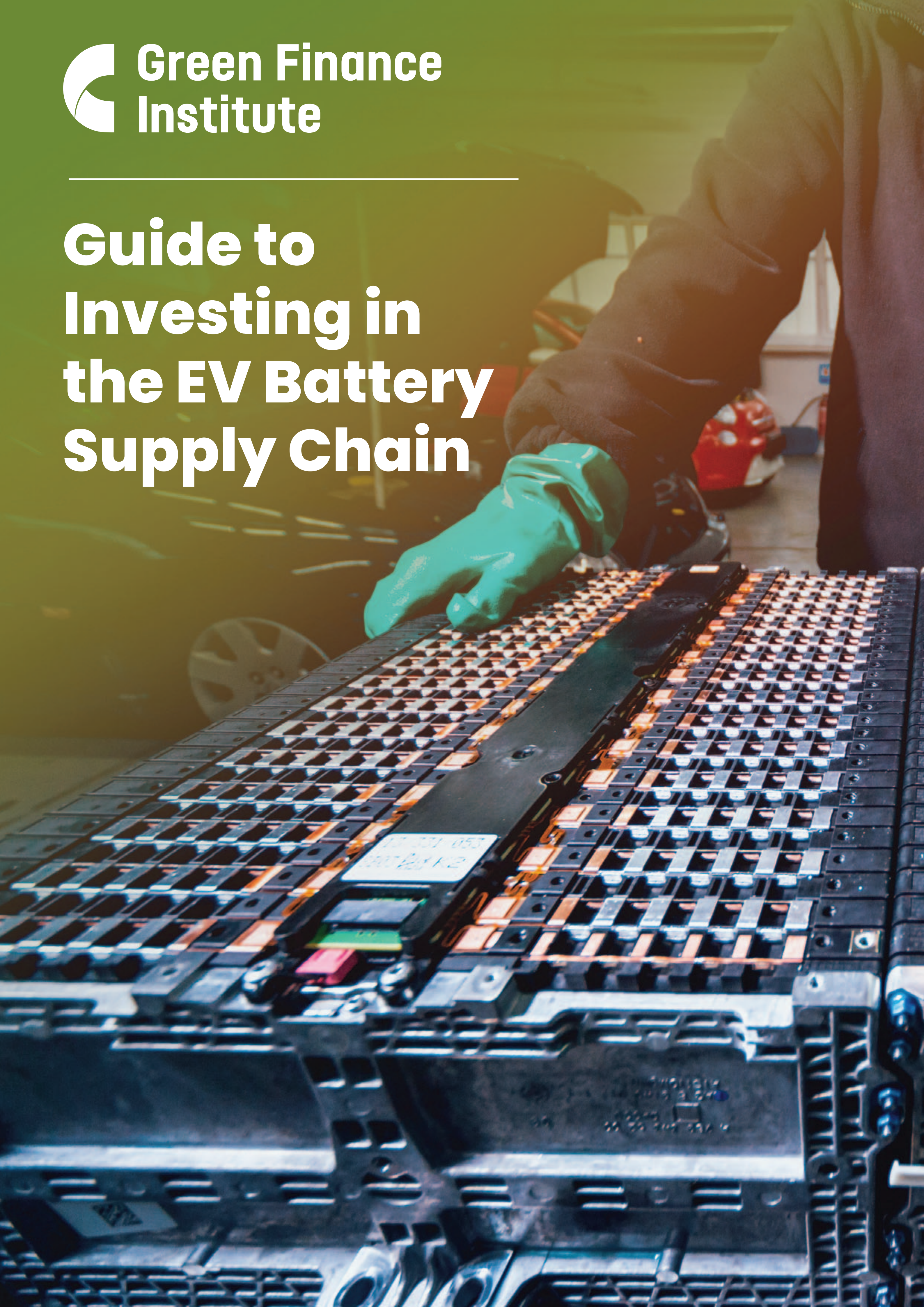
Green Finance Institute

Guide to Investing in the EV Battery Supply Chain



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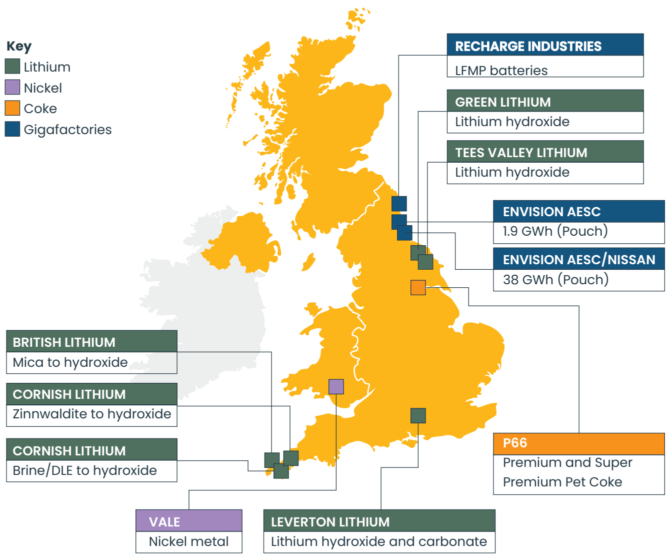
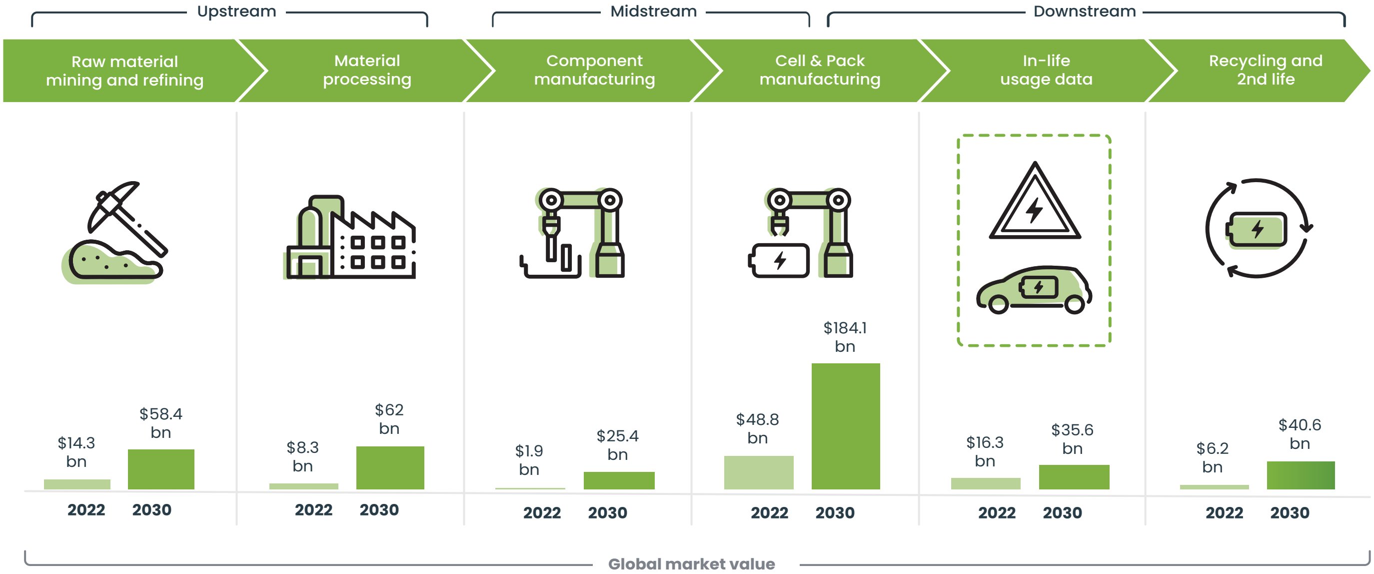
Executive Summary

The electric vehicle (EV) transition has potential to grow the automotive battery market to GBP 12 billion in the UK as early as 2025[1]. Growing battery supply chain capacity presents a significant opportunity for a wide range of investors, both those familiar with, and those new to the sector. The Green Finance Institute's Coalition for the Decarbonisation of Road Transport has created this guide to provide investors with information on the battery supply chain to unlock the investment the UK needs to capture this opportunity.

Batteries are a key enabling technology in the decarbonisation of numerous sectors, including transport, and will be needed for most light passenger vehicles, vans and some heavy goods vehicles. Demand for batteries in multiple sectors, including automotive, is creating a significant growth opportunity for companies scaling capabilities across the battery supply chain, requiring significant pools of capital from investors across the financial spectrum, new and existing. The UK has a window of opportunity to play a key role in the transition and grow its current battery manufacturing pipeline. Increasing investor understanding of the sector quickly is critical to seize this opportunity.



The Battery Supply Chain



Source: The Battery Report 2022, Volta Foundation

Upstream: Demand for key raw materials needed to manufacture automotive batteries is expected to grow by as much as 500% by 2040 [2]. Obtaining supply of these materials is a key concern and given the time taken to scale capabilities to extract and process materials, investment is urgently required. Existing extraction capabilities are relatively concentrated in a few countries globally, with China controlling much of the supply due to extensive capabilities in processing and investment in overseas extraction. Although the UK is unlikely to satisfy the entirety of its raw material demand for batteries from local supply, there are a variety of investment opportunities to grow the UK's promising pipeline of raw material extraction facilities, which includes companies experimenting with new faster extraction technologies, and expanding pre-existing processing capabilities. Regulation is driving increased transparency across the supply chain and demand for domestic extraction and processing projects from battery manufacturers downstream.

Midstream: Most cells used today for electric vehicles use lithium-ion (Li-ion) technology, referring to the specific chemicals used to manufacture the key components such as the anode and cathode. Investment is needed in both companies innovating in Li-ion technologies, as well as new technologies which use different chemicals. New technologies take time to be proven at scale and are expected to fit into existing production lines. Several investment opportunities exist to help the UK build on its strong heritage in chemicals to increase electrolyte production, and establish anode and cathode facilities, with regulation governing rules of origin driving demand for local producers [3]. Automakers looking for batteries with strong green credentials will be attracted to UK-based producers able to take advantage of the UK's green energy mix. Cell manufacturing refers to the process of combining the cell components, typically done in a gigafactory. It is considered the most important step in the battery value chain, expected to account for up to 40% of battery industry value creation by 2030 [4]. China currently dominates the production of most cell components, and has 79% of global cell manufacturing [5], though the US and EU are rapidly growing their pipelines. The UK has one gigafactory (<1% of global capacity) operated by Envision AESC, but more are needed to meet the forecast demand, requiring significant investment.

Downstream: A battery supply chain needs companies able to assemble the battery module and pack using cells acquired from cell manufacturers. These capabilities can be performed by different actors, including automakers, with assembly often occurring in close proximity to vehicle manufacture. Currently the UK has some assembly capabilities but needs to grow capacity to meet future EV demand [6].

End of life – second use and recycling: Current EV batteries degrade an average of just 2.3% per year, which means that after use in an EV, they can either be used in another application or recycled [7]. Like many countries, the UK is yet to build battery recycling at industrial scale, primarily due to lack of UK-based battery manufacturers to provide feedstock [8]. However, strong recent EV adoption combined with legislative battery recycling targets is expected to create a steady pipeline of retired EV batteries; a spate of recent announcements indicates this is a growth sector.

Policy: Governments globally continue to commit to electrify transport and meet net zero targets, stimulating EV uptake and demand for automotive batteries. Extensive policy support in major markets to attract some of the supply chain speaks to the strategic importance of the sector and its role in energy security; the Inflation Reduction Act (IRA) in the US, and the EU Green Deal have both already stimulated huge amounts of private investment. Though the UK already offers extensive support for the automotive sector, it is yet to respond with a similar broader strategy.

2. Introduction

In 2022, the global lithium-ion (Li-ion) battery market size was sized at GBP 78 billion [9]. By 2030, it is expected to grow rapidly, with estimates for the market value in 2030 ranging from GBP 225 billion [10] to as high as GBP 328 billion [11].

Introduction

The global shift to electrification and specifically electric vehicles (EVs) to decarbonise the transport sector is creating a huge investment opportunity to meet the rapid increase in demand for batteries.

An estimated GBP 20 billion investment is needed in the UK battery supply chain alone by 2030 to scale production capacity to meet demand [12]. While there are many established players in the automotive sector, this needed capital provides an opportunity for new investors to move into the sector. The UK has a window of opportunity to play a key role in this transition, with the second largest EV market in Europe, ambitious plans to phase out internal combustion engine (ICE) vehicles and a strong automotive sector.

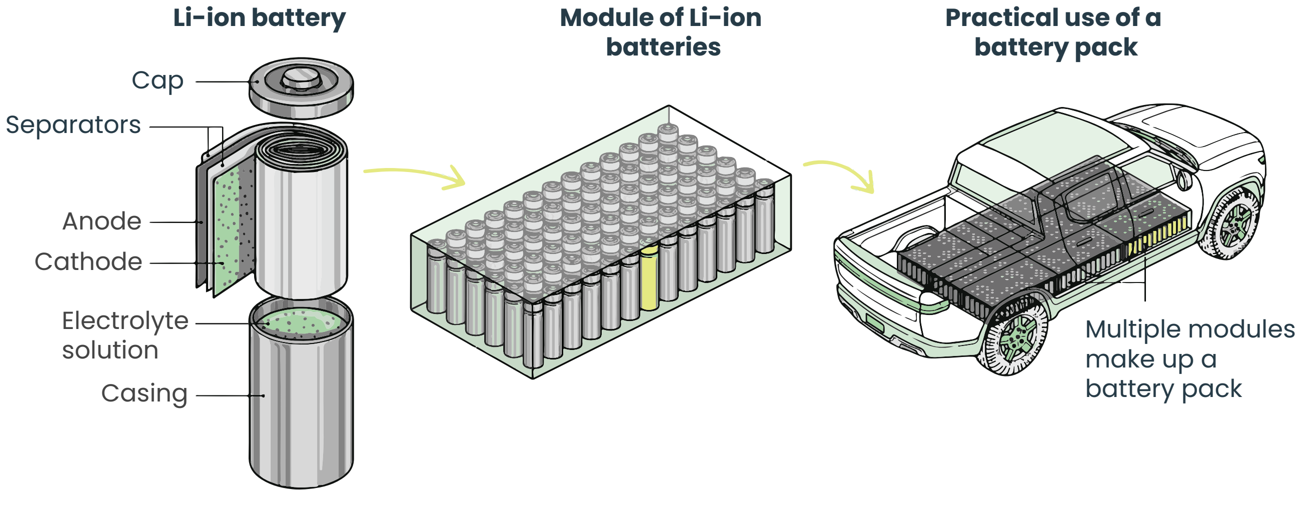
1: What is an EV battery?

Batteries form a key part of the EV powertrain, which is the mechanism that transmits the drive from the battery of a vehicle to its axle (i.e. drives the wheels of a vehicle). The power is provided by a battery pack. Battery packs are typically composed of multiple modules, which themselves are made up of numerous cells - the basic unit in a battery. The number of modules in a battery pack depends on the shape and size of the cells. The way a battery pack is constructed of modules and cells is known as its format, which can significantly impact a battery's properties and performance. **Figure 1** illustrates the difference between a cell, module and battery pack. This is discussed in more detail in Sections 5 and 6.

Internally, all cells are made of at least three components - the negative anode, the positive cathode, and an electrolyte that allows ions to pass between the anode and cathode. Cell components are discussed in more detail in Section 5. Battery format is discussed in more detail in Section 6. Further information on the production processes of Li-ion battery cells, modules and packs can be found in guides published by RWTH Aachen University.

Figure 1: Li-ion battery

An electric vehicle is powered by thousands of Li-ion battery cells



2: How do EV batteries work to power the motor?

Chemical reactions in a battery involve the flow of positively charged ions (atoms with a deficit of electrons) moving from the anode to the cathode through the electrolyte, releasing electrons along the way to create an electric current.

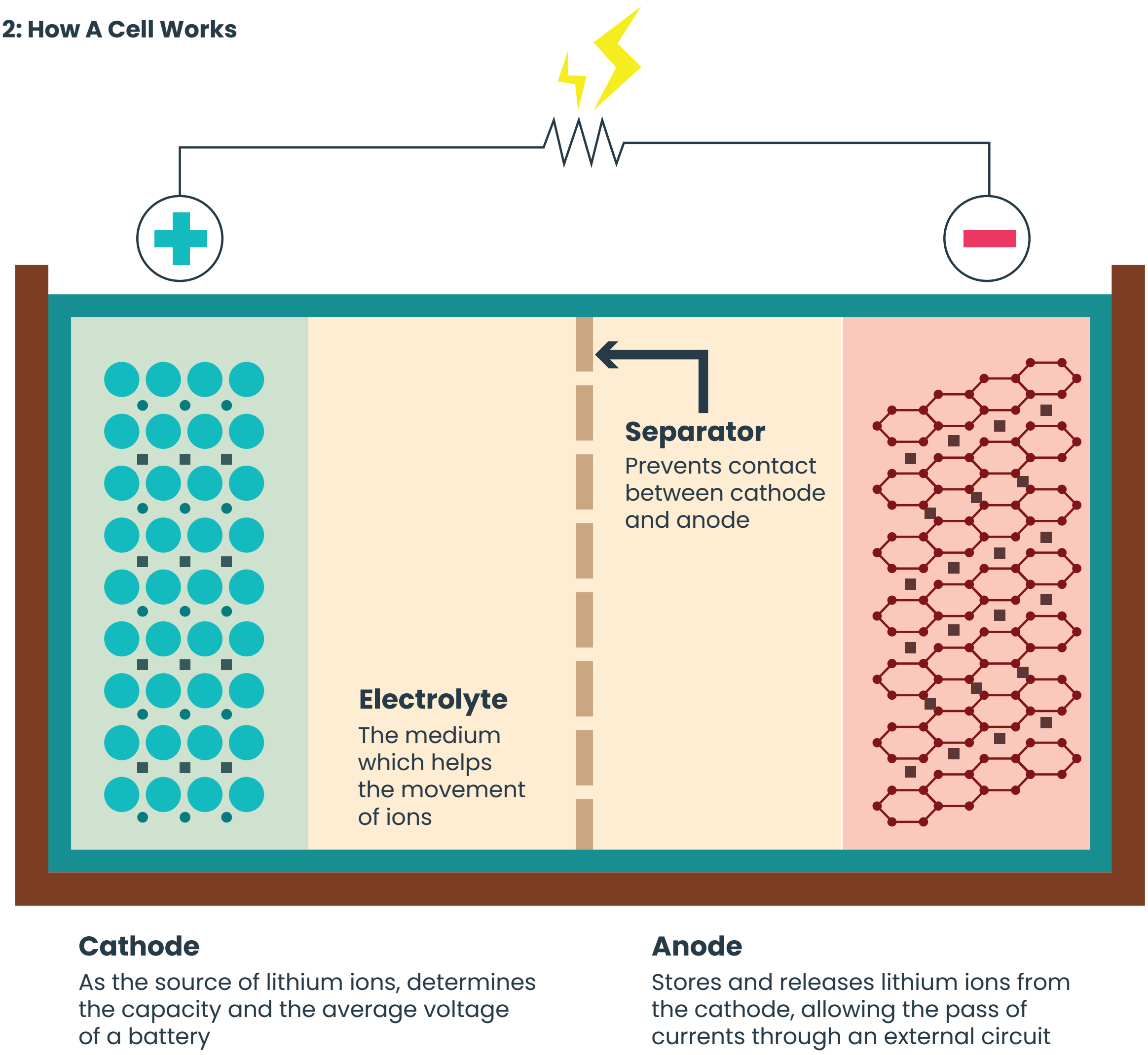
Direct current (DC) leaves the battery which then has to be converted to alternating current (AC) before it can enter the motor. To recharge a battery, the opposite happens – electrons flow into the battery, and ions flow back from the cathode to the anode, creating electric potential energy that the cell can later discharge. **Figure 2** demonstrates this process. Charge cycling degrades components in the system so over time the battery loses performance.

3: What are EV battery cells made of, and what is cell chemistry?

The components within an EV battery cell are each made of a different combination of chemicals made from highly processed raw materials. The specific combination of materials will vary depending on the chemistry being used in the cell. For further information on cell chemistries, see Section 5.

