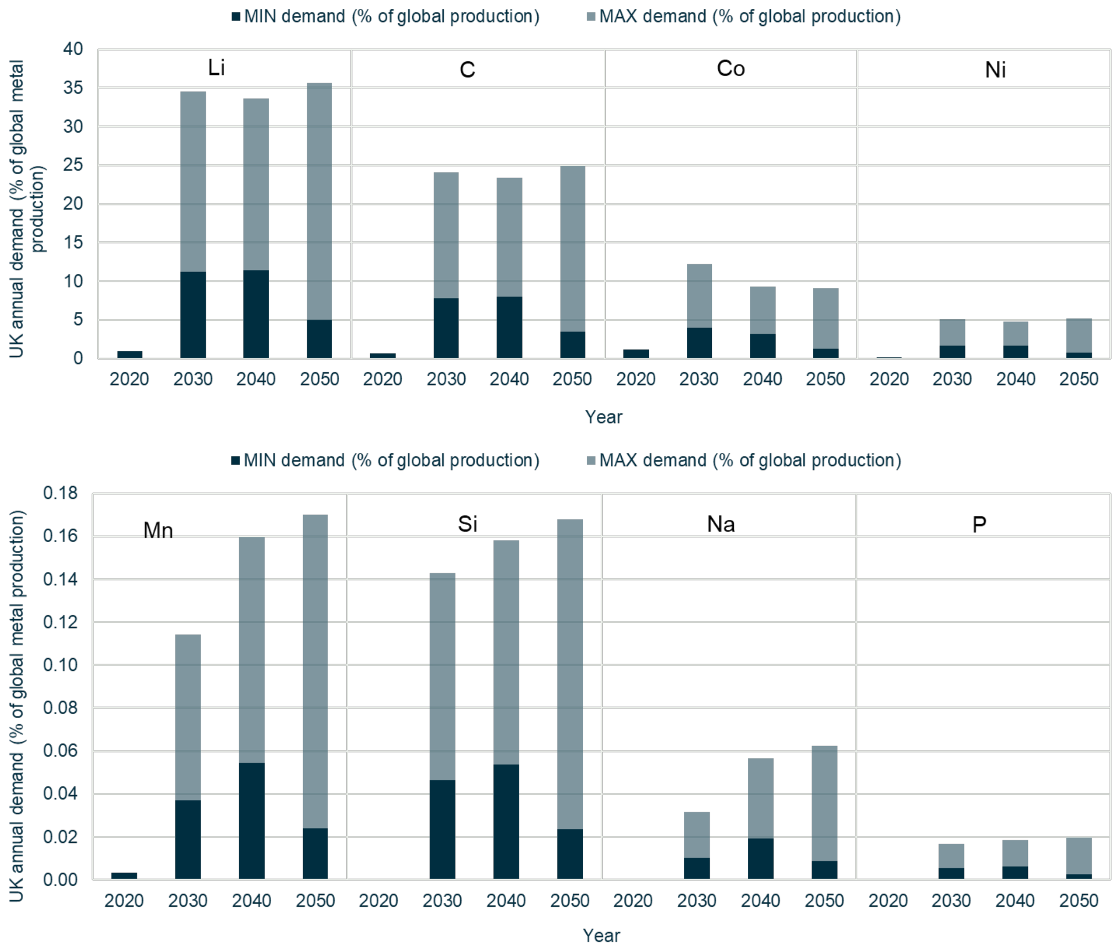


**Figure 15** Annual UK demand of the EV fleet in 2030, 2040 and 2050 as a percentage of current global metal production (five-year average, 2017 to 2021). Data from BGS World Mineral Statistics Database (BGS, 2023). The minimum and maximum values represent outputs of the different scenarios. C = graphite. BGS © UKRI.

The cumulative forecast demand for the UK battery manufacturing sector follows a similar pattern to the UK fleet model. However, due to the focus of UK battery manufacture on NMC high-Ni chemistries, the demand for graphite and Ni is the highest up to 2030, at 167 kt and 112 kt, respectively. In the same period, the demand for Li, Co and Mn equates to about 20 kt. Between 2030 and 2040, the demand for Ni is expected to increase four-fold, whilst the demand for Li and graphite will increase three-fold and for Mn and graphite two-fold. Between 2040 and 2050, the quantities required are only slightly higher than in the previous decade, so the demand for graphite and Ni is estimated to be 630 kt and 470 kt, respectively, 80 kt for Li and 40 kt for Mn and Co. These demand forecasts are larger than the equivalent quantities estimated in the UK EV fleet.

Under the 'Leading the way' and 'Consumer transformation' FES, the annual demand for all elements included in the analysis peaks in 2030 except for Mn and Na, which continue to increase up to 2050. For Mn and Na, the increase in annual demand stems from the market penetration of Na-ion batteries post-2030. The 'System transformation' and 'Falling short' scenarios show an increase in annual demand for all the elements up to 2050 (Appendix B).

Comparison of the demand projections with current global production highlights the scale of future demand increases required for many battery materials (Table 3; Figure 15, Figure 16). For example, for Li and graphite, the UK fleet alone would require between 11 and 35 per cent (minimum to maximum) and 8 and 25 per cent (minimum to maximum), respectively, of current global production in 2030. In 2040, the corresponding figures would be between 11 and 34 per cent and 9 and 25 per cent. Comparison of the UK demand to global production for other elements used in battery technologies highlights similar potential supply concerns, including Co and Ni (in 2030 and 2040).

The UK battery manufacture annual demand presents similar trends to the UK fleet demand. Li and graphite requirements in 2040 and 2050 are estimated at 8 per cent and 5.5 per cent, respectively, of the current global annual mining production. The demand for Co and Ni in 2040 and 2050 is slightly lower, estimated to be about 3 per cent and 2 per cent, respectively, of current global mine production.

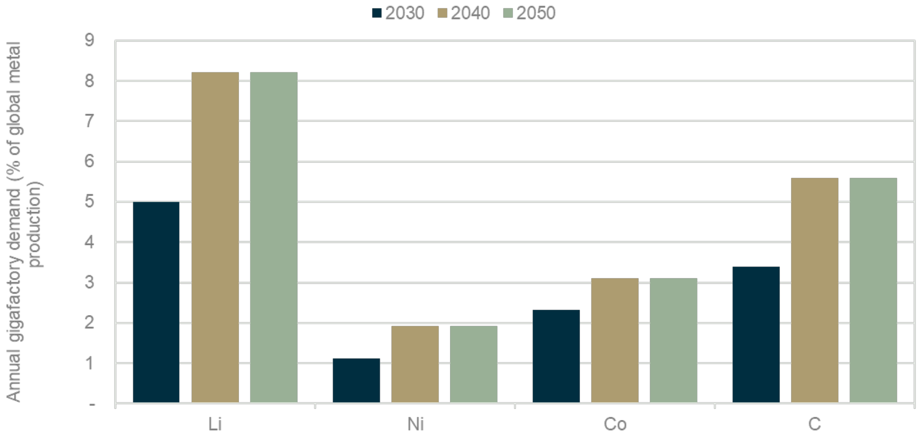


**Figure 16** Annual UK battery manufacture demand in 2030, 2040 and 2050 as a percentage of current global metal production (five-year average, 2017 to 2021). Data from BGS World Mineral Statistics Database (BGS, 2023) and (Benchmark Mineral Intelligence, 2024). C = graphite. BGS © UKRI.

## 5.3 GLOBAL DEMAND VS UK DEMAND PROJECTIONS

The global material demand projections are based on data published by the International Energy Association (IEA) (International Energy Agency, 2023). The scenarios used by the IEA are comparable with those for the UK, as they focus on net zero pathways. Figure 15 shows the minimum and maximum values associated with the global and UK demand projections produced from different scenarios. The results show that the global demand for the assessed elements is significantly higher, owing to the different pace in the electrification transition happening elsewhere (for example, China) and the larger number of EV vehicles deployed globally.

The pace of global demand up to 2030 is higher than in the UK. For example, the global cumulative demand for Li, Mn and Co will increase from an average of 70 kt to 1500 kt by 2030. The global demand up to 2020 for Ni and graphite was 557 kt and 326 kt, respectively, and it is estimated to be around 10 000 kt and 16 000 kt by 2030. Between 2030 and 2040, and 2040 to 2050, the pace of demand increase globally is similar to the UK, with some small discrepancies observed in the cases of Ni, Co and graphite. The UK rate of increase between 2030 and 2040 is therefore higher than the global rate. For example:

- Ni: three-fold UK increase compared to two-fold globally
- Co: two-fold UK increase compared to a one-fold increase globally
- graphite: three-fold UK increase compared to two-fold increase globally

This is mainly due to variations observed in battery technology adoption for jurisdictions such as China (for example, on LFP cathode chemistries) that drive the electrification transition compared to the UK and the rest of the world (Marie and Gifford, 2023).