The chemistry of a particular cell refers to the specific combination of materials used to create the anode, cathode and electrolyte that will create the chemical reaction to generate electric potential energy. Along with cell and pack format, a cell's chemistry is a key factor in determining its properties and performance.

Figure 2: How A Cell Works



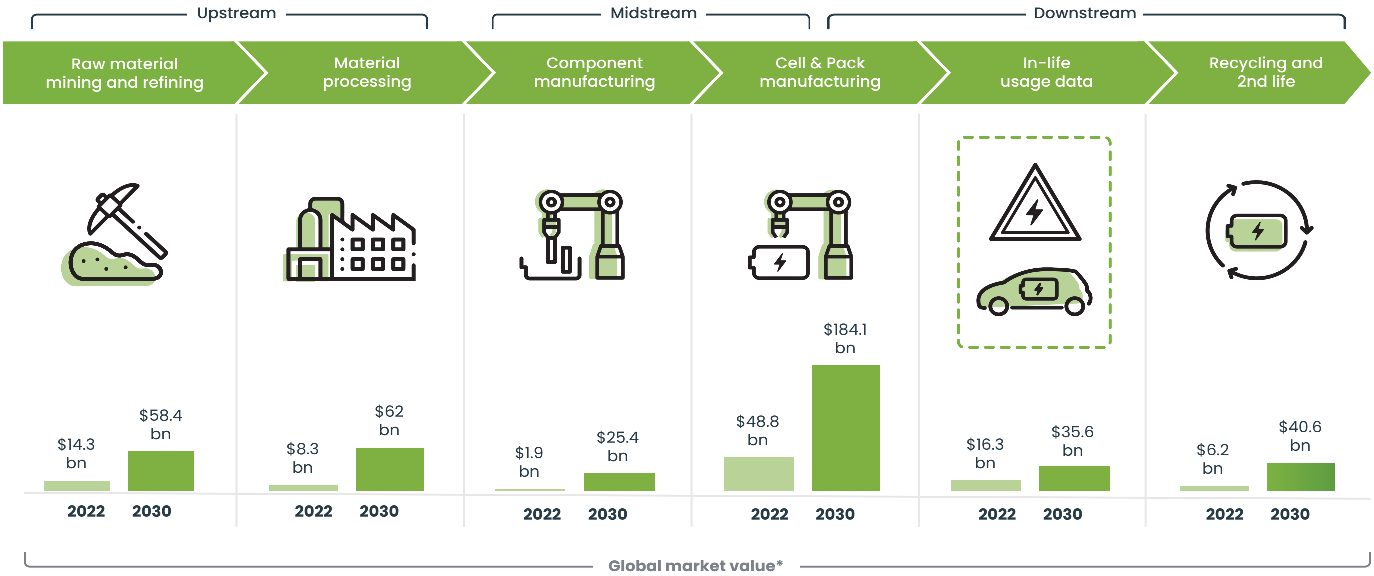
4: What is the Battery Supply Chain?

The battery supply chain refers to the interconnected network of processes that work to transform raw materials into the devices used to power EVs. The supply chain can be divided into four main parts: upstream, midstream, downstream and end of life.

Each part can be broken down into various steps, as illustrated in **Figure 3**. The structure of the Guide reflects the automotive battery supply chain, with a section on each stage. Each section describes the global and UK market, current key technologies, emerging technological innovations, business innovations and opportunities for investors, with relevant illustrative case studies which can be found in the Appendix.

This guide focuses only on the supply chain for batteries, and does not cover the many further processes for the production of a vehicle itself, and the integration and assembly of the batteries with the vehicle, though there is overlap between battery manufacturing and vehicle manufacturing.

Figure 3: The Battery Supply Chain



Source: The Battery Report 2022, Volta Foundation

3. Market Overview

Market Overview

1. What is the political context for the demand for automotive batteries?

One of the key drivers of demand for batteries is the imperative of decarbonising to meet climate targets [13]. Batteries are relevant to decarbonisation pathways in numerous industries. Road transport is responsible for a quarter of global greenhouse gas (GHG) emissions [14], meaning many governments have taken steps to encourage the shift towards green transport. For light passenger vehicles, vans and some Heavy Goods Vehicles (HGVs), these green alternatives will be powered by batteries (with some specific heavier applications expected to use hydrogen and e-fuels). This has catalysed demand for automotive batteries, which is expected to increase seven-fold by 2030 [15], by which date the automotive sector will account for over 80% of total battery demand [16].

In the UK, the government has committed to end the sale of new petrol and diesel cars and vans from 2030, and hybrid cars and vans by 2035. HGVs under 26 tonnes which rely on ICE are to be phased out by 2035, and those heavier by 2040. This context is echoed worldwide; at COP26, over 100 national governments, cities, and states committed to end the sale of ICE vehicles by 2035 in certain leading markets including Europe, and the worldwide end to the sale of ICE vehicles is expected by 2040.

Beyond targets for EV adoption, governments in major markets are also aiming to attract some of the supply chain for EVs and batteries. The demand for batteries globally has triggered an 'arms race' for local production capacity. China has been dominant in the battery market to date, but many factors are driving a diversification of the battery market geography globally. These include energy and technological security, the drive for localisation and co-locating battery production with existing automotive production, and the many niches of opportunity across the supply chain, which offer an economic opportunity countries are looking to exploit. Policy makers across Asia, Europe, and the USA are introducing increasingly protectionist measures to promote battery production. These are set out in Section 8.

2. How are automakers responding to Governments' phase out dates?

Alongside government regulatory interventions for ICE phase outs, automakers are also setting out their own timetables – not only as a way to comply with policy regulations or government incentives, but as an opportunity to capture market share and maintain a competitive edge. Some, such as PSA Group and Volkswagen, have announced they will end ICE investment, and others such as Jaguar Land Rover, Ford, Volvo, General Motors and Honda, have announced ICE vehicle production phase outs over the coming years (see **Figure 4**). Many are setting voluntary EV sales targets, either in terms of total sales volumes or sales shares which exceed both regulatory requirements and government ambitions [17]. Some countries, including the UK, are mandating the proportion of vehicles which need to be zero emission in the years leading up to 2030.

As these target dates approach, automakers are increasingly seeking vertical integration strategies to secure battery supply by engaging in joint ventures or making strategic upstream investments. For example, Toyota, GM, Hyundai and Ford are investing USD 2.5 billion, USD 6.6 billion, USD 5.5 billion and USD 11.4 billion, respectively, in EV and battery manufacturing sites in the US alone [18]. Others, such as Tesla, are also looking to develop their own battery manufacturing capabilities in-house [19].

Automakers are also taking steps to secure the wider supply chain, especially key raw materials, through partnering with mining companies, signing offtake agreements or investing in mining operations: Ford recently partnered with Vale and Huayou to build a processing plant in Indonesia with capacity to process 120 kt of nickel per year [20]; Stellantis invested USD 55m in the German lithium producer Vulcan [21]; and Tesla signed agreements with mining companies such as Albemarle, for lithium, and Prony Resources, for nickel [22]. For more information on the raw materials for batteries, see Section 4.

Figure 4: Automakers' targets for the phase out of ICE vehicles
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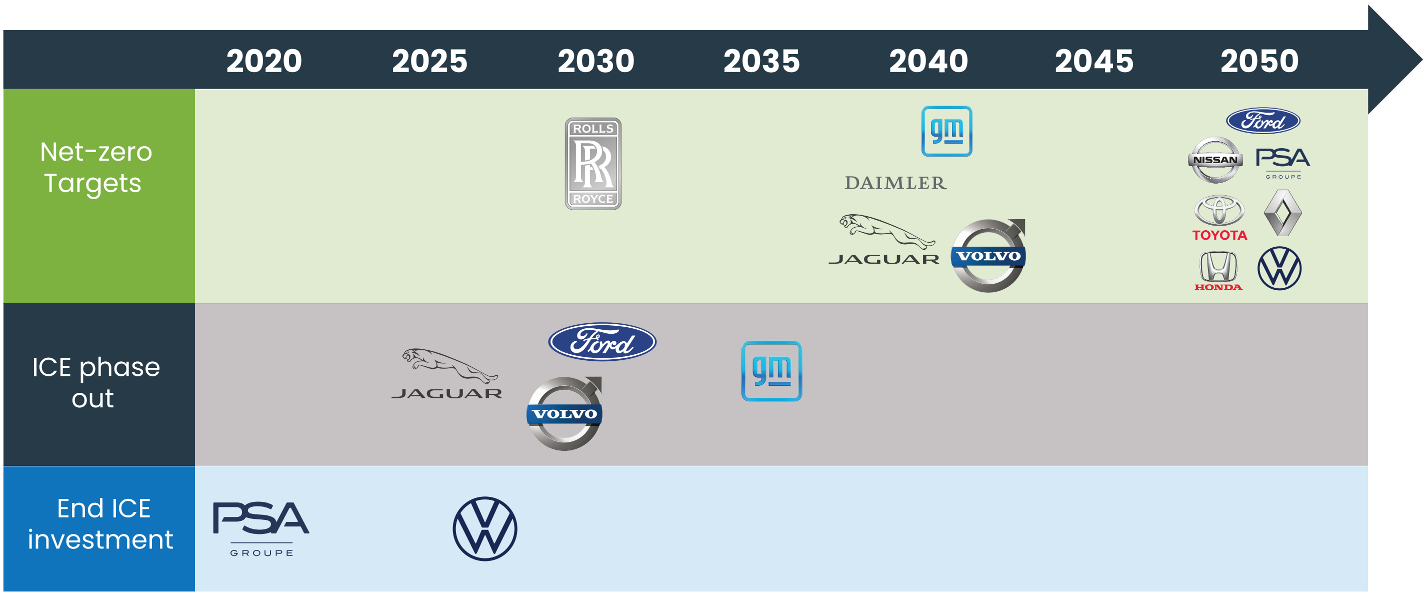
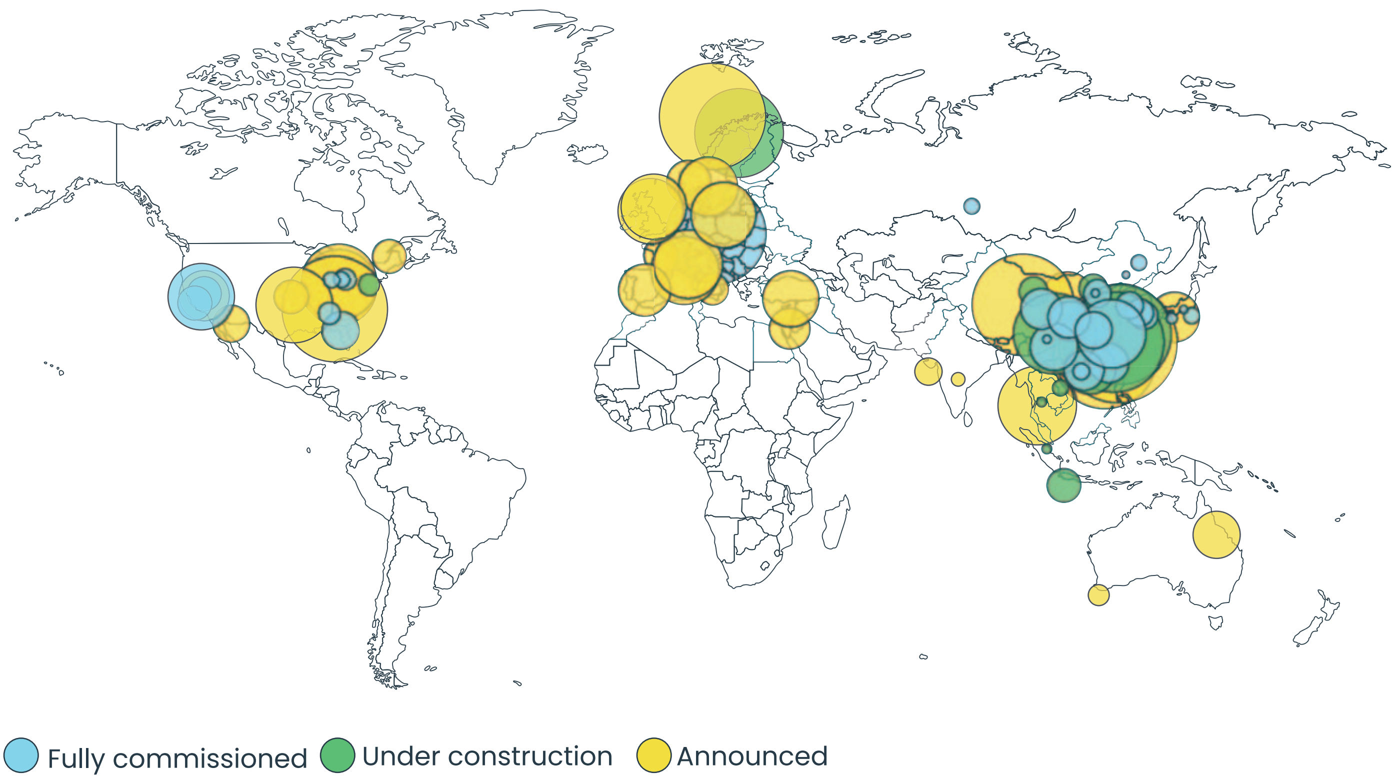


Figure 5 shows the spread of existing and future assets for Li-ion battery (currently the dominant battery type used in EVs) production. While there is established capacity in Asia, significant growth is occurring across Europe and the USA as countries seek to capitalise on the opportunities of the battery supply chain.

Figure 5: Li-ion battery manufacturing asset map
Reproduced with permission from BloombergNEF.



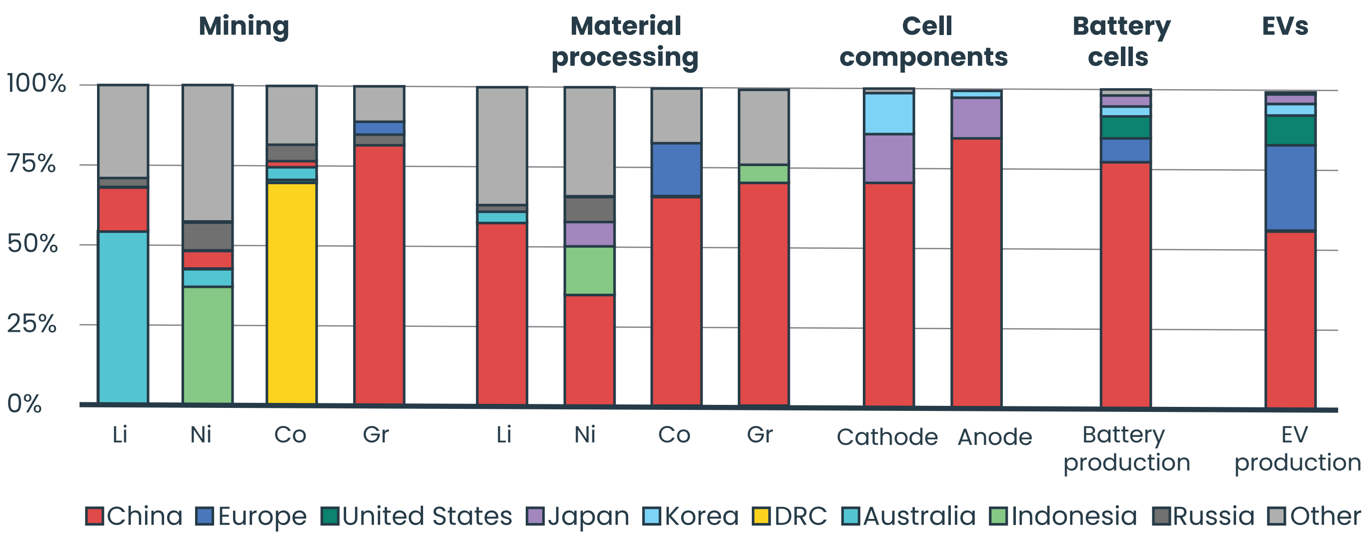
3. What does the geography of global battery manufacturing look like?

Asia

Asia leads the global battery supply chain, home to the headquarters of the ten largest companies, including CATL (32.6% market share), LG Energy Solution (20.3%), Panasonic (12.2%) and BYD (8.8%). Chinese companies account for 56% of the EV battery market, followed by Korea (26%) and Japan (10%) [23]. **Figure 6** shows the share of different parts of the supply chain by region.

As of 2022, China accounts for the majority of global processing capacity for key raw materials and a growing proportion of extraction capacity; up to 85% of the global market for anodes, cathodes, separators and electrolytes which together account for between 70% and 85% of a cell's cost [24]; and up to 75% of the global pipeline for gigafactories, with 226 due to be operational by the end of the decade [25]. Soon Chinese battery manufacturing capacity is expected to exceed domestic demand, meaning Chinese battery manufacturers are accelerating plans to grow exports into European markets [26] which could lead to Western automakers being forced to reduce the cost of their EVs [27]. That said, as set out above, many factors mean that Chinese dominance to date is not prohibiting growth elsewhere.

Figure 6: Geographical distribution of the global EV battery supply chain

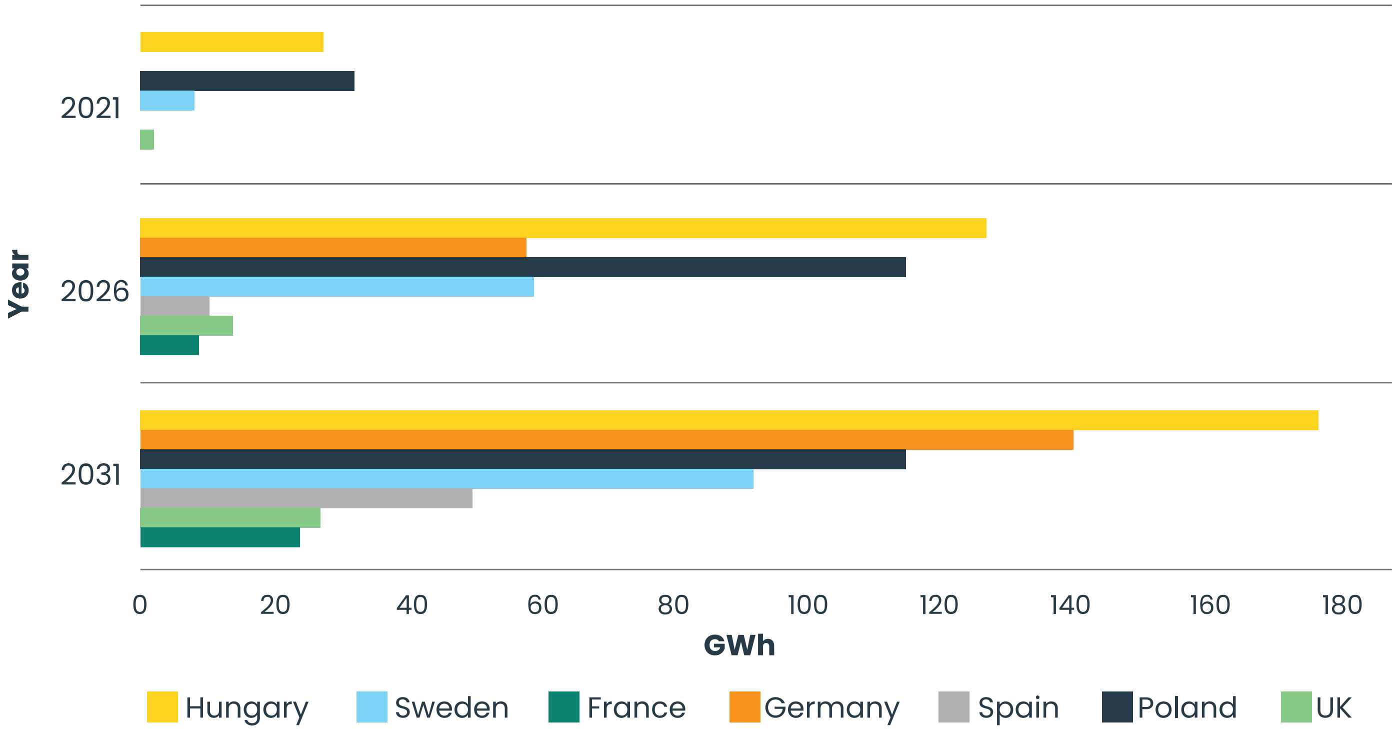


Europe

Europe is responsible for over a quarter of global EV production, but to date has played a smaller role in the battery supply chain [28]. However, this could change as analysts predict European market share, particularly around cell production capacity, is set to grow significantly based on current rates of investment – driven in large part by legislation [29].