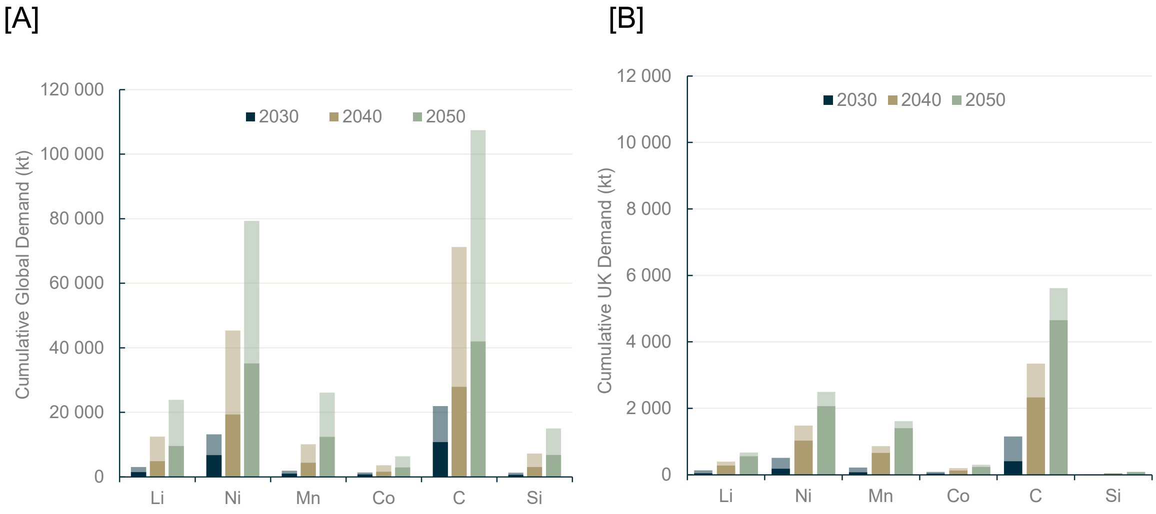


**Figure 17** Material demand for selected elements embedded in batteries in the UK and globally in 2030, 2040 and 2050. The data for the non-UK demand projections are based on the IEA estimates and scenarios (International Energy Agency, 2023). [A] Global material demand for EVs (showing the maximum and minimum values derived from of all scenarios (‘Stated policies’, ‘Announced pledges’ and ‘Net zero emissions by 2050’ scenarios)) and [B] UK materials demand for EVs (showing the maximum and minimum values derived from all scenarios (‘Leading the way’, ‘Falling short’, ‘Consumer transformation’ and ‘System ‘transformation’ scenarios)) (National Grid, 2023). C = graphite; kt = kilotonnes. BGS © UKRI.

The use of Si as an anode material is included in a range of battery chemistries in the IEA projections. In contrast, Si estimates in the UK only participate in next-generation batteries that are expected to penetrate the market after 2030.

Overall, these projections suggest that the UK demand for Mn, graphite and Co is significant, with an average of 8, 7 and 5 per cent, respectively, of the global demand between 2030 and 2050. For Li and Ni, the UK demand is forecast to be about 3 per cent of the global demand, and for Si, about 1 per cent of the global demand between 2030 and 2050.

# 6 Discussion and conclusions

Batteries are expected to play a pivotal role in decarbonisation, especially for transport systems. They use a wide range of materials, many of which are already deemed critical to the UK economy. The supply risk for some key elements used in batteries, such as Co, is elevated because they are extracted only as by-products of other commodities.

In this study, an analysis has been undertaken of the global supply chains and UK demand requirements for eight elements used in Li-ion and Na-ion batteries:

- Co
- graphite
- Li
- Mn
- Ni
- P
- Si
- Na

The UK material demand forecasts were produced using the National Grid FES. UK forecasts were also compared with global battery demand based on the projections and scenarios from the IEA.

Supply bottlenecks were assessed based on the following parameters:

- production concentration, derived from analysis of national production data and the ESG ranking of the main producers
- trade concentration, derived from analysis of national trade data and trade restrictions currently imposed by the main trading nations

Wherever possible, quantitative data from authoritative sources were used in this analysis. However, there are significant issues concerning the availability and quality of data (for example, for trade, material intensities, production levels, etc.). For instance, data for assessing the production of precursor materials are limited and, consequently, no systematic quantitative analysis of supply risk could be undertaken.

Production concentration in the upstream supply chain is significant, with China prominent in mining and, more importantly, in refining. China, Japan and South Korea dominate the midstream (anode and cathode manufacture) and downstream (cell and battery manufacture) stages of the battery supply chain. In the case of China, vertical integration is present across the whole battery value chain (from mine to market).

The lack of midstream capacity outside Asia and the exponential battery demand that is expected in the coming decade are significant obstacles for other countries, including the UK, that are currently looking to develop a battery industry. Additional midstream capacity is essential to increase supply diversification and to avoid further pinch points appearing in the battery supply chain in the future.

The analysis of trade has revealed a significant concentration of trade in both mined and refined materials used in EV batteries. The concentration of both imports and exports of raw materials at the mining stage (ores and concentrates) is greater than for refined commodities. In addition, a larger number of export restrictions are in place for mined raw materials than for refined materials. Some of these restrictions have been imposed by major global producers, such as DRC for Co and the Philippines for Ni. With the UK being close to 100 per cent reliant on imports for most of the battery raw materials required, trade restrictions may increase the supply risk to the UK, as well as the cost of importing these materials. Finally, it is very difficult to predict restrictions on traded commodities, which complicates predicting risks to supply.

Analysis of future UK demand for batteries and associated material requirements was undertaken using the Faraday Institution forecasts on the evolution of the battery market (Marie and Gifford, 2023). However, it is important to note that the battery market is very dynamic; the supply chain is not well established and significant technological advances are expected in the future. Consequently, any prediction is fraught with uncertainty, especially when long time periods exceeding a few years are evaluated.

In any case, the development of a domestic battery value chain in the UK is fundamentally dependent on the material security of supply. Overall, the battery technologies likely to be available in the UK electrified fleet will be dominated by NMC cathodes up to 2040, with mid-Ni chemistries dominant to 2030 and higher-Ni cathodes from 2030 onwards. LFP batteries will become the second largest technology, moving towards equal market shares with NMC-based batteries in 2040. Next-generation battery technologies such as SIBs will join the market by 2030 but will have a moderate market share of 10 to 15 per cent by 2035.

Demand for all materials assessed in this study is expected to increase greatly in the future in response to the UK net zero plan and the UK Government's proposed zero-emission vehicle mandate. There is a general rapid increase in material demand up to 2030 followed by a slower pace of increase up to 2040 and 2050.

Graphite, Ni and Mn are the elements with the highest UK demand for the projected electrified fleet, followed by Li and P. However, the supply constraints for Co, Ni, Si, Mn, Na and P are expected to be more significant than shown in Figure 15 and Figure 16. This is because mine production of these elements is orders of magnitude larger than the battery materials' refined capacity, which is constrained and monopolised by a few global players (Benchmark Mineral Intelligence, 2023a).

The forecast for the UK battery manufacturing sector follows a similar trend. The scale of UK demand for most of the elements assessed is large relative to current levels of global production. For example, Li and graphite requirements in the UK electric fleet alone would require on average 23 per cent and 17 per cent, respectively, of the current global production in 2030 and 2040. The UK battery manufacture annual demand for Li and graphite in 2040 and 2050 are estimated at 8 per cent and 5.5 per cent of the current global annual mining production, respectively. These figures are extraordinary considering the demographic and geographical size of the UK compared to other countries globally. In addition, the competing demand for battery raw materials globally is very high, which can further inhibit the UK's security of supply.

It is also important to note that there is limited reliable production data available for many of the highly specialised materials used in batteries. Consequently, it is difficult to assess the level of future demand for niche products such as Co, Ni and manganese sulfate ($MnSO_4$), high-purity Si, battery-grade graphite, etc. It is predicted that the supply constraints on these materials are likely to be far more significant than for mined materials.