For example, Europe currently has 11 battery plants but is expected to build 26 more by 2030: Poland, Hungary and Sweden are currently the largest European battery producers and are likely to continue to play a significant role over the next decade along with Germany, Spain and the UK, as shown in **Figure 7** [30].

Figure 7: Current and predicted geographical distribution of the EV battery supply chain in Europe



US

The US has only 7% of battery production capacity today [31] but investment is accelerating, with 12 new gigafactories announced in the US in 2022 [32], adding 343 gigawatt hours* (GWh) per year of capacity to the US pipeline (by comparison, in 2022 active US capacity was 70 GWh per yea) [33]. This acceleration is expected to continue after the US government passed the landmark Inflation Reduction Act in 2022 (IRA).

The IRA has already boosted battery investments in the North American market. Between August 2022 and March 2023, major EV and battery makers announced cumulative post-IRA investments of at least USD 52 billion in North American EV supply chains – of which 50% is for battery manufacturing, and about 20% each for battery components and EVs [34]. For further discussion of the IRA, see section 8.

4. What is the state of the UK's automotive sector?

The UK has a well-established automotive sector which plays an important role in the UK economy. The sector currently employs around 780,000 people, with more than 2,500 automotive-specific companies and generating GBP 67 billion in turnover annually [35]. Production in the UK is led by mass market and premium car manufacturing by a range of internationally owned businesses, including Jaguar Land Rover (whose global headquarters are based in Coventry), Toyota, Nissan, BMW and others. In addition, the UK is home to a broad array of commercial and vehicle manufacturers such as Alexander Dennis, Wrightbus and Leyland, as well as specialist luxury and performance automakers such as Aston Martin, Rolls Royce and McLaren.

Most of the models manufactured in the UK are ICE vehicles or hybrid vehicles, with a few exceptions such as the Nissan Leaf and the London Taxi Company's electric black cab [36]. Of the GBP 22.4 billion in exports generated by the automotive industry in 2022, 6% were EVs [37].

* A gigawatt hour is the standard measurement of the power output of electric power stations.

The latest known updates from the five largest automotive producers in the UK (those producing more than 100,000 units per year) regarding EV or battery production are:

- **Jaguar Land-Rover:** has a portfolio of fully electric, plug-in hybrids and mild hybrid cars and has stated in their global Reimagine strategy that the Jaguar brand will be all electric by 2025. A key part of the strategy is the new battery pack assembly centre at Hams Hall near Birmingham, which is expected to use 900 million battery cells in production each year. In May 2023, there were announcements suggesting that the company may look to build a multi-billion pound gigafactory at a site in Somerset, though this is yet to be confirmed [38]. This is following the company's earlier announcement that its first UK-made electric car would be a GBP 100,000 Jaguar four-door "grand tourer" built in Solihull in the West Midlands [39].

- **Nissan:** currently manufacturing its leading EV product, the Nissan Leaf, in the UK through a partnership with Envision AESC to supply batteries. Envision already have a gigafactory collocated at Nissan's Sunderland factory, and plans to expand capacity [40].

- **BMW:** In March 2023, the company announced plans to invest up to GBP 600 million in its Oxford plant where it manufactures its electric Mini, following financial support from UK government for GBP 75 million [41].

- **Stellantis (Vauxhall):** parent company Stellantis is currently developing European battery supply. In May 2023, the company warned that it was considering closing its Ellesmere Port factory where it manufactures electric vans due to European import tariffs [42].

- **Toyota:** in the UK, Toyota is focused on producing hybrids with smaller battery requirements. In January 2023 the company the company announced their first European battery assembly plant in Turkey [43]. In June 2023, the company unveiled plans for an EV that can do 600 miles on a single charge and targets to sell 1.5 million EVs a year by 2026.

5. Who are the main companies involved in the UK automotive battery sector today?

As highlighted previously, the UK automotive battery supply chain spans sourcing of raw materials, to production of cells, assembly of packs and recycling. This includes companies developing new technologies for the next generation of batteries, as well as those working to develop current battery production capacity such as automakers. Many of the new technology companies are home-grown university spinouts, while some are mass market automakers based in the UK but foreign owned. Both types of company play an important role in the UK automotive battery sector. **Table 1** shows a variety of companies which are either directly operating in the UK supply chain, or are working to develop new technology for next generation batteries. A more comprehensive list of the companies involved in the UK supply chain, is available from UK Research and Innovation's Cross-Sector Battery Systems Landscape Map.

Table 1: UK companies in the automotive battery sector

Raw material mining & refining	Materials processing	Component manufacturing	Cell & Pack Manufacturing	In-Life Usage Data	Recycling & 2nd Life
• Cornish Lithium Plc. • British Lithium Ltd. • Philips 66 Ltd. • Northern Lithium Ltd.	• Green Lithium Refining Ltd. • Tees Valley Lithium Ltd. • Mitsubishi Chemical UK Ltd.	• Echion Technologies Ltd. • Nyobolt Ltd. • Addionics Ltd. • Nexeon Ltd • Ilika plc. • Faradion Ltd. • Inobat Auto (UK) Ltd • Anaphite Ltd.	• AMTE Power plc. • Nyobolt Ltd. • Avid Technology Ltd. • Envision AESC Ltd. • Hyperdrive Innovations Ltd. • Hyperbat Ltd • Williams Advanced Engineering Ltd • Delta Cosworth Ltd	• Brill Power Ltd • Eatron Technologies Ltd • Breathe Battery Technologies Ltd • Spark EV Technology Ltd • Dukosi Ltd **EV Manufacturing:** • Tevva Motors Ltd. • Alexander Dennis Ltd	• Zenobe Ltd. • Powervault Ltd. • Acceleron Ltd. • Circulor • Everledger Ltd. • Veolia UK Ltd.

Some of the largest and most important companies in the UK automotive battery sector which are omitted from the table above are the mass market automakers, which although foreign owned, still play an important part in the UK battery sector, often through strategic investment or partnerships in EV production or battery research and development (R&D). According to the Society of Motor Manufacturers and Traders (SMMT), automakers have invested GBP 10.8 billion in EV production and battery R&D since 2011 [44]. Notable past examples include Nissan, which partnered with Envision AESC to build a gigafactory for producing cells for its Nissan Leaf in Sunderland which opened in 2013 [45], Ford's GBP 230 million investment into its Halewood plant to build electric motors [46], and Stellantis' GBP 100 million investment in its Ellesmere plant to build electric vans [47]. These projects generate local employment, tax revenue, and often bring new expertise to the UK. For example, Envision AESC's planned gigafactory in Sunderland has required an initial investment of GBP 450 million, and by the time it has finished is expected to require at least another GBP 1.35 billion and create over 6,000 jobs at Nissan and its local suppliers [48].

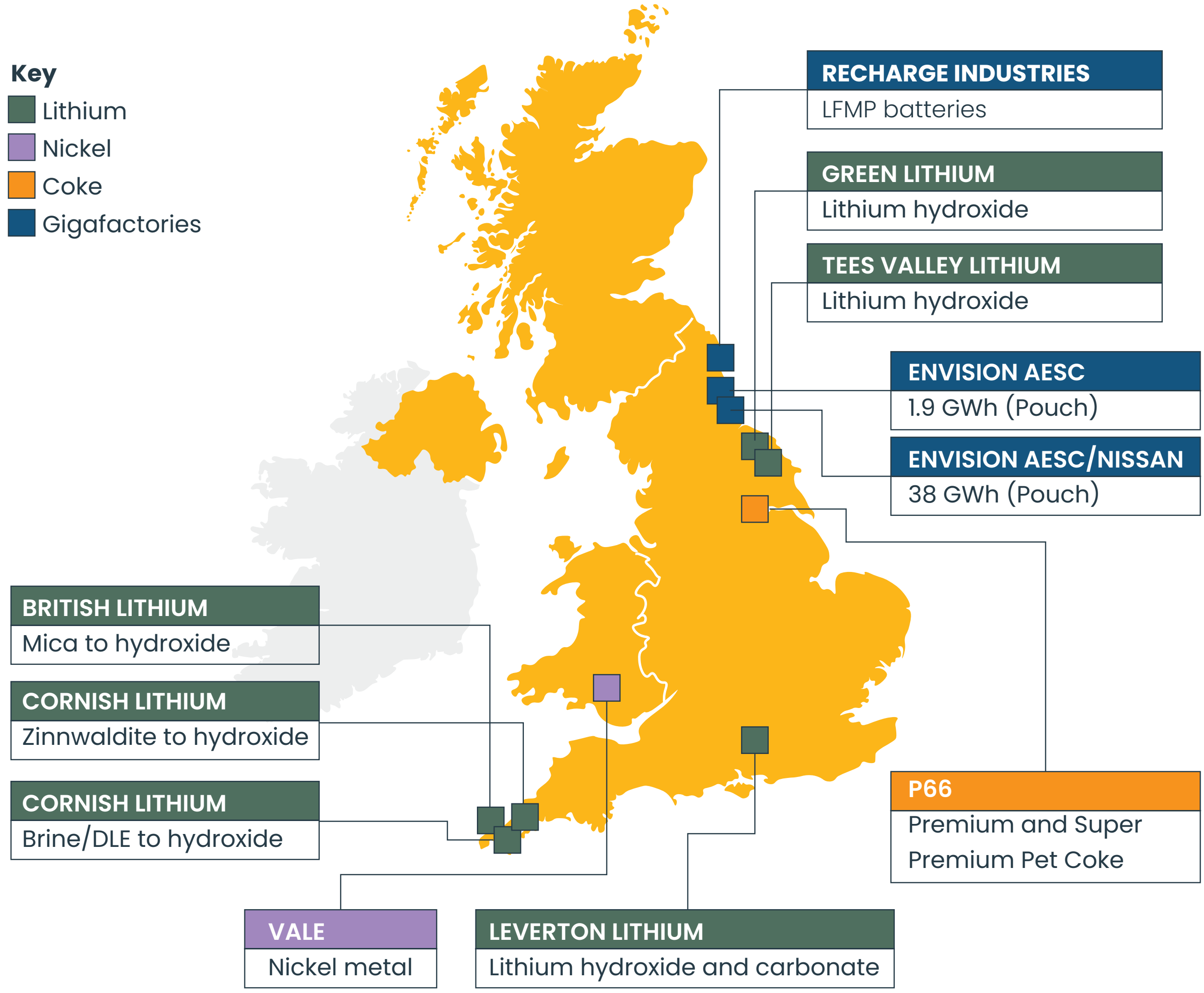
6. What is the state of the UK battery supply chain at present?

The UK's battery supply chain has a strong pipeline of developing projects in the upstream, a range of announced projects in the downstream, but as of yet relatively little current production capacity in the midstream portion as shown in **Figure 8** [49].

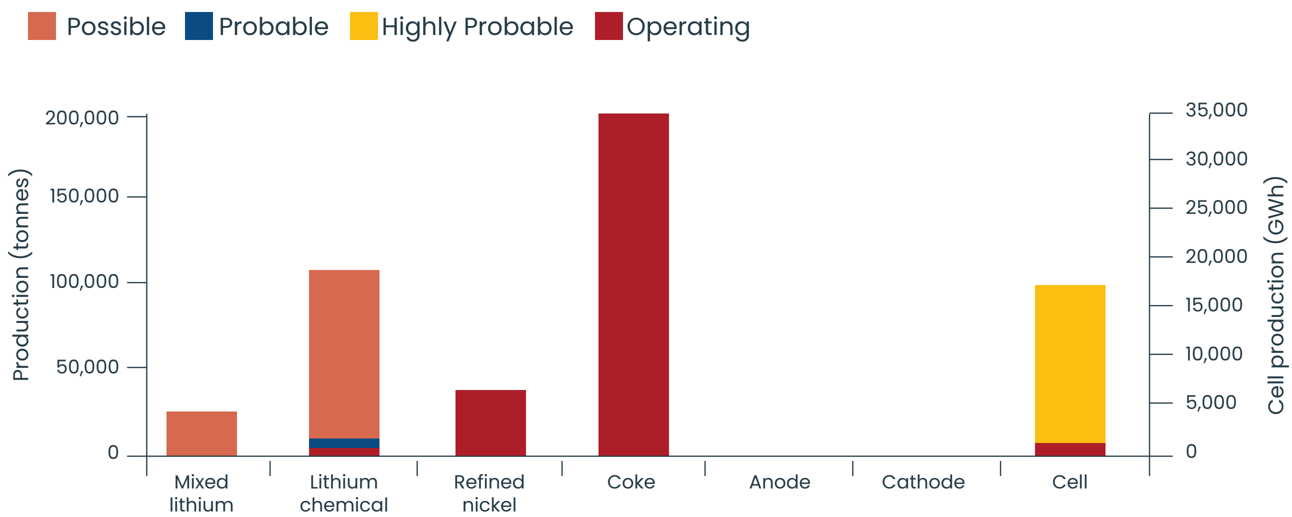
However, there are significant market opportunities that the UK is well placed to capture – not just in multi-billion pound gigafactories and battery production, but also in a wide range of businesses of various sizes across the entire supply chain.

Figure 8: The UK Battery Scene

Although the UK has some upstream and downstream production, it lacks any cathode or anode producers.



Source: Benchmark Lithium Forecast, Benchmark Nickel Forecast, Benchmark Synthetic Graphite Forecast, Benchmark Gigafactory Assessment



Source: Benchmark Lithium Forecast, Benchmark Nickel Forecast, Benchmark Synthetic Graphite Forecast, Benchmark Lithium Ion Battery Database

7. What is the state of the UK battery supply chain at present? (Continued)

Upstream

The UK currently has limited upstream capacity in the battery supply chain, producing and exporting some of the demand for key raw materials and chemicals needed in both the UK and Europe for automotive battery production. Currently, high needle coke is produced in the Philips 66 plant in Humber, electrolyte solution at Mitsubishi Chemical plant in Billingham, and nickel at a site in Wales. There are variety of projects in the pipeline which show potential to help meet some of the increasing demand for raw materials, including several plants for extracting and refining lithium, and others looking to produce graphite. For example, Cornish Lithium is planning to build a lithium extraction plant in Cornwall, two lithium refining plants are to be built in Teeside, (Teeside Lithium and Green Lithium), and Tokia Carbon aims to have sufficient graphite capacity for 600,000 EVs by 2030 [50].

Midstream

The UK is yet to establish cell component (anode and cathode) production facilities, characterised by some as 'the missing middle' [51]. Previously Johnson Matthey's pilot plant produced cathode active material in the UK, however the company exited the battery industry in 2022 and the plant and patents were bought by EV Metals for GBP 50 million. This presents an opportunity in light of European Rule of Origin [52] requirements, because companies in Europe will need to obtain cell materials from a limited pool of qualifying sources [53]. Local cathode and anode production facilities would also provide key customers for chemical producers in the Upstream.

The UK will need to grow its large scale cell manufacturing capacity (i.e. number of gigafactories) beyond the current pipeline of projects if it is to meet the forecast demand for EVs. By 2030, the UK is expected to need 100 GWh of production capacity per year, roughly equating to five gigafactories [54].

Currently the UK has one gigafactory, operated by Envision AESC in Sunderland, which produces 1.9 GWh. The company plans to expand its Sunderland operations initially to 12GWh capacity [55].

Recent announcements suggest that Jaguar Land-Rover may look to build a multi-billion pound gigafactory at a site in Somerset, though this is yet to be confirmed [56]. Other potential projects include plans by the West Midlands Combined Authority to use Coventry Airport as a preferred gigafactory site should investment be secured [57], and AMTE Power, a UK based startup, is looking to develop its capability to manufacture automotive cells in a megafactory (a small gigafactory) in Dundee [58].

Downstream

As well as cell manufacturers, a battery supply chain needs companies that are able to assemble the battery module and pack using cells acquired from cell manufacturers. The UK has some battery assembly capabilities but will need to grow capacity if it is to meet demand forecasts [59].

Second Use and Recycling

Recycling is a new sector, and like many countries, the UK is yet to build battery recycling at industrial scale, primarily because there are no UK-based midstream battery manufacturers to provide feedstock, a particular challenge for recycling plants which need minimum levels of waste material to process to be economically viable [60]. However, strong EV adoption in recent years, combined with legislative recycling targets for batteries, is expected to create a steady pipeline of retired EV batteries to recycle. Recent announcements, including Veolia's plan to open a new EV battery recycling plant in the UK, are a promising sign that this could be a growth sector. A strong UK recycling industry would also attract battery manufacturers to build gigafactories in the UK, particularly those interested in using recycled materials to produce EV batteries rather than using newly mined raw materials.

8. How does the UK sit amongst other nations in terms of its competitiveness to host a battery supply chain?

The UK is recognised as having a number of **strengths** which make it an attractive location to scale up the battery supply chain. These include:

- **the expertise of the existing automotive industry and academic institutions**, providing a steady source of new ideas, innovation and skilled talent [61]
- **one of the largest and fastest growing** EV markets globally [62], supported by a market leading commitent to ban the sale of ICE vehicles, beginning in 2030. For more information see Section 3
- **an interconnected support and grant system** to provide R&D and scale up support. Key programmes include the Faraday Battery Challenge, the Advanced Propulsion Centre, the Automotive Transformation Fund and the UK Battery Industrialisation Centre - see Section 8 for more details
- **an established automotive supply chain** [63] with over 180 companies producing components for EVs including electric machine developers and producers [64]
- **high quality academic research** into new battery technologies [65]
- **a strong pipeline of startup businesses** in the battery supply chain [66]
- **a largely decarbonised grid** meaning green energy is used in manufacturing [67]
- **skilled labour availability** in both the chemicals and automotive workforce [68]

The key **challenges** are:

- **policy support** equal to competing countries [69]; as other countries grow their supply chains and introduce more incentives to attract battery manufacturers, UK policy intervention will also be need to be competitive.
- **energy costs**, particularly industrial energy costs [70]
- **slow planning** and grid connection processes [71]

The outlook overall however includes several positives. The UK ranked 8th out of 30 countries for 'industry, innovation and infrastructure' on BNEF's 2022 battery supply chain ranking [72] and has also generated very strong levels of early stage investment in recent years [73].

The UK has a growing number of start-ups and a strong position in terms of early stage equity investment. In 2022, the UK EV Battery ecosystem had the second highest enterprise value in Europe at USD 1.2 billion, second to Sweden at USD 4 billion (most of which came from Northvolt). Investment in the UK ecosystem also nearly doubled from 2021 to 2022, showing stronger resilience than many of the top funded ecosystems [74].

Power Electronics, Machines and Drives (PEMD)

"EVs are propelled by electric motors, which require power electronics and drives to operate. Together these are commonly referred to as PEMD and with batteries make up an EV's drivetrain. The UK is world leading in many of the most advanced PEMD technologies such as silicon carbide (SiC) or rare earth free motors. These technologies and the UK's ability to innovate in their manufacturing and scale up will be fundamental to the growth of EV manufacturing in the UK."

Venn Chesterton, Innovate UK Knowledge Transfer Network (KTN)

9. How does the automotive battery market relate to other battery markets, such as energy storage?

Current demand for Li-ion batteries in the UK comes primarily from private cars and portable consumer devices [75]. However, the UK's planned phase-out of ICE vehicles will mean that by 2030, 84% of total battery demand is expected to come from the automotive sector (80% for light duty vehicles and 4% for buses and trucks) [76] with the remaining 16% to come from consumer electronics, micromobility and stationary storage [77].

These sectors will continue to generate significant demand, offer potential alternative markets for the future UK battery supply chain, and also likely benefit from the R&D and manufacturing advancements that will arise due to demand from the automotive sector [78]. The scale of automotive demand to date has already been hugely beneficial to the battery industry - battery pack prices have plummeted from an average of USD 1,100/kWh in 2010 to USD 132/kWh in 2021 [79].