Global demand for the materials evaluated in this study is estimated to be at least an order of magnitude greater than the UK demand. Most of this demand is in countries that have EV manufacturing capacity. It is led by China, followed by Europe and the USA (International Energy Agency, 2023). However, plans to expand battery manufacture capacity globally will require a massive expansion in production capacity of raw, refined and intermediate materials and supply chain development over short timescales. Ensuring the UK has access to secure and sustainable material supplies in such a highly competitive environment will be a major challenge. It is likely that battery production will become increasingly concentrated in those locations that are able to secure the supply of key battery raw materials and rapidly develop battery ecosystems.

Another factor of relevance to the future of batteries and the electrification of transport is the adequacy of charging infrastructure and the connection of electric vehicles to the grid. The improved availability of charging infrastructure in the UK will strengthen the current EV market and encourage the widespread adoption of EVs.

# 7 Recommendations

This assessment leads to the following key recommendations relating to the future deployment of batteries in the UK.

## 7.1 RAPIDLY EXPAND THE UK BATTERY SUPPLY CHAIN

Despite a variety of ongoing activities aimed at strengthening the UK battery supply chain, there remains an urgent need for further rapid expansion to ensure that electrification of transport targets are met and that the UK automotive sector remains competitive in the global market.

The UK Battery Strategy published in 2023 (Department for Business and Trade, 2023) identifies several actions for accelerating the development of the domestic value chain. With respect to materials, this includes:

- provision of Government support for investment, for example through the Automotive Transformation Fund
- increased international cooperation such as trade agreements and strategic partnerships
- Government funding to strengthen innovation and research capabilities related to batteries and their supply chains

While these measures are consistent with the results of this study, it is important to stress that there is less than a decade available for the UK to develop a competitive domestic battery value chain underpinned by secure and sustainable material supplies.

## 7.2 DIVERSIFY THE BATTERY MATERIALS VALUE CHAIN

The UK demand for all the elements assessed is large relative to current levels of global production. Therefore, diversification of the battery materials value chain through investment in projects aiming to scale-up material supply would reduce UK and global supply risks.

There is an urgent need for new mining and refining projects to increase the supply of Ni, graphite, Mn, Li, P, Co and Si. The provision of additional capacity to produce speciality battery-grade materials is a priority. The UK Government should support existing domestic refining projects to bring new commercial activities on stream in the near-term, within a period of about five years. It should also assist through providing technical assistance for capacity building, training and knowledge sharing, particularly in developing countries. Support for overseas investment by UK companies in battery material supply should also be made available.

## 7.3 ADDRESS DOMESTIC VALUE CHAIN VULNERABILITIES

The midstream stage of the value chain, which produces cathode and anode active materials, is most problematic as it is concentrated in a few countries. The same countries typically also dominate the downstream cell and battery manufacture. The lack of investment in cathode active material production in the UK creates vulnerabilities across the whole domestic value chain. For example, any mined or refined battery material produced in the UK will have to be sent overseas for processing prior to being imported again in a battery cell. However, there is little incentive to develop cathode manufacture in the UK in the absence of secure, long-term supplies of battery raw materials.

The slow pace of development of battery gigafactories has also been a deterrent to the co-location of cathode and cell manufacture in the UK. The development of a secondary supply chain for battery raw materials is also at risk due to the absence of the midstream battery value chain. Any material recycled in the UK would have to follow a similar route to primary materials for the manufacture of cathodes and cells. To mitigate supply risks in midstream supply chains, investment in cathode manufacture in the UK, or by UK companies overseas, should be actively encouraged. For example, support could be given to projects aiming to develop circular economy battery ecosystems, in which spent batteries and manufacturing scrap from UK battery gigafactories are used as feedstock to domestic cathode production projects.

Despite the current low volumes of spent batteries, the feedstock of scrap and EoL batteries will increase substantially by 2040 as the UK EV fleet grows and gigafactories are developed (Advanced Propulsion Centre UK, 2022c). As a first step, funding to develop detailed underpinning models and forecasts is essential to prove the feasibility of such initiatives. Establishment of trade agreements with important producing nations and assistance with collaborative research and development would help to build resilience against security of supply issues associated with the midstream supply.

## 7.4 SUPPORT GROWTH IN DOMESTIC BATTERY CELL MANUFACTURE

The UK has limited domestic manufacturing capacity for battery cells, which is an essential step in the downstream value chain. Supporting growth in this stage would assist the UK in meeting its gigafactory demand and help to mitigate competing demand challenges from global markets. The provision of subsidies and tax incentives could support the establishment of a domestic sector and de-risk manufacturing investment. Development of a skilled workforce would be essential to support growth in the manufacturing stage.

## 7.5 IMPROVE ANALYSES AND DATA

The assessment provides many useful insights into potential material bottlenecks associated with the expansion of battery technology and the electrification of transport. However, the robust estimation of future material demand and identification of supply issues depend on reliable supply chain analysis and data of many types. Improving data availability, transparency and quality is essential. At the same time, developing infrastructure for harmonised data collection and new data generation, while ensuring key data providers are fully engaged, is also of fundamental importance.

## 7.6 MONITOR SUPPLY CHAIN DYNAMICS

Like other decarbonisation technologies, the battery sector is dynamic; market conditions, geopolitical challenges, techno-economic changes and other social and environmental factors can rapidly affect any part of the supply chain. Ongoing supply chain monitoring, together with the development of stocks and flows models supported by scenario analysis, can provide critical insight into future material challenges and contribute to the development of effective mitigation strategies and increased resilience of the supply chain.

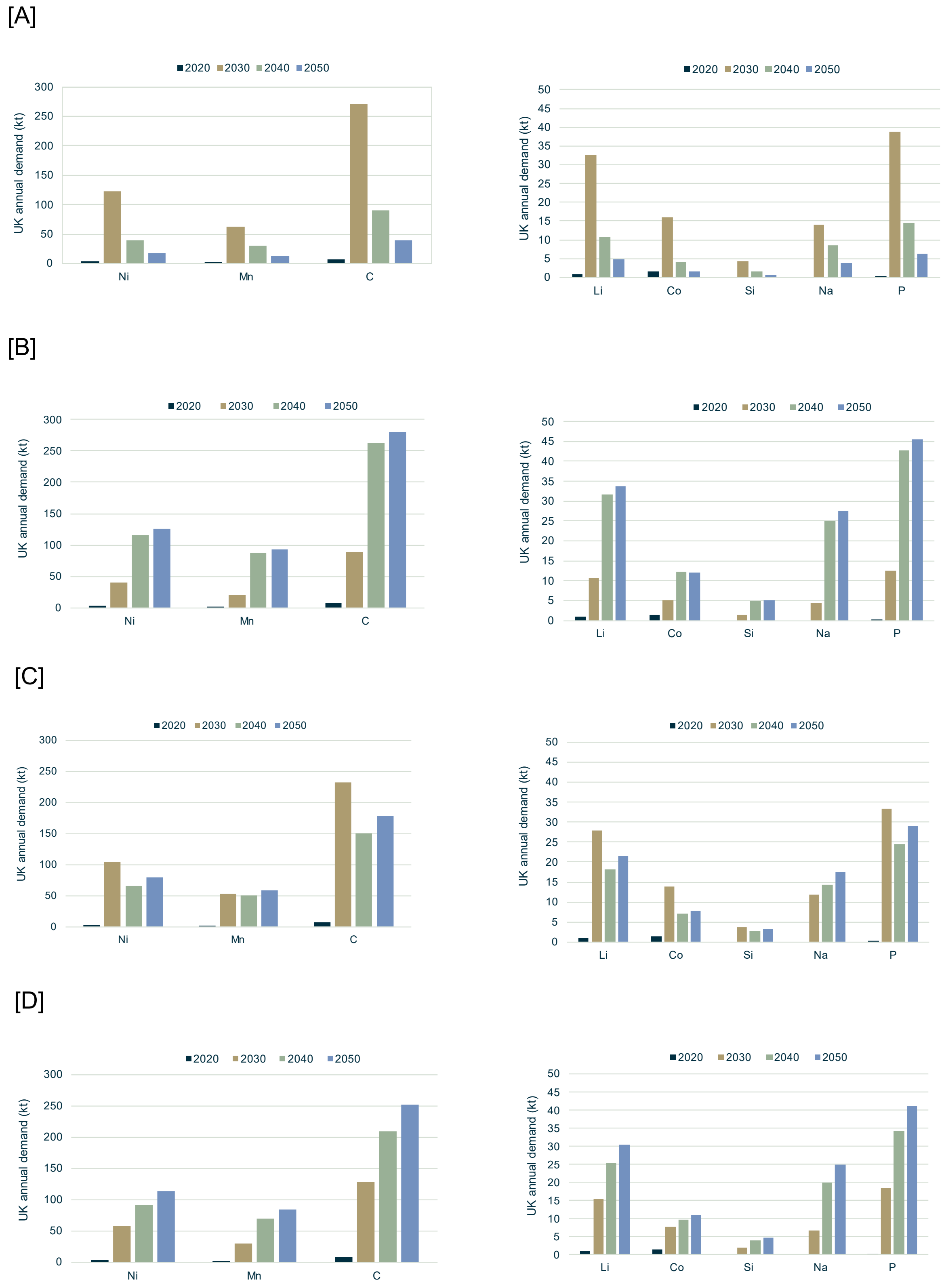
Current and planned actions by the UK Government, outlined in (Department for Business and Trade, 2024), will assist in the implementation of some of these measures. For example, the strategy sets goals for making the UK a centre of excellence for supply chain analysis and risk assessment, and for developing the capability to forecast and respond to external shocks to global supply chains. Both are relevant to critical raw material supply chains, especially so for the rapidly evolving battery sector.