Energy Storage

Automotive batteries are increasingly being seen as an asset due to their potential to be used for energy storage both whilst they are in an EV due to new vehicle-to-grid (V2G) technologies, and their 'second life' in stationary storage applications, creating potential residual value for investors in new automotive batteries today. Both V2G and stationary storage applications, such as grid-sclae storage, will be key to decarbonising the UK electricity system and regulating seasonal variations in renewable generation. Cost and cycle life (the number of charge and discharge cycles that a battery can complete before losing performance) are more important metrics than energy density (the measure of how much energy a battery contains in proportion to its weight or volume) for energy storage batteries, making lower-cost chemistries such as lithium iron phosphate (LFP) and sodium-ion (Na-ion) batteries suitable (see section 5 for details on chemistries). Automotive batteries can also be used for stationary storage in their "second-life" (see section 7), creating potential residual value for investors in new automotive batteries today.

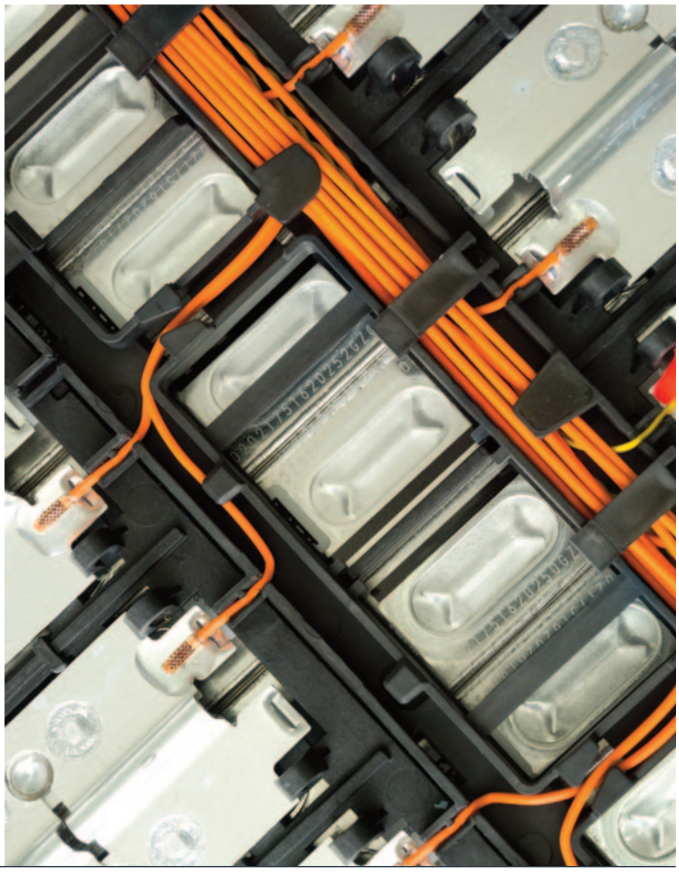
Furthermore, as automotive battery technology evolves, those chemistries that may become less attractive for EVs can be deployed at a lower cost for stationary applications on the grid [80]. The UK already has around 4 GW of energy storage in operation, 25% of which is provided by batteries [81].

Micromobility

Micromobility is projected to make up an increasingly important part of the EV market with the global fleet of two- and three-wheel vehicles expected to increase from 290m in 2022 to 800m in 2040 [82]. Lower energy requirements mean micromobility vehicles have much smaller battery packs than passenger cars. However, the batteries use similar chemistries, presenting further offtake options for manufacturers of Li-ion cell components in the UK battery supply chain [83].

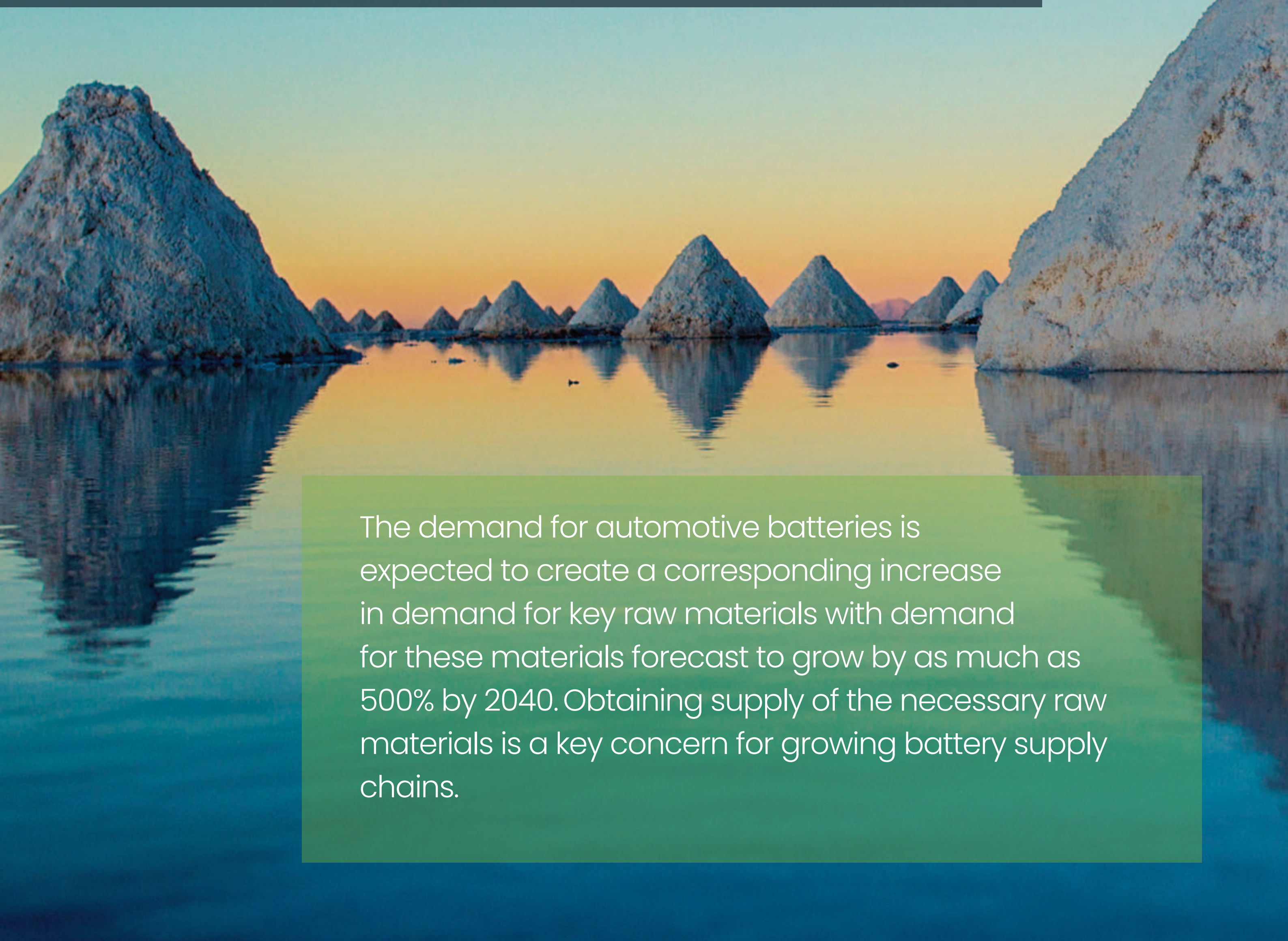
HGV's & Aerospace

HGV's, aviation, and maritime are expected to be more difficult sub-sectors of transportation to decarbonise and electrify. However, progress is being made and there are likely to be opportunities for emerging battery technologies, albeit in lower volumes than for cars and vans.



4. Upstream:

Raw material extraction and processing



The demand for automotive batteries is expected to create a corresponding increase in demand for key raw materials with demand for these materials forecast to grow by as much as 500% by 2040. Obtaining supply of the necessary raw materials is a key concern for growing battery supply chains.

Raw material extraction

1. Why are raw materials important to EV battery production?

There are two main ways to source raw materials today:

1. Primary raw materials: Sourced directly from the earth, and extracted in a variety of methods [84]. Currently, primary raw materials account for the vast majority of global supply [85].
2. Secondary raw materials: Recovered from waste products through various methods. Although this currently accounts for a minimal amount of supply, in the shift to a circular economy the distribution of supply is likely to shift towards secondary sources, driven by regulation and improved recoverability of raw materials from older batteries [86].

Although current estimates suggest that there are sufficient raw material reserves in the earth to meet long-term future demand, investment in production facilities is needed if the mining industry is to keep up with investment in battery manufacturing. Global investment in gigafactories is reportedly three to four times the pace of investment upstream [87], and extraction projects take 16 years on average from discovery to first production [88]. New regulations are now being introduced to require battery manufactures to source more raw materials from recycled sources [89], for example, the EU's recently approved battery market regulations has introduced minimum and increasing thresholds for battery raw materials from recycled sources.

This section will focus on primary raw material extraction, with secondary or recycled raw materials being addressed in section 7.

2. What are the opportunities for investment in raw material extraction in the UK?

Although the UK is unlikely to satisfy the entirety of its key raw material demand for batteries from local supply, there are some UK-based investment opportunities:

- Local extraction projects which could provide a more reliable source of key raw material for UK businesses that also have stronger Environmental, Social, and Governance (ESG credentials than foreign sources;
- Technologies being developed by UK companies that could be commercialised for the global mining industry to help them improve extraction capabilities or lower the carbon footprints of their operations;
- Refining and manufacture of precursor materials;
- Developing technologies using next generation chemistries which reduce reliance on current high-demand raw materials. For example, Faradion is a UK-based company developing technology which uses sodium instead of lithium [90]. For more information on Na-ion batteries, see Section 5.

There is likely to be high demand for raw material extracted in the UK because of the increasing pressure on companies to develop transparent supply chains, both from regulation – such as the Modern Slavery Act 2015 - and from consumers increasingly focused on ethical purchasing. The UK can also boast greater sustainability due to its green energy mix [91]. UK companies, which are exploring more environmentally friendly sources of extraction, present an opportunity for automakers looking to produce an EV battery with strong green credentials and lower carbon footprint. For examples of UK opportunities in this area, see the Appendix.

3. What are the key raw materials for battery production?

Common raw materials required for batteries include lithium, manganese, cobalt, nickel, phosphate and iron in the cathode, graphite and silicon in the anode, copper or aluminium in the current collectors, and steel or aluminium in the protective casing of the battery pack. Recently, sodium has also started to be used as an alternative to lithium.

The most important raw materials (**lithium, nickel, cobalt** and **graphite**) for producing batteries are used in the battery cell, and these will be the only materials covered in the Guide. These are the most important because they make up significant proportions of the cathode and anode (which combined account for more than half of a cell's raw material) and are specifically selected for their chemical properties.

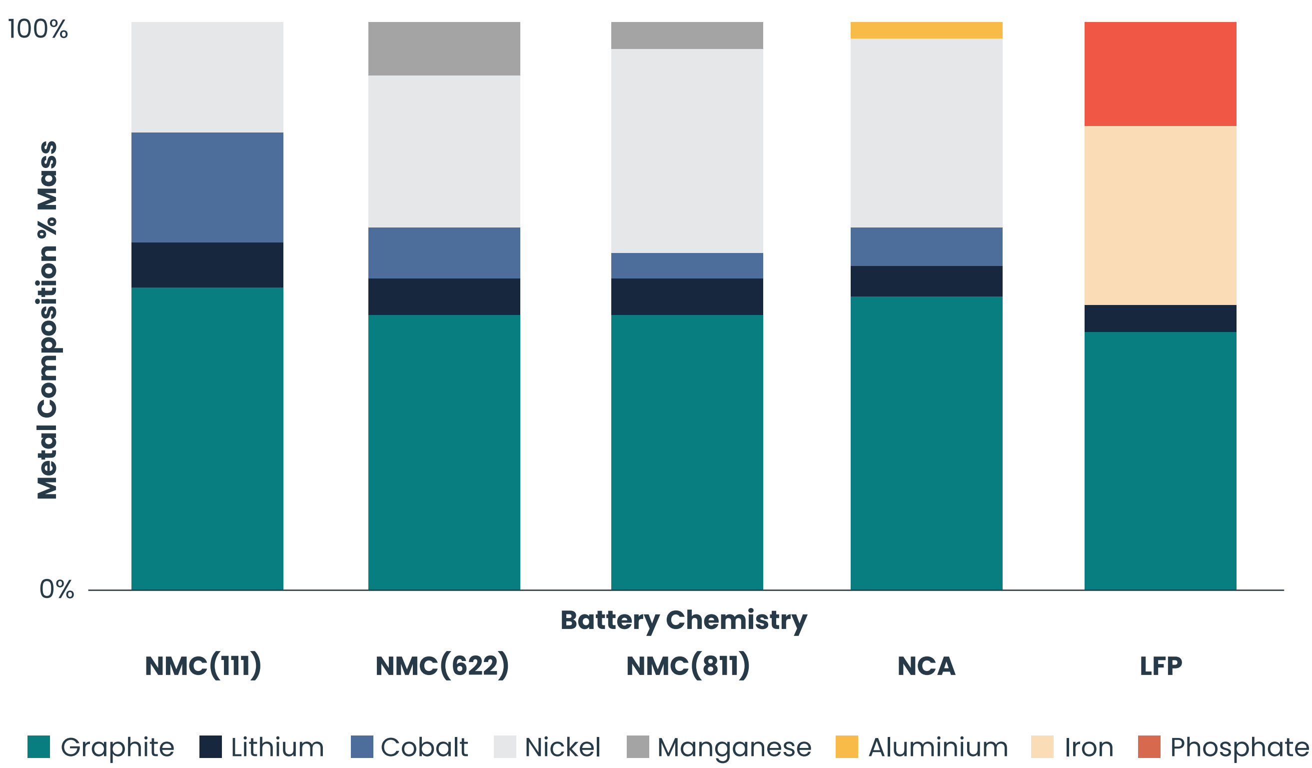
This means they tend to be harder to substitute with other materials, and often have smaller and less developed supply chains, which means they suffer from higher risk of global supply chain disruption [92].

Other raw materials mentioned above (manganese, silicon [93], phosphate [94] etc.) either tend to be more abundant, have multiple end uses or have more developed supply chains, and therefore will not be discussed in this Guide.

4. What is the balance of raw materials used in different battery chemistries?

Figure 9 shows a comparison of the internal raw material composition for some of the most common types of batteries used in EVs today, according to their chemistry [95]. Availability and sustainability of these key materials are likely to influence development of future chemistry market share. Technological developments in different chemistries could also affect raw material demand - for example, there is a growing trend of using silicon in anodes due to benefits offered in performance, and also growing potential for non-lithium based chemistries, such as Na-ion. For further detail on the market share and adoption rates of these types of battery, see section 5.

Figure 9: Raw Materials Composition of Batteries

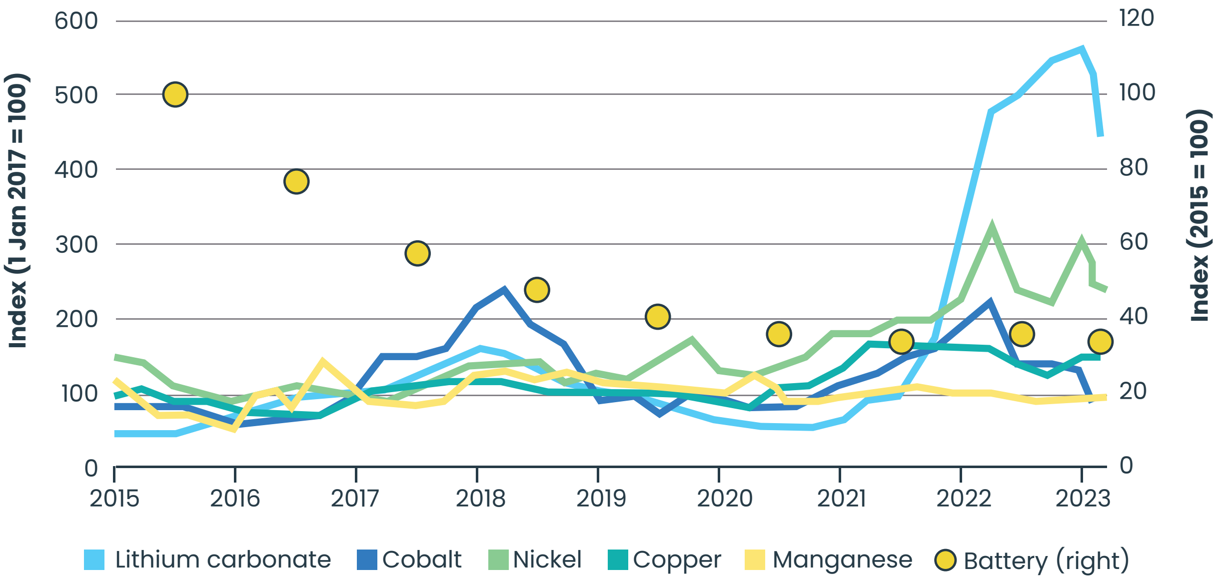


5. What are the main sources of key raw materials?

Overview

Due to the nature of raw material deposits and the long time and high upfront cost required to set up mining operations, the sources of key raw materials tend to be heavily concentrated in a few locations which can lead to large fluctuations in price, as shown in **Figure 10**.

Figure 10: Price of selected battery materials and Li-ion batteries, 2015-2023



Notes: Data until March 2023. Li-ion battery prices (including the pack and cell) represent the global volume-weighted average across all sectors. Nickel prices are based on the London Metal Exchange, used here as a proxy for global pricing, although most nickel trade takes place through direct contracts between producers and consumers. The 2023 battery price value is based on cost estimates for NMC 622.

Source: IEA analysis based on material price data by S&P, 2022 Li-ion Battery Price Survey by BNEF and Battery Costs Drop as Litium Prices in China Fall by BNEF.

Lithium

Lithium is extracted from two sources, brine or hard rock. Brine extraction involves drilling down through the crust and pumping the brine up to the surface into evaporation pools. This creates a salty mud mixture of different minerals which are then moved to another open-air evaporation pool. Lithium brines are typically located in areas of Bolivia, Argentina and Chile in South America (known as the lithium triangle). Lithium spodumene on the other hand, is obtained from rock deposits, typically open-pit mines, primarily located in Australia.

Currently, lithium supply is highly concentrated, with the top-five suppliers accounting for approximately half of global production [96].

Although there are believed to be sufficient lithium reserves, there is a concern that certain future supply of high quality lithium will continue to be concentrated in a few sources which could lead to short term supply shortages if investment is not made into new extraction projects. For example, although China currently has relatively little extraction capacity, large amounts of Chinese investment are going into African extraction projects [97].

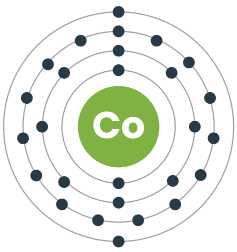
Lithium is expected to remain the dominant material in EV batteries for the foreseeable future, which means local extraction projects will be in high demand as they will enable companies to increase control over their supply chains and reduce reliance on overseas sources [98].

Nickel

Nickel is found primarily in two types of deposit – sulfide and laterite. Sulfide deposits are mainly located in Russia, Canada and Australia. Despite being in much lower supply (and being affected by Russia's invasion of Ukraine) this tends to be more desirable since it is more easily processed and less energy intensive than laterite, which is mainly found in Indonesia, Philippines and New Caledonia [99].

Nickel production is less concentrated than lithium with nine companies supplying half of global nickel production, and forecasts range from slight undersupply to potential oversupply of nickel if stakeholders achieve their planned mining and refining potential [100]. However, companies could still have difficulty acquiring sufficient quantities because of quality requirements [101] and the limited geographic distribution of mines.

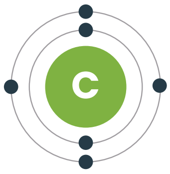
Batteries with high nickel content have continued to grow in popularity because of their high energy density. For more information on energy density and next-generation battery technologies being developed in the UK, which provide alternatives to high-nickel batteries, see section 5.



Cobalt

Cobalt is predominantly mined as a by-product of copper or nickel mining which can lead to volatility in supply and price [102]. Over 70% of cobalt is produced from Chinese owned mines in the Democratic Republic of Congo (DRC) [103], where regulation is limited and child labour is a concern [104].

These factors combined with the growing need for supply chain transparency have led to a decrease in popularity of battery chemistries which use cobalt [105].