# Appendix A

| Component | Function | Reason for exclusion |
|---|---|---|
| **Raw materials** | | |
| Al | NCA cathode materials | Demand is negligible compared to other Al applications |
| Cu | Collector foils; conductive parts; wiring | Not part of key technology parts (battery cathode or anode) |
| F | Liquid electrolyte in Li- and Na-ion batteries | Focus of this study is on cathode and anode material |
| Fe | Li-iron phosphate cathode materials | Demand is negligible compared to other Fe applications |
| Nb | Nb-based anode material | Nb-based anodes are not commonly used and future uptake is uncertain |
| Ti | LTO anode material | Ti-based anodes are not commonly used and future uptake is uncertain |
| **Precursor materials** | | |
| Li metal anode | Anode material, mainly for SSBs | Still in research and development and future uptake is uncertain |
| LTO anode | Anode material | Still in research and development and future uptake is uncertain |
| Nb-based anode | Anode material | Still in research and development and future uptake is uncertain |
| **Battery cell technologies** | | |
| Flow battery | Highly flexible and long-lasting technology, mainly used in energy-storage systems | Not used in automotives due to low energy density |
| Li-S batteries | High-energy density battery cell type in development with S as the cathode material | Still in research and development and future uptake is uncertain |
| Metal-air batteries | Highest theoretical energy density possible with metallic anode (such as Li) and oxygen as the cathode | Still in research and development and future uptake is uncertain |
| SSBs | Advantages in safety, energy density and fast charging | Still in research and development and future uptake is uncertain |

# Appendix B

Annual forecast UK demand (tonnes) for the elements considered in this study up to 2050 compared with 2020 under four different FES. [A] ‘Leading the way’; [B] ‘Falling short’; [C] ‘Consumer transformation’; [D] ‘System transformation’ scenarios. BGS © UKRI.



# Acronyms and abbreviations

| | |
|---|---|
| AESC | Envision Automotive Energy Supply Corporation |
| APC | Advanced Propulsion Centre |
| DRC | Democratic Republic of the Congo |
| EoL | End-of-life |
| ESG | Environmental, social and governance |
| FES | (National Grid) Future Energy Scenarios |
| HPMSM | High-purity manganese sulfate monohydrate |
| HPPA | High-purity phosphoric acid |
| HS | Harmonized System (trade codes) |
| IEA | International Energy Agency |
| JLR | Tata Motors Jaguar Land Rover Automotive Plc |
| LFP | Lithium-iron phosphate |
| LIB | Lithium-ion battery |
| LTO | Lithium titanate oxide |
| NCA | Nickel-cobalt-aluminium oxide |
| Ni-Cd | Nickel-cadmium (battery cell) |
| NiMH | Nickel metal hydride (battery cell) |
| NMC | Nickel-manganese-cobalt oxide |
| NMCA | Nickel-manganese-cobalt-aluminium oxide |
| PBA | Prussian blue analogue |
| SIB | Sodium ion battery |
| SSB | Solid-state battery |

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