Graphite

Graphite is the dominant anode material and can be found in natural (flake) form or produced synthetically from two main sources of feedstock, either petroleum coke from oil refineries or pitch coke which is a by-product of coal production. Synthetic coke products need to go through an energy intensive process called 'graphitisation' in order to be used in batteries. Once natural graphite is mined, it is ground into spherical graphite before it can be used in an anode.

Anode producers tend to use a blend of synthetic and natural graphite because they have different qualities – the former is safer, has greater longevity and is 55% less energy intensive to produce whereas the latter has higher capacity [106]. The feedstock for natural graphite is more common and therefore also lower cost. Recently, Western anode producers have preferred natural graphite because of its lower cost and carbon footprint. Forecast supply surplus in the near-term suggests this trend is likely to continue [107].

Both sources of production are dominated by China: it currently accounts for 64% of natural graphite mining, and over two thirds of synthetic graphite. Just nine companies across six countries are forecasted to produce either form of the material outside of China by 2030 [108].

There is some potential for this to diversify, with natural graphite mining projects being developed in Africa, North America, and Europe, and over a quarter of estimated global reserves currently held in Turkey. Some firms in the US are also looking to develop synthetic production capacity using locally produced needle coke [109].

Graphite is likely to remain the dominant material in anode production for the foreseeable future.

6. What are the UK capacities in raw material extraction?

The UK currently has no extraction capacity for key battery raw materials, but it does have a pipeline of projects looking to develop lithium capabilities. The UK government has set out plans in its Critical Minerals Strategy to capitalise on the country's heritage and R&D capabilities in mining [110] to support growth of domestic extraction capacity [111]. However, current forecast demand for lithium means the UK is always likely to need additional foreign sources of supply.

Planned capacity:

- Cornish Lithium are exploring lithium extraction in Cornwall, with plans to use direct lithium extraction to produce lithium hydroxide, though the resource and technology have yet to be proven at a commercial scale. It has raised a total of GBP 14.7 million in funding over seven rounds, most recently in September 2022 which included a GBP 2 million grant from the government's Automotive Transformation Fund (ATF) for construction of its geothermal lithium recovery pilot plant near to Redruth. The round was participated in by TechMet, a corporate investor in renewable technologies based in Malta [112].
- British Lithium has been researching and developing the extraction of lithium carbonate from Cornish granite. In 2022, it received GBP 2 million grant from the ATF to progress to the next stage of the project [113].
- Weardale Lithium is seeking to extract sustainable lithium from underground lithium-enriched brine in Weardale, County Durham using geothermal energy. It recently received a grant from the ATF to trial the effectiveness of its extraction technologies [114].

7. What innovations are happening in extraction of key raw materials?

New technologies are being developed that are helping to provide new sources of key raw material supply, and do so in a way which is more sustainable and lower cost. For example, direct lithium extraction (DLE) and direct lithium to product (DLP) both show potential in enabling the industry to respond more swiftly to soaring lithium demand, offering key benefits including shorter production times and lower usage of resources such as water.

To date only adsorption DLE has been used on a commercial scale in Argentina and China, but outside of these countries there are a number of companies testing various DLE approaches, including Cornish Lithium in the UK [115]. The company has created a plant which is the first of its kind in Europe, with its goal being to demonstrate that lithium can be produced from geothermal waters with minimal impact on the surrounding ecosystems. At scale, the innovation has potential to achieve higher recovery levels with lower operating costs and carbon footprint than traditional sources of lithium.

Battery supply chains, ESG concerns, and battery passports

The growth in demand for batteries globally has highlighted the environmental and social risks across the battery supply chain, including greenhouse-gas (GHG) emissions, pollution and human rights issues. To ensure growth of a sustainable and circular industry, there is a need for greater transparency to ensure that investment can be channelled into companies which maintain transparent and sustainable practices.

A proportion of embedded GHG emissions (estimated at 60%) in EVs comes from the manufacture of batteries due to the energy-intensive raw materials required. Reducing embedded emissions presents a significant opportunity, however it can be challenging to do this without more data around the provenance of batteries and materials used.

Beyond emissions, there are significant social and environmental challenges across the battery supply chain. The extraction and refining of raw materials, as well as cell manufacture, can have severe environmental effects, such as land degradation, biodiversity loss, creation of hazardous waste, or land and water contamination. Raw material extraction operations also risk violations of labour laws, child and forced labour , and contravention of indigenous rights. Downstream, unprofessional or illegal battery disposal can cause severe toxic pollution.

There are various initiatives which are helping to address investor concerns about the lifecycle environmental and social impact of their investments. Battery passports, which use digital twins of physical batteries can keep track of their components to ensure transparency, will be essential for demonstrating the sustainability of investments in the battery supply chain. Companies are also innovating new supply chain management tools to help players in the battery supply chain develop strategies to understand, manage, and improve supply chain sustainability (for examples of UK opportunities in this area, see the Appendix.)

The Global Battery Alliance (GBA), is a collective of 140+ members, spanning the entire battery value chain from miners to recyclers, who are developing battery passports. At the World Economic Forum's Annual Meeting in Davos in January 2023, the GBA launched a proof of concept to show how battery passports can help investors track emissions more reliably and ensure that batteries are produced in a socially responsible manner. The Battery Passport will provide trusted information on indicators related to responsible and sustainable practices, resulting in a 'quality seal' capturing authenticated records of the responsible sourcing, management, recycling and use of a battery across its full lifecycle.

Primary & secondary raw material processing

1. What is raw material processing?

After extraction, raw materials need to be processed to create high-purity chemicals and precursors that can be used for battery cell manufacture. Often refining is done by the mining company together with the extraction (for instance British Lithium in the UK is looking to develop operations both to extract and refine lithium) whereas in other cases the raw material is exported to third parties to be processed.

2. What opportunities are there in the UK for investors in raw material processing?

The various steps involved in transforming raw materials into the chemicals needed for battery manufacture each add value and present a potential opportunity for companies in the UK to participate in the global battery supply chain. Building on the UK's expertise within the chemicals industry could provide an opportunity to develop local refining capabilities. One driver for this is regulation; the proposed Critical Raw Materials Act, specifies that Europe will need to meet a minimum percentage of its own demand for processed minerals [116].

Local refining projects could, in future, be viewed as viable green investments, presenting a promising opportunity for investors drawn to this sector due to their potential for strong revenue certainty and the high demand for their products. This possibility, however, is contingent upon green taxonomy definitions being broadened to encompass the entire supply chain.[ii] This idea is underscored by the mounting ESG obligations placed on cathode mixers in the EU and UK, which put pressure on the transport supply chain to abide by greener standards. Differentiation is possible for companies processing material using more sustainable processes - particularly if done locally, since transport significantly raises the carbon footprint of these assets. Demand for green products is also growing in other industries, which means that local material processing companies could have a variety of options for offtake – for example, a refiner of high quality and sustainable needle coke could have options for offtake in the steel industry, as well as batteries. For examples of UK opportunities in this area, see the Appendix.

3. What are global capacities for primary raw material processing?

Raw material processing is currently even more geographically concentrated than extraction, with the majority of processing for battery materials currently residing in China. Five major companies are responsible for three-quarters of global production capacity and many larger companies are embarking on capacity expansion and acquisitions in order to gain share and drive competitive edge in the market [117].

China's share of global refining capacity is around 35% for nickel and 50-70% for lithium and cobalt [118]. It also processes 100% of the world's spherical graphite and 69% of synthetic graphite [119]. Chinese companies support their processing capacity dominance by making substantial investments in overseas assets in Australia, Chile, the DRC and Indonesia, giving it a significant advantage in securing unprocessed raw materials. For example, 60% unprocessed Australian lithium spodumene is exported for processing to China [120], as is 75% of Congolese cobalt [121].

Governments are regulating to ease reliance on processed materials from China. Both Europe and the US currently have limited raw material processing capabilities compared to China [122], though this is expected to change following introduction of the Critical Raw Materials Act in the EU and IRA in the US, both of which require increasingly high minimum thresholds for processed minerals to be sourced from certain territories [123]. This is driving American and European investment to secure refining capacity both locally and overseas – for example, Tesla is looking to build a lithium refinery in Texas [124], and GM has invested in nickel and cobalt operations in Australia [125].

[ii] The EU Taxonomy is considering inclusion of broader supply chain activities. This extension to cover comprehensive value chain-enabling activities could potentially recognise companies like Green Lithium in future frameworks, given that their refining operation at Teeside is projected to deliver an 80% lower carbon footprint than similar processes globally.

4. What are the UK capacities in raw material processing at present?

The UK has some raw material processing capabilities including nickel and coke refining, and has lithium processing in the pipeline. These present opportunities to export to wider markets such as Europe.

Current Capacity:

- **Nickel:** The UK also has a long-standing tradition of nickel refining, dating back to 1902 in South Wales. Today, with 40 kilotonne battery grade capacity, the Vale's Clydach refinery is one of the largest nickel refineries in Europe. It produces around 40,000 metric tons of nickel products per year and supplies around 280 clients in over 30 countries across the world [126].
- **Coke:** The Philips 66 refinery in Humber is the only coking refinery in the UK and the largest producer of specialty anode cokes in Europe, with plans to expand capacity [127]. Currently it produces 700,000 tonnes per year [128] which is mostly exported to China for graphitisation before it is used in battery production [129]. Increasingly, graphite producers are developing in-house graphitisation capabilities to attempt to capture more value in the graphite supply chain and reduce reliance on China [130].

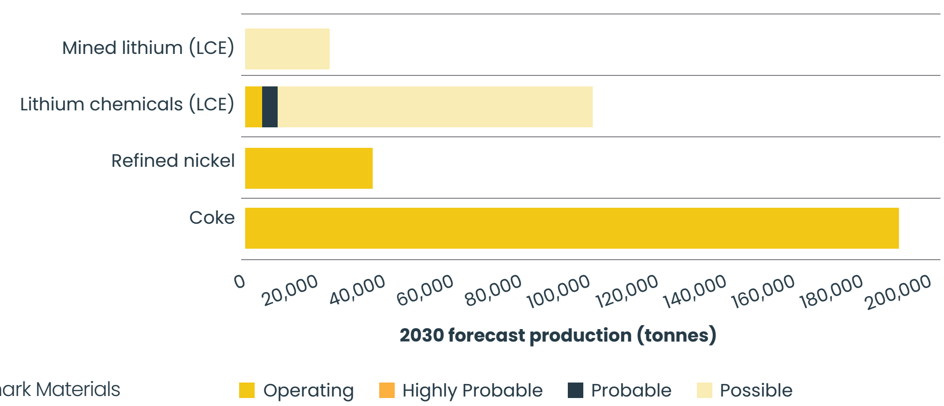
Planned Capacity:

- Announcements were made towards the end of 2022 for the UK's first lithium refinery in Teesside. Tees Valley Lithium is currently completing engineering and design work to be ready to start construction in 2023. The GBP 600 millon refinery will produce around 50 tonnes of battery-grade lithium hydroxide from 2025, enough for around one million EVs. The project is backed by commodity trader Trafigura, who will help source feedstock for the plant.
- Leverton Lithium has long produced lithium chemicals in the country, though many of its products are not destined for the battery market. At the start of the year, the company joined forces with European chemical producer Helm to expand its production capacity to 20,000 tonnes a year of "high-quality lithium chemicals" [131].
- Green Lithium has plans to produce battery-grade lithium hydroxide in Teesside with less than 50% of the carbon emissions seen in refineries in Asia. It also plans to use hydrogen instead of natural gas in the calcination step and deploy carbon capture to further reduce emissions. It expects to commission the plant around 2025 [132].

5. What are the latest innovations in raw material processing?

New processing technologies are increasing the flexibility of raw material processing routes, which could produce new sources of supply in response to growing demand for raw materials. For example, several techniques are being explored to increase the number of ways of processing nickel to produce nickel suitable for use in Li-ion batteries from lower grade laterite resources [133]. Other companies are exploring ways to refine key raw materials by recycling used Li-ion batteries (this will be discussed in Section 7.)

Figure 11: The current UK raw material processing pipeline, including current and future capacity



Source: Benchmark Materials

5. Midstream:

Cell and cell component manufacturing

To meet rising demand for batteries, 9,300 GWh of annual production capacity is required by 2030. According to data from BloombergNEF, the global capacity of Li-ion battery production reached 1,163 GWh in 2022.

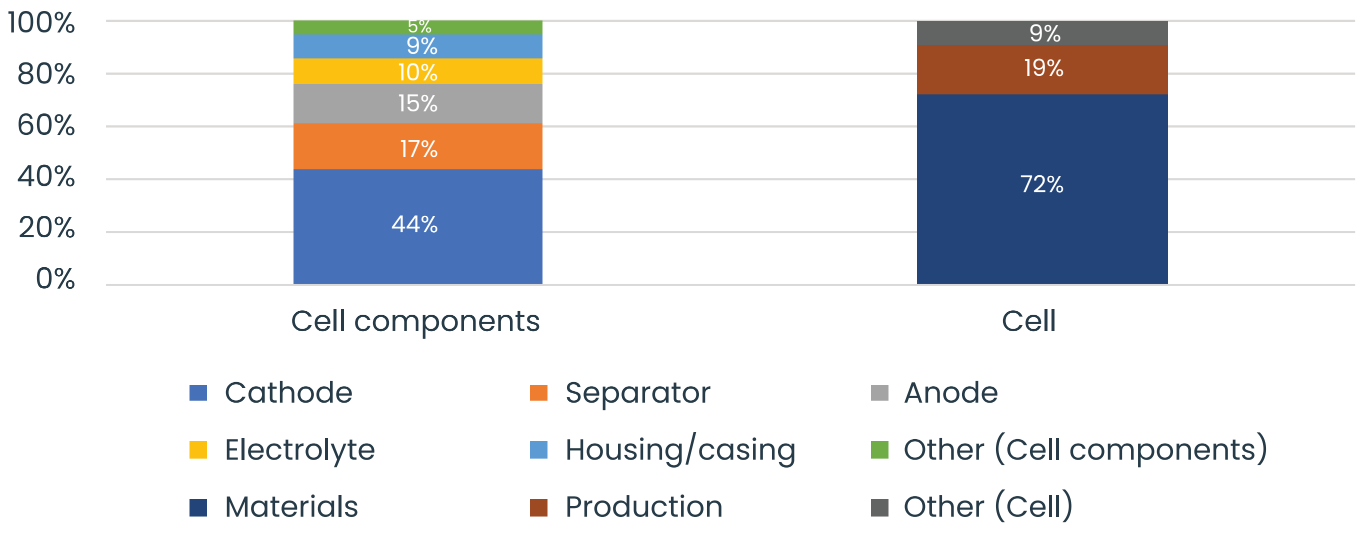
Cell component manufacturing

1. What is a cell and how are they manufactured?

Cell component manufacturing refers to the production of the different components that make up a cell. In its simplest form, a cell is made up of one cathode (positive), one anode (negative), an electrolyte solution, a separator and the cell housing (or casing). The types of materials used for these different components varies, and using different materials in the anode, cathode and electrolyte results in different cell chemistries (i.e. lead acid batteries or Li-ion batteries).

The cell account for about 77% of the cost of an average battery pack [134], meaning the success of the EV transition is largely determined by the price of the cell and can be realised by reducing the cost of the cell components, high volume production and process improvements. Looking at the cell by its different components, **Figure 12** illustrates how the share of the cost is split.

Figure 12: Share of cost of cell components and cell production



Source: Aachen University

2. What opportunities are there for UK investors?

Cathode manufacturing is rich in intellectual property (IP) and is very energy intensive. For this reason, cathode manufacturing facilities are often located in areas with access to low-cost, low-carbon electricity, near sources of pre-cursor materials with good transport links to customers.

The UK is well placed with two lithium hydroxide and carbonate producers who supply to existing cathode manufacturers. Since localisation is important to cathode manufacturers, because it can be difficult to transport materials like lithium hydroxide, the UK is an attractive location to these producers.

The UK is a significant European producer of high grade needle coke, a key material in the production of synthetic graphite used in Li-ion battery anodes. Most needle coke produced in the UK is currently being sent to China for graphitisation. However, there is an opportunity for anode manufacturers to set up in the UK to benefit from lower transport costs, tariffs and access to research networks.

The UK has an electrolyte production supplier, Mitsubishi Chemical Group, one of the two biggest players in Europe. With demand for electrolyte solutions growing as the EV market expands, there is an opportunity for the UK to build on its strong heritage in chemicals to significantly increase electrolyte capacity. In addition there is both intellectual property (IP) and material manufacturing revenue to be found in the highly specified electrolyte additives which make up just a few percent of the electrolyte by mass, but which impacts on the time it takes to make a cell, and the life of the cell in its end application. The UK's strong research base is attractive to suppliers who want to develop state of the art solid electrolytes [135], which will play an important role in future technologies such as solid state batteries (see section 5).

These opportunities require investment from both early and late stage investors as the market is made up of both well established players, in the case of Mitsubishi Chemical Group, and startups, in the case of cathode and anode manufacturers.

3. What are the main chemistries used for EV batteries in cars sold today?

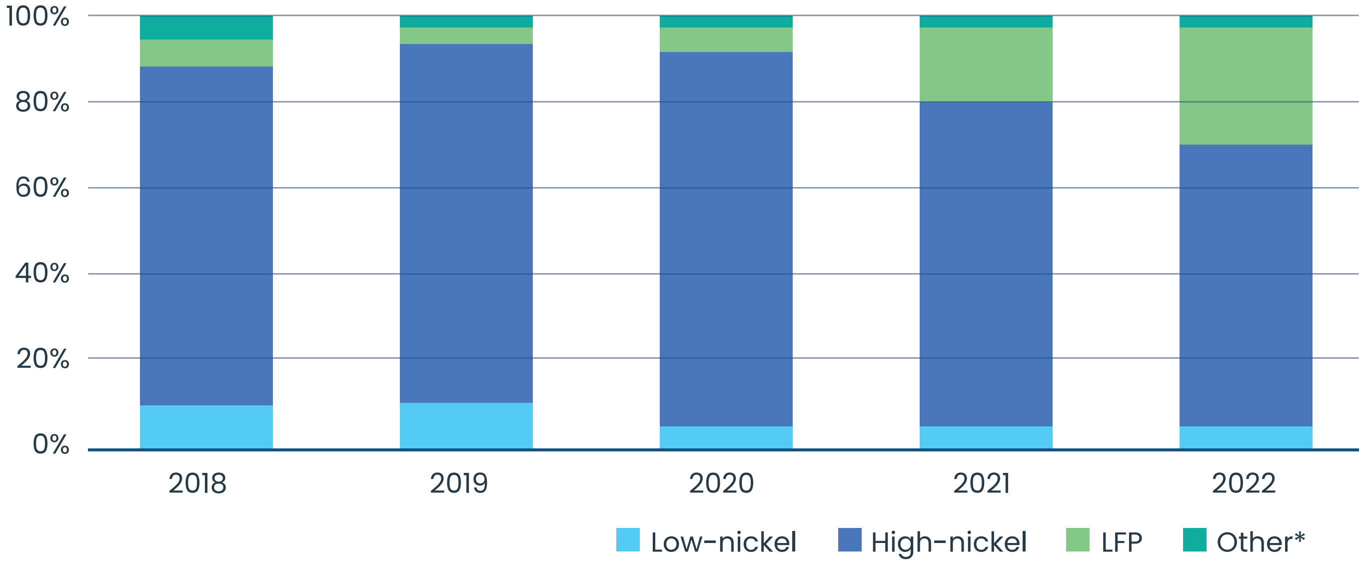
Most existing commercial EV batteries are based on Li-ion chemistry, which currently offers the best combination of energy density, longevity, versatility and affordability, making it the benchmark against which all potential alternatives are measured.

Li-ion is an umbrella term, encompassing a variety of different chemistry formulations which all use lithium ions to transfer charge between the anode and the cathode. Two main formulations of Li-ion battery dominate market share today – those which are nickel-based, and those which are iron (Fe) phosphate based (LFP batteries). There are also several different varieties of each formulation that contain different amounts of each material and are named accordingly – for example, NMC811 is a nickel-based Li-ion battery which contains 80% nickel, 10% manganese and 10% cobalt.

High nickel cathode chemistries have seen robust growth as demand for longer range EV batteries continues to increase; in 2022 they held a 60% market share [136]. Along with higher energy density, they also offer faster charging and better performance in colder climates. Currently 90% of LFP batteries are produced in China [137], however they are growing in popularity globally, reaching 30% market share in 2022 due to longer lifecycle, lower cost to manufacture and not relying on expensive raw materials such as nickel and cobalt [138]. **Figure 13** shows the market share over time, by chemistry [139].

Due to these different properties, automakers are already beginning to use different chemistries for different vehicle models, preferring high nickel chemistries for premium models and LFP for lower priced, mass market models [140]. Going forwards this trend is expected to continue as chemistries continue to diversify, though other factors such as recyclability (which is currently a challenge for LFP batteries) could also play a role. For more information on recycling, see Section 7.

Figure 13: Electric light-duty vehicle battery capacity by chemistry, 2018-2022



Note: Other includes previous generation Li-ion batteries, lithium manganese oxide (LMO) and lithium cobalt oxide (LCO). LMO was used in the 1st generation Nissan Leaf battery pack, and now some consumer electronics. LCO was the first Li-ion chemistry to be commercialised by Sony in 1982, mostly now used in consumer electronics and power tools industry.

Source: Faraday Institution (2020, January) High-Energy Battery Technologies

In recent years, Na-ion options have been emerging, currently the only commercially viable chemistry that does not contain lithium. This battery chemistry has the dual advantage of relying on lower cost materials than Li-ion, leading to cheaper batteries, and of completely avoiding the need for some critical minerals. Na-ion batteries are a very new technology, representing a tiny fraction of the market and are only being produced on a commercial scale in China [141]. However, there are opportunities to develop Na-ion production in the UK due to companies such as Faradion which are driving new innovations in this technology [142].

As well as racing to develop new chemistries, manufacturers are also racing to unlock cell capability through designing new cell formats. For example, until recently, many automakers were struggling to integrate LFP batteries into their vehicles due to their limited battery density – fitting a large enough battery was not feasible for many automakers. However, BYD's blade cell format, which is considerably larger than a cylindrical cell, increased the energy density by 50% compared to a cylindrical LFP cell, revolutionising the use of LFP batteries in EVs [143].

4. How are cell components manufactured?

Cathode

The positive electrode in a battery is referred to as the cathode. Originally, for Li-ion batteries, lithium cobalt oxide was used as the cathode active material (defined below). It is still used in some applications such as portable electronics but is not used for vehicles due to safety concerns. In recent years, many alternative material systems have been developed and used, such as NMC and LFP. Most Li-ion batteries can be described as lithium metal oxide cathodes.

Lithium metal oxides are produced as solid powders. The suitability of the powder to be used as a cathode in a battery depends on its chemical and phase composition, microstructure, morphology, particle size and degree and type of contaminations, making quality control one of the most crucial aspects of manufacturing (this is also the case for anode manufacturing and cell assembly). These factors affect the electrochemical characteristics of the battery, including life cycle and energy density, which influences the range of EVs.

These powders are referred to as "Cathode Active Materials" (CAM), and are made into the cathode component of the cell by first being mixed into a slurry together with binders (adhesives), solvents and electrically conductive additives such as carbon black or carbon nanotubes. This slurry is coated onto an aluminium foil then dried in a hot air environment. The resulting coated foil is then pressed between rollers (calendering) to increase density and remove surface asperities, and is known as the cathode electrode.

Anode

The negative electrode in a battery is referred to as the anode. The anode active material is typically made from graphite. Higher energy density cells tend to blend silicon (silicon oxide) into the anode to increase energy density. Whilst silicon gives very high storage capacity, it expands and contracts dramatically as it charges and discharges, so only small quantities can be tolerated before the life of the cell is adversely affected.

As with the cathode, the anode electrode is manufactured by mixing the active material into a slurry, coating, drying and calendaring.

The raw material graphite remains heavily important to the EV transition (particularly as it makes up 45%, by mass, of the raw materials used in a battery cell).

Electrolyte

The electrolyte is a liquid solution that allows an electrical charge, in the form of lithium ions, to pass between the cathode and the anode. It generally comprises lithium salts dissolved in organic solvents with small quantities of specialist additives for a variety of purposes including extending cell lifetime.

Separator

The separator is a critical component for ensuring the safety of an EV battery. The separator is a thin porous membrane that separates the cathode and anode, while allowing Li-ion transport through it. The separator's primary function is to prevent the electrodes from touching each other, which could result in a short circuit or failure.

Housing/casing

To create the cell, alternate layers of anode, separator and cathode are packed together and sealed into a casing. The electrodes may be cut into sheets and stacked on top of each other, or wound together around a mandrel to form a cylinder or elongated cylinder.

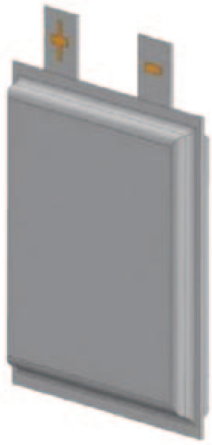
Stacked electrodes may be sealed into a metalised foil pouch to create a "pouch cell", or placed in a rectangular aluminium can to create a "prismatic cell". Cylindrically wound electrodes can be placed into a (usually steel) can to create "cylindrical cell", or elongated cylindrical windings can be placed into a rectangular prismatic cell casing. Prismatic and cylindrical cells have rigid casings, whereas pouch cells do not – and therefore require structural support in their end application. **Figure 14** illustrates the different types of cells.

Other than shape, prismatic and cylindrical cells differ in size, connection and power. Prismatic cells are typically much larger than cylindrical cells and therefore hold more energy per cell (a prismatic cell can contain 20 to 100 times more energy than a cylindrical cell). Due to this, fewer prismatic cells than cylindrical cells are required to achieve the same amount of energy. Therefore, using the former requires fewer electrical connections that need to be welded, which can reduce the cost of production and the number of potential defects. However, smaller cylindrical cells allow for more complex spaces to be effectively filled with batteries.

For this reason, cylindrical cells are deemed more suitable for high performance vehicles such as Formula-E cars and performance cars. For passenger cars, the general trend is for cell sizes to get bigger (for all formats) to reduce the number of electrical connections required and reduce the complexity of the battery management system.

Figure 14: Different types of cells

Pouch Cell



Prismatic Cell

Cylindrical Cell

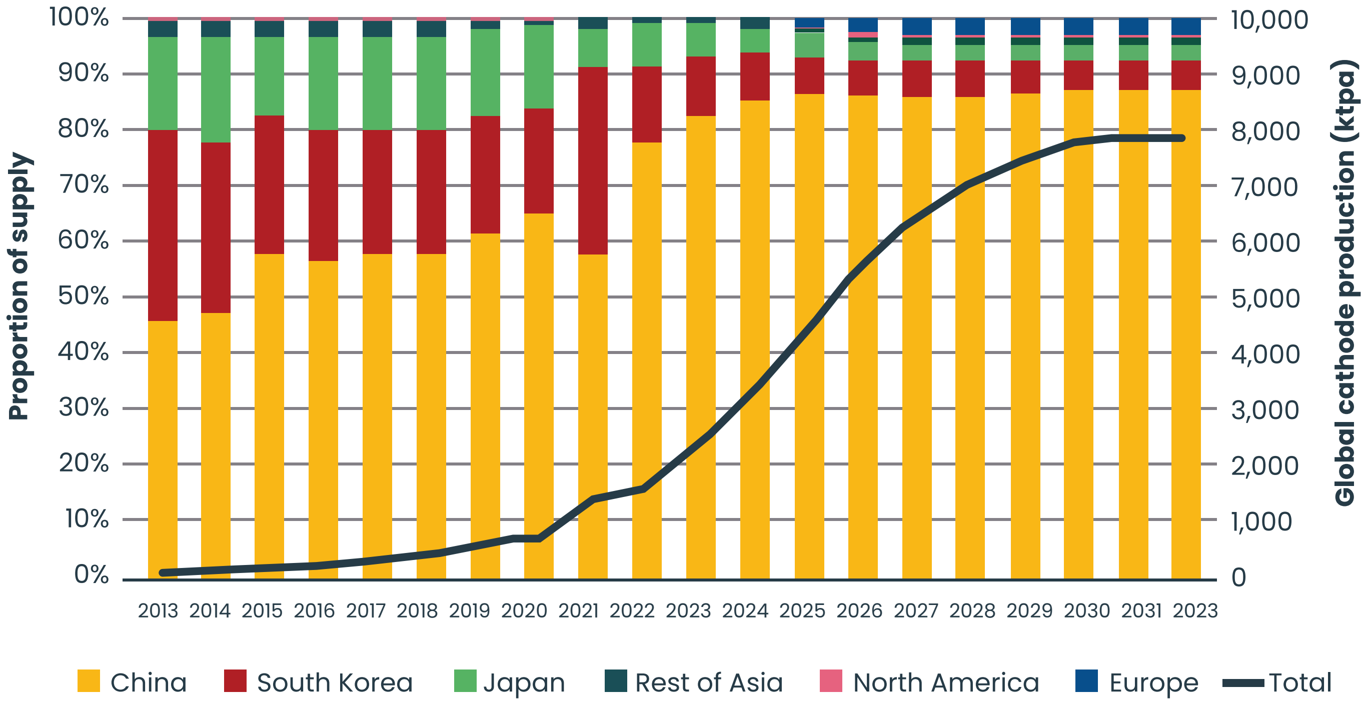
5. Where are cell components produced globally?

Cathode manufacturing is currently dominated by China. Chinese manufacturers produced 78% of global cathode supply. The data also projects China's dominance in the market to increase to 87% through to 2030.

Despite efforts to increase cathode production, the rest of the world is forecasted to grow production at half this rate in the same period [144]. **Figure 15** shows the share of cathode production by country.

Chinese dominance in cathode production could be problematic for geopolitical reasons and rules of origin requirements, which are driving the UK and Europe to establish their own supply of cathodes.

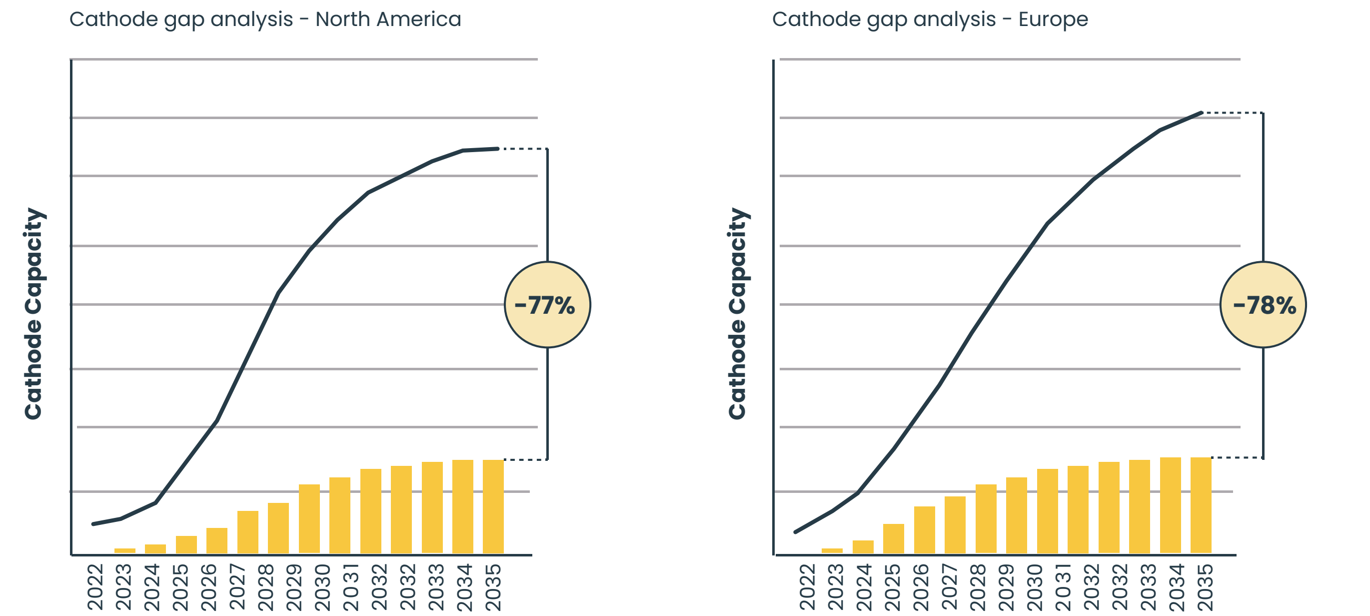
Figure 15: Cathode Supply by Country/Region



Source: Benchmark Cathode Forecast

For the US and North America, cathode production is projected to struggle to keep up with demand. By 2035, production will make up 22% and 23% of demand in Europe and North America, respectively [145]. **Figure 16** shows the difference in future production and demand in these regions, where the bars in yellow are expected production capacity and the black line depicts expected demand.

Figure 16: Regional Cathode Capacity

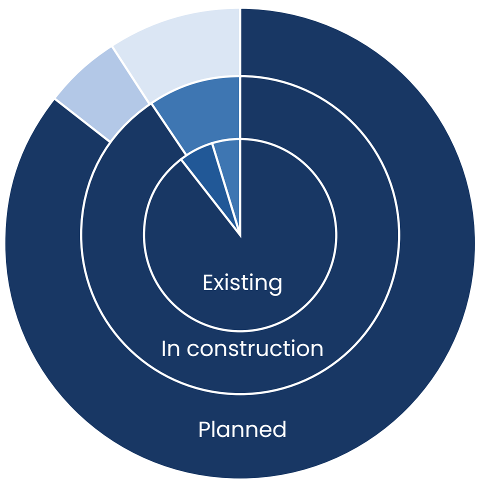


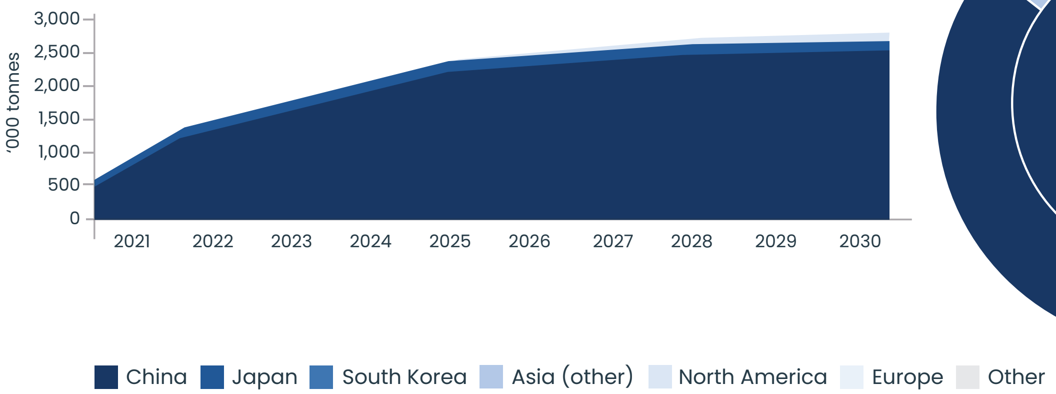
China is also dominant in anode production - it is responsible for 91% of global anode production [146], where Europe has the largest shortfall. It is forecasted that Europe's anode supply will make up 3.9% of what is demanded in 2031, meaning there will be significant customer demand for offtakes of any new companies seeking to expand into this market [147]. North America has a similar growth need, as anode supply will only make up 3.4% of domestic demand [148].

Figure 17 illustrates current and planned anode production capacities by region.

The global battery electrolyte market was worth USD 7.6 billion in 2022 and is projected to grow to USD 16.8 billion in 2027. The market was dominated by Asia in 2021, with Europe coming second [149]. The global battery separator market was valued at USD 5.3 billion in 2022, and is forecasted to reach USD 11.4 billion. Again, the market was dominated by Asia, with Europe coming second [150].

Figure 17: Anode production by region





6. What is the UK's capacity to produce cell components?

In the UK, there are currently no cathode or anode production facilities [151]. Given that Europe's production of electrodes is projected to be significantly lower than what the continent demands in the next decade, the UK may not be able to depend on Europe for its supply. Sourcing from China, the only country without a deficit of electrode production, also carries geopolitical, supply and regulatory risks.

The UK/EU free trade agreement requires that by 2027 all cars sold between the UK and EU must use cathode active materials sourced from the UK or EU, or pay a 10% tariff on the price of the vehicle [152]. Therefore, the UK and/or EU will have to build CAM manufacturing capacity if they want to produce and trade EVs.

There is therefore an opportunity for the UK to expand domestic electrode production through recycling end of life batteries. The Advanced Propulsion Centre predicts that UK battery capacity available for recycling and reuse in the UK could increase eight fold from 28,164 tonnes in 2030 to 235,508 tonnes in 2040 [153]. This could supply enough CAM to supply 60 GWh of new batteries (roughly 600,000 EVs – accounting for more than a third of EV manufacturing capacity by 2040 in the UK) [154]. Altilium Metals, a green technology group, are planning a recycling facility that will include a cathode manufacturing plant capable of producing 30,000 tonnes of CAM [155].

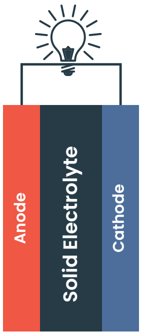
7. How does evolving EV battery chemistries impact investors?

The global drive towards the electrification of road transport has led to a plethora of research programmes to develop new cell component technologies and evolving cell component technologies, especially CAM. This continuing trend has made investors apprehensive because of the risk that current technologies could become redundant as new developments are announced, leading to stranded assets. However, the high value nature of cell component materials (such as CAM) is such that production plants are likely to be fully depreciated before reinvestment is required. Rather than causing concern, new innovations can be viewed as opportunities to further develop the EV battery market.

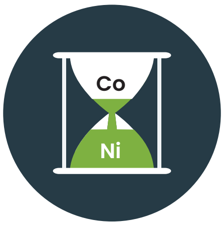
> "The high capital and operating cost of running gigafactories means that equipment and facility investment always tends towards gradual evolution of lines, rather than total revolution. Large scale battery manufacturers will always need to invest large sums in inherently expensive equipment, therefore they will aim to only change a small percentage of assets over time to give a gradual improvement, rather than a full high risk strip-out and step change."
>
> **Jeff Pratt**, Managing Director, UKBIC

In addition, it takes considerable time for new cathode chemistries to be proven at commercial scale, and developments are typically incremental with production lines able to be amended to suit similar chemistries. For example, the technologies with the highest potential to displace Li-ion cells over the next decade, such as lithium manganese iron phosphate (LMFP) or Na-ion, are expected to be able to drop-in to existing Li-ion production lines with minimal or low levels of adaptation required [156]. Some future cell component technologies are discussed below.

Lithium-sulphur: this technology has potential advantages around weight, cost and energy density (double the energy density of current technologies [157].) OXLiD are an R&D scale company who, in collaboration with Nottingham University, are exploring this technology [158]. Initial markets are likely to develop where range and weight considerations are more important than cost (e.g. high-altitude pseudo satellites and drones). Cells may also be suitable for heavy duty vehicles, the short-range aviation industry, and potentially stationary energy storage. Given its use of a similar chemistry to current Li-ion batteries, manufacturing readiness is at an early stage.

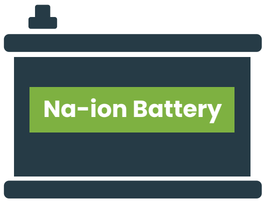


Solid electrolyte (solid state batteries): one of the most discussed new technologies involves replacing the liquid electrolyte with a solid one, which would also act as a separator between the anode and cathode. This could unlock the use of different types of active materials in the cathode and anode, which could have added benefits in safety, performance and cost. The current benefits known today arise when the anode active material is deleted and replaced with metallic lithium (sometimes referred to as an anode-less cell). The main benefit of solid state batteries is improved energy density (2 to 2.5 times higher than current Li-ion batteries at the material level and 30-40% benefit at the cell level [159].) 70% of existing Li-ion battery equipment can be re-used for solid state batteries manufacture, limiting the stranded asset risk of investing in current technology [160].

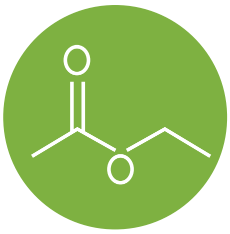


Cobalt free cathodes: Over time, the NMC chemistry has evolved to reduce the amount of manganese and cobalt but to increase the amount of nickel. The NMC 811 cathode, is composed of a reduced amount of cobalt (80% nickel, 10% manganese, and 10% cobalt) which is beneficial as cobalt is scarce, expensive, and open to ethical mining concerns. For these reasons, the long term industry aim for the NMC chemistry is to continue to reduce the use of cobalt with the potential for an NMC9XX cell in the future.

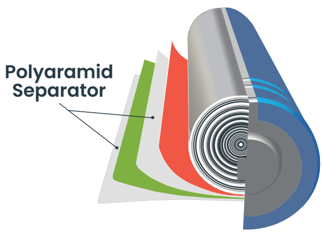
Silicon dominant anodes: some companies have begun to experiment with silicon dominant anodes in contrast to the small traces of silica currently used in some anodes. Benefits include higher storage capacity, but limitations include the risk of cracks in the anode, and poor performance, caused by swelling and shrinking when charging and discharging. Significant research, such as by Sila Nanotechnologies, has gone into stabilizing silicon anodes to reduce swelling and prevent cracking [161].



Sodium-ion batteries: a nascent technology which works very similarly to Li-ion batteries, but substitutes lithium for sodium as a charge carrier. These batteries have advanced beyond the research stage with nearly 30 Na-ion battery manufacturing plants currently operating, planned or under construction, almost all in China. The main uncertainties around the deployment of Na-ion is the time required to develop an industrial scale supply chain. However, due to the similarity with Li-ion technology, it is likely that these batteries will be able to fit into existing production lines. The key benefit of Na-ion batteries, particularly those that do not use nickel, are that they do not require use of expensive raw materials – notably lithium, copper and cobalt. It is also possible to ship and store these batteries when they are fully discharged, making them safer to handle and easier to store than Li-ion batteries. However they have a lower energy density, which is likely to make them more relevant for urban vehicles with lower range, or for stationary storage.



Ethyl acetate electrolyte: the Beijing Institute of Technology has developed an electrolyte, made from dissolving a larger than usual amount of lithium salts in a solvent made of 90% ethyl acetate and 10% fluoroethylene carbonate, which allows a standard NMC 811 battery to run in temperatures as low as negative 40 degrees Celsius (currently limited to negative 20 degrees Celsius). The researchers say that this technology is scalable but the challenges are reducing the cost and further reducing the minimum temperature [162].



Polyaramid separator: Microvast, in collaboration with General Motors, has developed a polyaramid separator which is capable of resisting temperatures in excess of 300 degrees Celsius, unlocking greater safety in future EV batteries. The company opened a plant (worth USD 500 million), in April 2023, to produce this patented technology.

Cell manufacturing

1. What is cell manufacturing?

Cell manufacturing refers to the process of combining the different cell components (as introduced earlier in this section) together to form a battery cell which is capable of storing and discharging electrical power. Cell manufacturing is considered the most valuable part of the battery value chain as it is estimated to account for up to 40% of battery industry value creation by 2030. The market for battery cells is expected to grow by 20% a year until 2030, reaching USD 360 billion globally [163]. Cell manufacturing is an expensive and complex multi-step process, requiring many different machines. To make this process economically viable, cells are typically produced in gigafactories.

2. What opportunities are there in the UK for investors?

The UK cell manufacturing market is made up of several startup companies aiming for large scale production, including AMTE Power, Acutronics, and AGM batteries. The UK is also a leader in designing high performance batteries, such as those produced by Hyperbat, which is a joint venture between Williams Advanced Engineering and Unipart Manufacturing. Some of these companies have been awarded government support

(through Advanced Propulsion Centre's (APC) GBP 10 million R&D projected funded by the government [164]), alluding to their potential and the investment opportunities that lie within.

The UK market also includes a more well-established manufacturer in Envision AESC, which is expanding its UK capacity. In addition to this, there have been recent reports that a deal between Tata Group, which owns Jaguar Land Rover, and the UK government to build a multi-billion pound gigafactory in Somerset is imminent [165].

3. What is a gigafactory?

The term gigafactory was coined by Elon Musk and refers to the factories capable of producing multiple GWh per year of battery cell capacity. Gigafactories require high amounts of energy to power; the focus for choosing the location to build a gigafactory is access to uninterrupted clean energy. The Northvolt Ett plant in Sweden, a venture involving the Volkswagen Group, is estimated to require approximately 2TWh, equivalent to 2% of Sweden's annual electricity consumption [166]. Skilled workers and nearby research universities to develop their technologies are also important factors for location selection.

Through leveraging economies of scale, gigafactories can significantly reduce the cost of battery production. Since batteries account for 30 to 40% of the total cost of EVs, savings on the cost of battery production can reduce the price of EVs, helping to make the transition affordable for all, thereby making gigafactories a critical asset in developing the EV sector.

To date, the challenge with financing gigafactories is the mismatch of high capex requirements, with high risks such as technology and revenue uncertainty. Gigafactories require significant upfront investment for construction. To secure this funding through project financing, a project requires proof of future revenue, and assurances the company can source the input materials required. In turn, automakers need to know cells can be produced in sufficient quantities, at the right price, before placing orders. For a new battery start up, this can create a chicken and egg situation whereby accessing capital is reliant on securing a customer, but securing a customer is reliant on having scaled production facilities. A number of battery production companies are also startups with limited credit history or disposable capital to facilitate financing.

There are three models to address these challenge to scale battery manufacturing:

1. Be a large corporate and use revenues from other product streams to bankroll gigafactories until they are ready to sell cells (LG, Panasonic, etc.)
2. Capitalise on significant state support (CATL, BYD, EVE, etc.)
3. Grow from a start up raising investment in stages as you develop your product towards commercialisation - this inevitably means frequent and exponentially increasing rounds of fundraising, all in advance of firm customers. This can work (eg NorthVolt) but is much harder, especially in financially and politically volatile environments.

4. Where are cells manufactured globally?

To meet rising demand for batteries, it is estimated that around 9,300 GWh of battery supply is required [167]. According to data from BloombergNEF, the global capacity of Li-ion battery production reached 1,163 GWh as of the end of 2022 [168], which is 12.5% of the estimated 9,300 GWh required by 2030. **Table 2** below shows battery production capacity by country.

Source: Visual Capitalist (2023, January) Battery Manufacturing Capacity, by Country.

Table 2: Battery production capacity by country

Rank	Country	2022 Battery Cell Manufacturing Capacity (GWh)	% of global capacity
1	China	893	77%
2	Poland	73	6%
3	United States	70	6%
4	Hungary	38	3%
5	Germany	31	3%
6	Sweden	16	1%
7	South Korea	15	1%
8	Japan	12	1%
9	France	6	1%
10	India	3	0.2%
	Other	7	1%
	Total	**1,163**	**100%**

Source: Visual Capitalist (2022, February) Mapped: EV Battery Manufacturing Capacity, by Region

The projected growth in EV batteries has led to over 300 gigafactories in the global pipeline, i.e. gigafactories that are either in the construction or planning stage. China continues to dominate, with 75% of all facilities in the global pipeline [169]. However, North America and Europe are looking to close the gap, with several announcements of planned facilities. In these regions, joint ventures between automakers and battery companies have been major drivers of growth in battery production. In fact, 14 of the 23 gigafactories in the North American pipeline are wholly or jointly owned by automakers.

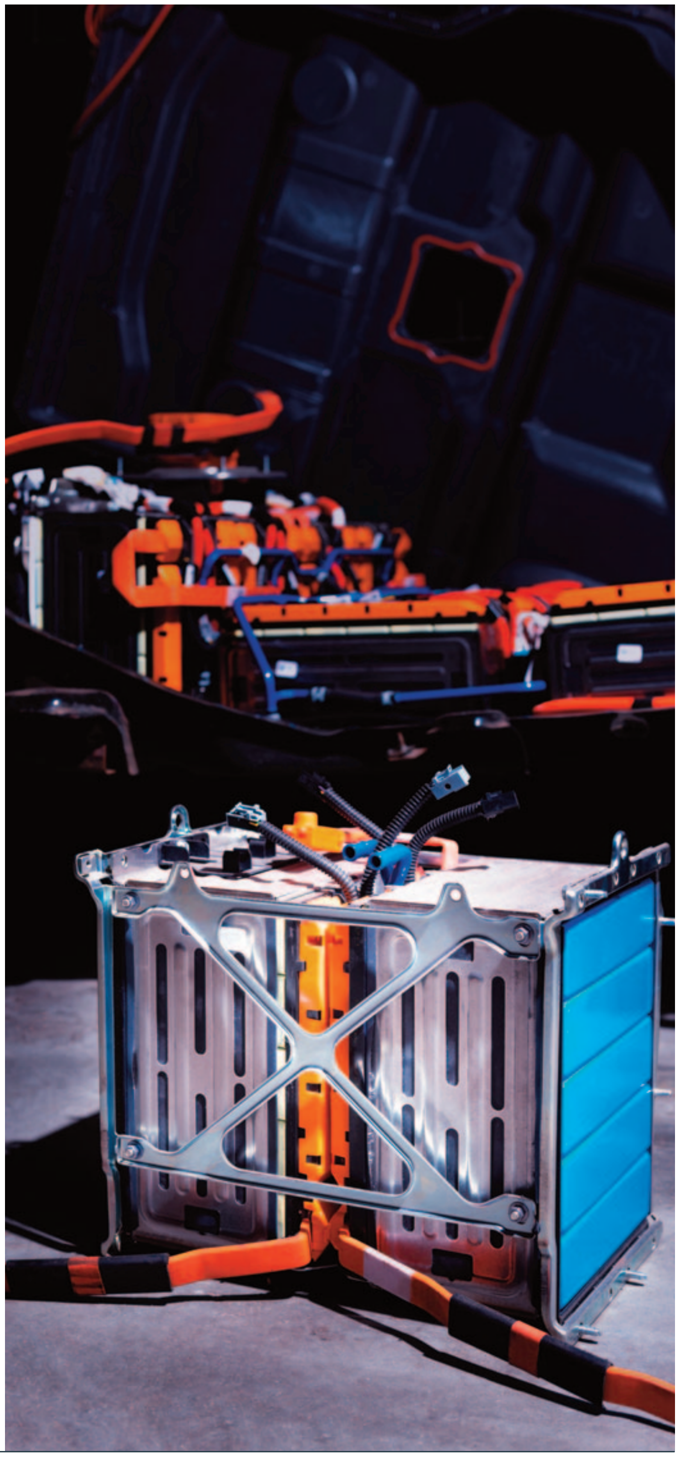
5. What is the UK's capacity to produce cells?

Currently the UK has one gigafactory in Sunderland, owned by Envision AESC, which is supplying batteries for the Nissan Leaf and has a capacity of 1.7 GWh. However, to keep up with demand for EV batteries the UK will require an estimated 10 gigafactories by 2040, with each one producing an average of 20 GWh annually (i.e. 200 GWh total capacity) [170]. Recognising this demand, Envision AESC and UK politicians have earmarked GBP 1 billion investment to increase capacity of the Sunderland plant to 11 GWh by mid-decade which is now under construction. A further GBP 1.8 billion could take the gigafactory to 38 GWh by 2030.

Britishvolt, a UK battery manufacturer startup, had plans to build a UK gigafactory, expected to produce 38GWh and cost GBP 3.8 billion [171], but filed for administration in January 2023 after failing to reach construction milestones to access funding. Being a startup company, Britishvolt followed the hardest model to scale to large cell production, but this does not mean that other companies (whether startups or well established cell manufacturers/corporates) cannot achieve large scale production in the UK. This is further backed by recent reports that Jaguar Land Rover and the UK government are working on a deal to establish a multi-billion pound gigafactory in Somerset, as mentioned previously, which could significantly increase the UK's cell manufacturing capacity.

6. What innovations are happening in cell manufacturing?

The biggest driver of innovation in cells is to change the cell formats by continuing to increase their dimensions, increasing their energy density and resulting in cheaper and lighter battery packs. These non-chemistry related gains will require new equipment, processes and tighter quality control, representing large investment opportunities.



6. Downstream:

Module and Pack Production & Battery Management Systems

The EV battery module and pack global market is currently worth USD 5.5 billion and is projected to grow to USD 29.3 billion in 2030 [172].

Module and Pack Production

1. What is a battery module and pack?

Powering EVs requires large amounts of energy, which can only be achieved by combining many cells together into a module, and multiple modules into battery packs. Therefore, battery and pack production requires different machinery and expertise compared to cell or cell component production.

2. What opportunities are there in the UK for investors?

Battery module and pack assembly is often performed by automakers. This gives the UK an opportunity as it already produces approximately 10% of all vehicles in the EU. Therefore, battery module and pack producers have an incentive to source components in the UK, thereby helping the market to develop. Much of this capability and intellectual property lies within the UK's extensive high-performance automotive sector, offering the scope to develop higher performing systems in the future [173].

3. How are modules and packs produced?

The mechanical assembly process of producing the battery module typically involves insulation and tensioning, electrical contacting, and mounting of the circuit board and housing cover. Pack production is the process of combining several modules together, which involves electrical and thermal integration, sealing, and charging and flashing. The battery pack comes in different shapes to fit different EV models. Increasingly, to reduce cost, the trend is towards pack designs using fewer, larger modules – and in the future, a cell-to-vehicle assembly method will be desirable to reduce cost and weight of the vehicle.

4. Where are modules and packs produced?

Battery modules and packs are sometimes produced by the same companies that manufacture battery cells. For example, CATL, the largest battery cell producer in the world, also produces modules and packs. However, automakers will typically purchase cells and produce battery modules and packs themselves as it is easier to transport battery cells than it is to transport battery modules and packs. As a result, a significant proportion of module and pack production is based in countries with high EV production, such as China. There are some companies, such as HyperDrive Innovation (based in the UK and owned by Turntide), which focus primarily on module and pack production. These companies will usually target lower volume automakers who lack the capability or capacity to build their own battery packs. Over time, automakers may develop the capability to produce their own modules and packs, and collocate EV production facilities with cell manufacturing facilities, which could potentially reduce the demand for standalone companies focused primarily on battery module and pack production.

5. What innovations are happening in battery modules and packs?

A key technological innovation for battery modules and packs is CATL's next generation cell-to-pack battery. This design proposes to remove the need for battery modules and have the cells directly connected to the pack. CATL claims that this new technology will improve power by volume resulting in a higher range with a lower weight and smaller size battery. This battery pack technology has been mass produced in China since 2020 and is used in production models like Hyundai, Kia, and Genesis [174]. BYD's blade pack is another example of a cell-to-pack design [175].

Most car companies are looking to innovate cell-to-vehicle solutions in the future, and as EV sales volumes increase, it could become financially viable to have cell designs which are bespoke to a single model of vehicle.

Battery Management Systems

1. What is a battery management system?

Li-ion battery cells must be managed during operation. If they are overcharged, overdischarged, short circuited or allowed to overheat then they will degrade more quickly, or in extreme cases, may go into "thermal runaway" which may cause a fire. Since a battery pack generally comprises many batteries in parallel and in series, a battery management system is required to manage each cell or cluster of cells individually for optimum and safe operation. This means that the temperature and voltage of any parallel block of cells must be known and acted upon at all times.

The term Battery Management System (BMS) refers to the electronic system which manages a battery pack, by controlling and protecting the way in which it operates. The oversight that a BMS provides typically includes:

- Providing battery protection, which includes:
    - Electrical protection - ensuring the connections to the battery pack and within the battery pack retain their electrical insulation (and disconnecting the pack if they do not), and ensuring the voltage and current of the cells is maintained within limits for safety and durability
    - Thermal protection – monitoring the cell temperatures, heating or cooling the pack if required and taking safety measures if the cells are at risk of thermal runaway
- Controlling the charging process to get the fastest possible charging without impacting durability
- "Balancing" the cells, especially during charging, to ensure that stronger cells and weaker cells in the pack are all utilized to best effect
- Estimating and reporting the amount of energy remaining in the battery (State of Charge) to the vehicle control system
- Monitoring how the battery is ageing over time (State of Health)
- Controlling the battery cooling and/or heating systems
- Retaining and communicating diagnostic information
- Retaining "passport" data to allow their materials content, manufacturing history, usage history, and current state of health to be interrogated – especially for re-use, remanufacturing or recycling purposes

2. What opportunities are there for investors in the UK?

There are two main opportunities in BMS production, namely the hardware opportuntiy and the algorithm / design IP opportunity. The hardware is generally low voltage microprocessors and custom application specific integrated circuits (ASIC), which is not diffrerent to any other electronic device in a vehicle. Manufacture of these can be easily commoditised and outsourced. There is a greater opportunity in the IP design of the BMS and the algorithms that run on it. If the BMS can help to make the battery live longer or perform better then there is value to be had.

A big challenge therefore is how to protect and defend that IP (it can be hard to prove another company has embedded "your" algorithm into their BMS). Big automakers will keep BMS design and algorithms in-house. Smaller automakers would seek to buy reliable BMS systems at a sensible price, but there are few on the market which are ISO26262 certified and of high quality. However, there are several UK based startup companies that are designing high quality BMS and looking to scale up to large production. These companies include Dukosi, Eatron and Brill Power, who have already secured investment from Barclays, Legal and General, IP Group and NMC ventures [176].

3. What does the battery management system market look like, globally and in the UK?

The global BMS market size was valued at USD 18.5 billion in 2022 and is forecasted to reach USD 55.1 billion by 2032, representing a 19.5% CAGR between 2023 and 2032 [177]. The BMS market is being driven by an increase in demand for EVs and high-power applications such as grid-scale energy storage and electrical aircraft. As with batteries, the Asia Pacific region's market share is the highest and fastest growing globally, attributable to the region's increase in demand for EVs and renewable energy solutions. North America's BMS market share is also significant and is growing as a result of increasing adoption of renewable energy sources, and the need for energy storage solutions, with Tesla a major player.

4. What are the latest innovations in battery management systems?

BMS architectures are continuously evolving. As BMS becomes more prevalent, many semiconductor manufacturers already have custom BMS chips, which makes the construction of a BMS system far faster and cheaper than it used to be. Increasingly the value in the BMS is in the algorithms rather than the hardware platform. See '**Appendix**' for further examples of innovations.

7. Second Use & Recycling

The reuse and recycling of batteries could generate additional revenue of approximately USD 34 billion [178] globally by as early as 2030 if enough investment is mobilised to allow technologies and processes to scale.

Second Use & Recycling

1. What happens to a battery after it is used in an EV?

The strong uptake of EVs over the coming years will produce large amounts of both manufacturing battery waste, and batteries that have completed a first life in an EV. At the end of life (EOL) in their first EV, the vast majority of batteries in the UK are collected and sent to the EU for recycling [179]. Scaling capabilities to process used EV batteries presents challenges, but also a significant opportunity, given the many potential ways to extract value from automotive batteries.

There are currently three potential pathways* to extract additional value from a battery after its first use in a vehicle:

1. **Remanufacture** - Refurbishing used battery packs, for example by replacing or upgrading some of the battery components before the battery is then used in the same or another EV.
2. **Repurpose** - Repurposing the battery in a second use that is different from its original production purpose.
3. **Recycle** - Breaking the battery down to recover its valuable raw materials. Batteries are also scrapped during the the manufacturing process for failing to meet quality requirements for EVs, which creates an opportunity for recycling technology companies to work alongside gigafactories.

Taken together, these could help reduce the primary supply requirement for raw materials needed to make batteries by up to 12% by 2040 [180], and also help create circular economies within the supply chain that could help reduce waste and minimise energy consumption; raw material produced from recycling plants produce an estimated 23% lower GHG emissions than mined material [181].

These advantages both mitigate the risks of raw material supply for projects, and can result in lower lifecycle emissions for EVs.

2. Where are the opportunities for investors in EOL processes in the UK?

The UK has one of the largest EV markets in Europe, which means that large amounts of batteries are expected to be available for second-use or recycling. By 2040 there will be approximately 1.4 million EOL EV battery packs entering the market every year [182]. There is a huge opportunity for a new recycling industry to emerge as many European battery and vehicle automakers will be looking for local recyclers both to as a source of raw material, and to provide offtake for their EOL batteries. This industry will be catalysed by the recently approved EU battery regulations which seeks to increase local battery manufacturing and mandate minimum and increasing thresholds of recycled material in EV batteries.

Scaling up EOL process operations presents an opportunity for both early and late stage investors. These projects need to start as soon as possible, to progress through the establishment processes of planning, permitting, plant construction and process development, to be ready when feedstocks and revenues start to grow.

3. What are the challenges with EOL processes?

All three pathways above present some technological and operational challenges. For example, removing and transporting batteries requires significant cost due to their considerable bulk and weight [183]. Additionally, the different batteries in the market vary in terms of their pack formulation and chemistry, which can cause complexity – and added

* Another pathway: 'Replace' is also important whereby components of the cell module and pack are replaced when needed to extend operating life. This has implications for adapting the design of the original components to be replaceable.

costs – to process them. The importance of these costs will depend largely on whether remanufactured and repurposed batteries can be cheaper than the cost of new batteries (which continue to fall) to drive consumer demand [184].

There are also questions regarding liability for second-life batteries, especially in relation to battery safety. In the UK, the responsibility for dealing with EOL batteries is covered under Waste Batteries and Accumulators Regulations 2009 [185]. However, this is out of date since it does not refer to Li-ion technologies and there is regulatory uncertainty about which parties bear responsibility for repurposed battery safety issues [186]. Innovations like Battery Health Certificates could help track battery safety and provide confidence for consumers.

4. What is battery degradation and why is it important?

Batteries physically degrade over time, which reduces performance and eventually makes them unsuitable for use in an EV. The current proportion of capacity or power a battery is able to support is known as its state of health (SOH).

Below a certain SOH, batteries are at risk of degrading more quickly and becoming unsafe - at which point they will have reached the end of their useful life and may only be suitable for recycling. Exactly when batteries will reach this point can be difficult to predict, as it depends on application and use, however there is recent data which suggests that it may not be for up to 20 years for most EV batteries manufactured today [187]. As the capacity of new batteries continues to improve, remaining useful life will also continue to increase. For the current generation of batteries, more data about performance and ageing will increase confidence in determining when a battery is suitable for a second-life application, and when it should be recycled.

5. When is a battery suitable for a second-life?

Automakers need the batteries to be able to deliver a certain range in a single charge and enough power to be capable of driving the vehicle certain speeds. As such, most new EV batteries are warranted to 70% or 80% of their original capacity and power SOH; data suggests most EVs today would take more than ten years to reach this level [188]. Countries are also working to standardise this - in 2022, the United Nations Economic Commission for Europe (UNECE) updated regulations with the aim of developing a battery durability standard for EVs. These mandate a minimum of 70% capacity remaining after 8 years, or 100,000 miles in range. The durability standards are currently to be adopted in Europe in 2027 (it is yet to be confirmed in the UK which is still considering options for implementation) [189].

Batteries with less than the SOH required for an EV may still be suitable for other applications which have lower demands, which creates the opportunity for remanufacturing or repurposing. For example, in stationary storage applications, lack of capacity can be compensated for with a higher volume of cells. Different applications may require a higher capacity rather than power, or vice versa, which means that one type of SOH may be more important than the other; applications like frequency balancing on the grid require high power but less capacity, whereas solar PV storage needs capacity more than power (both discussed below).

6. What are the challenges and innovations in determining battery state of health?

There are challenges with predicting when a battery will reach a certain SOH because individual batteries will degrade differently as they are used differently/under different conditions.

Factors such as use of rapid chargers, exposure to higher or lower temperatures, using the vehicle at higher speeds, or even keeping the battery fully charged for extended periods of time can all cause batteries to degrade faster.

Automakers will typically monitor the SOH of a battery using the BMS. Although traditionally this data was only gathered when the automaker had access to the vehicle, for example when it was serviced. Many automakers are now collecting telemetry data via mobile phone links from cars. This means automakers are able to monitor the health of the battery more closely, and if necessary even request that the customer bring the vehicle in for repair. The data also enables improved design of future batteries.

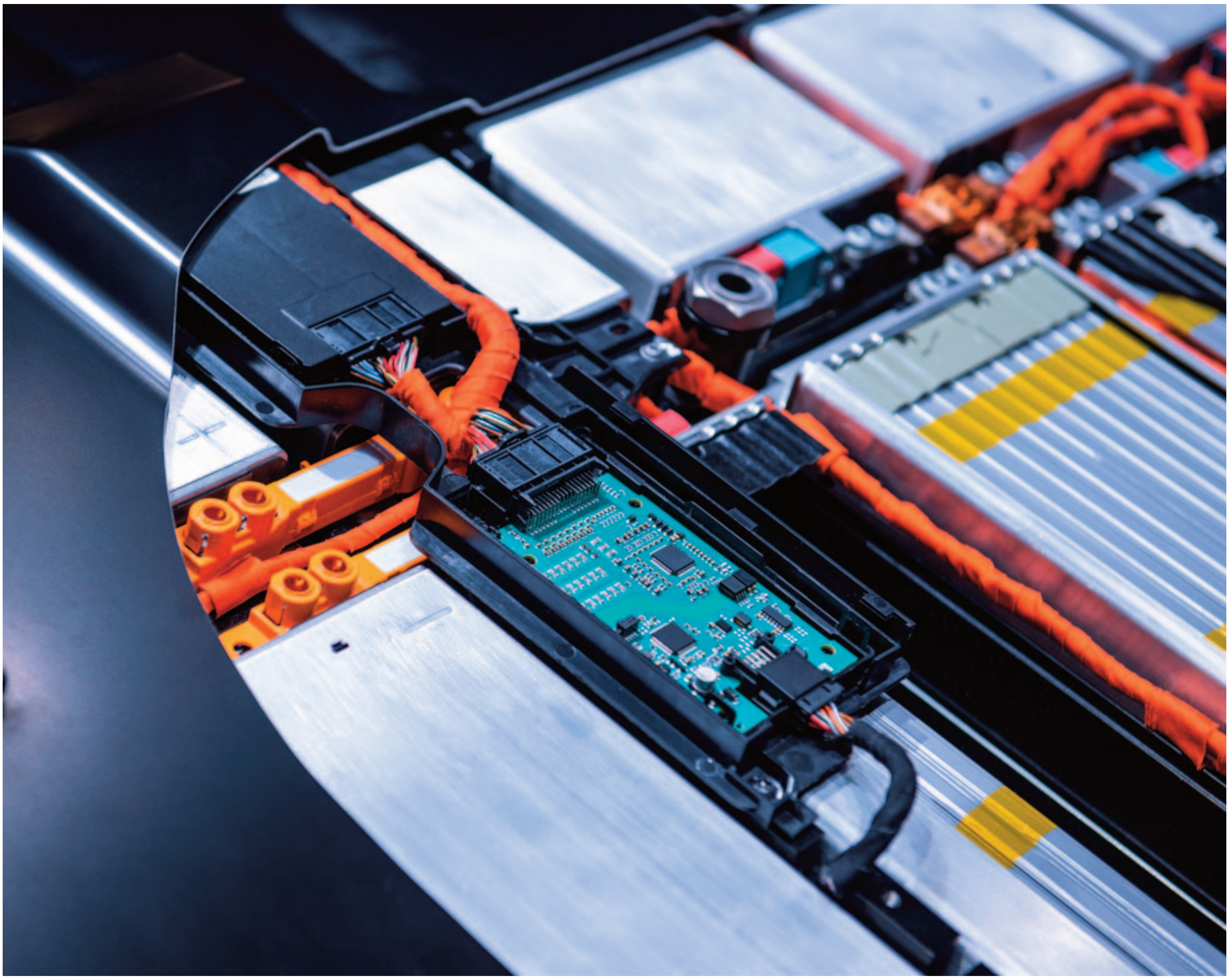
Automakers have largely been unwilling to share SOH data with third parties [190], which means repurposing and refurbishing companies are often forced to accept the risk that a battery they are acquiring might be unusable, or find ways to measure the battery performance once they receive it. In the absence of data from automakers, companies are innovating new ways of determining the condition of cells.

These technologies include:

1. Discharge models - developed to reduce SOH test time from hours to minutes.

2. Digital twin - a model of a battery that can be run through simulations to predict what the battery might be sensitive to and what its end of car condition will be, often using machine learning. These models can also be fed real-time data such as driving and charging behaviour to enable companies to build a picture of the SOH, and predict how it might degrade. Digital twins are also a key enabler for battery passports because they enable supply chain tracking. For more information on battery passports, see page 26.

For examples of UK opportunities in this area, see the **Appendix**.



Re-purpose

1. What second-uses can automotive batteries have?

There are several well-established use cases for second-use automotive batteries :

- **Energy Suppliers & Grid Operators** - Energy storage systems can enable energy suppliers and grid operators to take advantage of grid stabilising and power-arbitrage opportunities by storing renewable power when there is excess supply for use during periods of scarcity.
- **Homes & Individuals with Distributed Energy Resources** - Consumers can store energy from the grid and their home energy systems, such as roof-top solar.
- **Energy Communities** - Warwick Manufacturing Group are running a project at the University of Warwick to repurpose EV batteries as small battery energy storage systems for off-grid communities.

For examples of UK opportunities in this area, see the **Appendix**.

Recycle

2. What are the main battery recycling technologies used today?

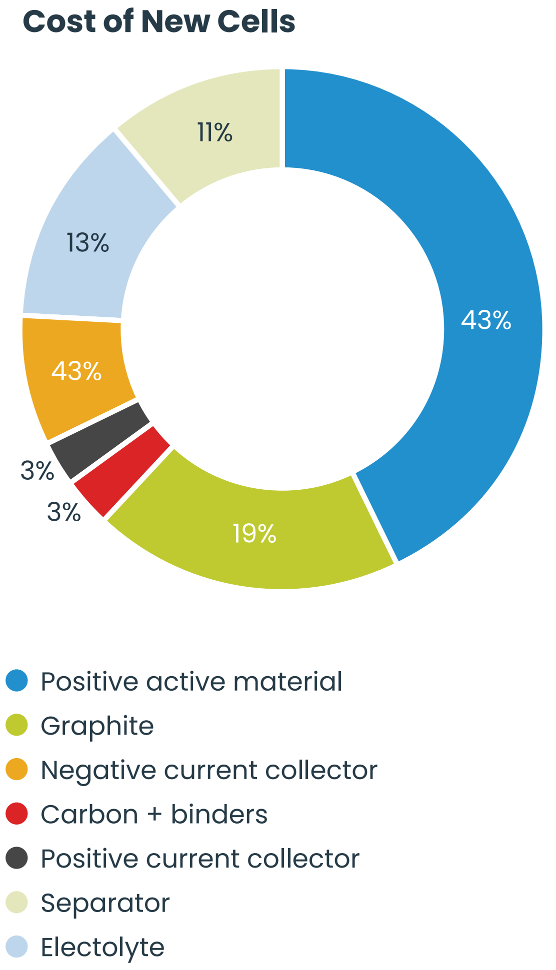
Recycling plants will generally use one of two different approaches detailed below, though companies are experimenting with hybrid approaches which involve a combination of the two in an effort to maximise material recovery rates [191].

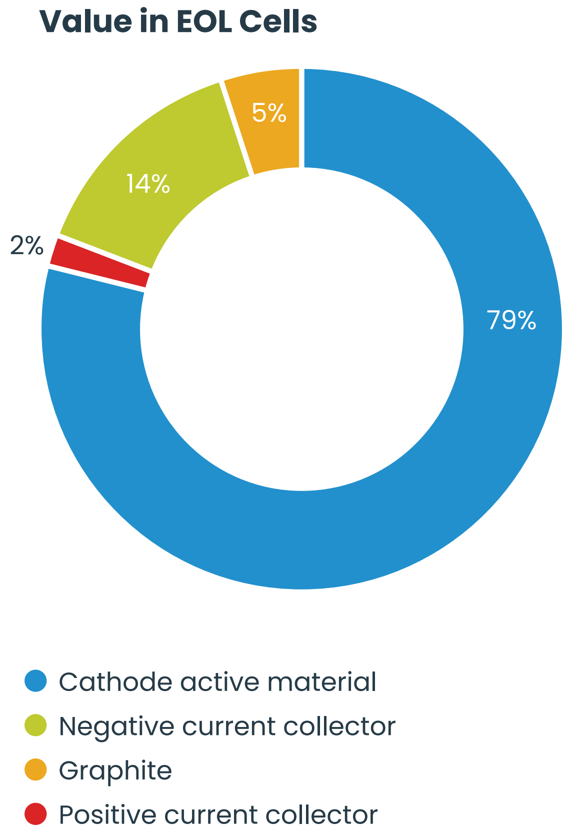
1. **Pyrometallurgical:** smelting the battery to create a mixed waste product of slag alongside an alloy of the valuable metals. The alloy then needs further processing to recover the materials in a usable form. This method can be used to recycle batteries of varying chemistry types, but it only recovers certain raw materials (cobalt and nickel but not manganese or lithium), the recovery rates are generally no higher than 50% [192], and it is energy intensive [193].

2. **Hydrometallurgical:** mechanical processing through dismantling or shredding. The anode and cathode materials are then collected in the form of "Black Mass", and active materials are then leached from the separated material using strong acids. This can result in yield of up to 99% [194] [195], however it is more time-intensive, uses more water, and there is no electrolyte recovery.

The most valuable minerals that are typically recoverable in recycling are those found in the cathode [196], including lithium, cobalt, manganese and nickel as seen in Figure 20. The chemistry of the battery can therefore greatly affect whether it is economically viable to recycle. For example, high-nickel batteries yield much higher rebates because they contain valuable nickel and cobalt, where LFP batteries are often a cost burden to recycle, since they instead contain lower value materials such as phosphorus and iron. .

Figure 19: Comparing the Breakdown in Value of New and EOL Cells





3. What are the main innovations in battery recycling?

Research is ongoing to optimise current processes, as well as innovate new technologies to extract raw materials. Labour typically accounts for 23% of a recycling plant's costs, and there are companies looking to automate parts of the process through robotics [197]. Other companies are working to improve the capabilities of these processes. For example, Redwood Materials in the US is creating a hydrometallurgical plant that will be able to process both mined and recycled materials. Doing so enables them to circumvent the lack of EOL batteries by instead using gigafactory scrap, and also means they can offer customers chemicals with a lower carbon footprint. Ecoshred in the UK have recently received GBP 1.82 million in grant funding to develop technology to optimise the recovery of materials from gigafactory waste products [198].

An emerging alternative recycling technology is "direct cathode recycling" which could deliver improved efficiency compared to current recycling routes as it does not involve breaking the battery down into its raw elements. Instead, components are separated while retaining their structure, which can then be restored with their initial properties and electrochemical capacity. The intention is that the cathode can then be directly reused for the manufacture of new batteries. It also offers the potential benefit of recovering more from the other components, such as the separators which are typically lost using current processes. Being able to extract more value from the batteries will increase the economic viability of recycling batteries, especially those which contain less valuable raw materials.

4. What does the market look like for battery remanufacturing, repurposing and recycling globally?

Globally, recycling, re-using and repurposing EV batteries is currently a relatively new market but is expected to grow significantly. Most battery recycling companies operating today are independent recyclers, but automakers, battery manufacturers, miners and processors are starting to enter the market. Regulation is spurring growth, including the Chinese government issuing a series of directives over the last few years to incentivise battery reuse [199], and the recently approved EU regulations for recycling of battery materials is likely to create a more valuable market for EOL batteries.

At present, with few EOL EVs to recycle, battery recycling tends to happen close to battery manufacturing, and its business case is heavily based on manufacturing waste as feedstock. As a result, China dominates global recycling capacity (80% share [200]) because it hosts the majority of battery cell producers, which also generate the largest quantity of process scrap [201]. Recently, CATL, the world's largest battery producer, made an investment of GBP 2.79 billion to build a facility in Guangdong, southern China, which would more than quadruple its current Li-ion battery recycling capacity, and almost double China's current recycling capacity [202]. **Figure 20** illustrates recycling capacities by region as of 2021.

South Korea is one of leaders in the recycling of Li-ion batteries due to access to scrap from the cell manufacturing process and buyers of materials [203] and strong government support. Recently, the government invested GBP 25 billion to support a four year Li-ion battery technology development project to develop infrastructure to support recycling and reuse of batteries [204].

Europe and the US host fewer battery manufacturers and therefore has less material and fewer recyclers, however the legislation to increase manufacturing and to mandate thresholds of recycled material in EV batteries (the IRA in the US, and the recently approved EU Battery Directive [205]) is driving change. Growing recycling capabilities is expected to intensify competition globally for the constrained supply of scrap amongst battery manufacturers, with many companies looking to form partnerships to secure recycled material.

Figure 20: Global Recycling Capacity, In Tons

More than 80% of the world's battery-recycling capacity is located in China

Source: BloombergNEF

For example, Glencore, the leading recycler of electronic waste in North America, has recently established a partnership with Li-Cycle, a Li-ion battery recycler. It is set to invest USD 200 million via convertible debt, and will supply Li-Cycle with battery recycling feedstock and establish offtake agreements for battery materials. Glencore also recently announced plans to build Europe's largest battery recycling plant in Italy, ready by 2027 [206].

5. What are the current UK capacities for dealing with EOL batteries?

For remanufacture and repurposing, various companies in the UK are already designing systems for repurposing EV batteries for a variety of second-use applications, and by 2030 retired EV batteries are expected to provide a significant proportion of the battery demand from other sectors [207]. The largest companies currently include Connected Energy, Zenobe, Powervault and Acceleron. However, automakers are also launching second-use initiatives – for example, Jaguar Land Rover announced a partnership with Pramac, a global energy leader, to develop a portable zero-emission energy storage unit powered by second-life Jaguar I-PACE batteries [208].

For recycling, the UK currently has insufficient feedstock for recycling at industrial scale, so most batteries are exported to European recycling facilities. As the volumes of EOL vehicles increase, it will be easier for UK battery recycling plants to make a strong business case [209]. UK plants would also be helped if more gigafactories opened in the UK to provide manufacturing scrap. An additional UK opportunity is shredding capabilities, as the growing number of shredding facilities coming online in Europe is enabling a growing trade in Black Mass [210].

In light of the growing opportunity there have been a number of recent announcements of companies launching large scale recycling projects which, if realised, would dramatically increase the UK's recycling capacity. Most operators are planning facilities that specialise in both the reuse and recycling of batteries to ensure diversity of income.

- **Veolia**, a waste management company, announced in 2022 its plans to open a new EV battery recycling plant capable of producing Black Mass in the UK.
- **Gigamine** intends to establish a recycling facility in the UK. In early 2022, it announced a seed round led by early-stage fund 7percent Ventures with participation from a group of angel investors including the founder of Formula E.
- **Recyclus** is looking to establish a hydrometallurgical recycling plant in the West Midlands, with aims to recycle 41,500 tons by 2027.
- **Altilium** has received GBP 3 million in grant funding from the UK government's Advanced Propulsion Centre, and GBP 632,000 from Faraday Battery Competition to set up a battery recycling plant in Teesside which it claims will be able to produce enough raw materials to power 20% of new EVs produced in the UK by 2030.
- **EMR** is in a consortium with government, academia and automakers including Bentley, Jaguar Land-Rover and BMW looking to develop new recycling technologies. The project has received GBP 4.4 million funding from APC, with the aim of the establishing the UK's first commercial-scale recycling facility for EV battery packs.
- **The Faraday Institution** ReLIB project is looking at novel ways to efficiently separate the materials in battery cells, and Warwick Manufacturing Group has a highly active battery recycling group.

8. Policy and public finance for the transition

Policy and public finance for the transition

1. What is the policy direction for EVs and battery manufacturing globally?

As stated in the introduction, governments globally continue to commit to electrify transport and meet net zero targets, stimulating EV uptake and increasing the demand for automotive batteries. To support the transition to zero emission vehicles, governments in major markets are also working to address the wider EV supply chain, introducing policy support for automotive battery manufacturing and the supply chains. The policies have already stimulated huge amounts of private investment, but also signal a new level of global competition, state support and protectionism which speaks to the strategic importance of this sector. Some key interventions are summarised below.

US

In August 2022, the US introduced its landmark Inflation Reduction Act (IRA), with the aim of spurring domestic investment in green technology. The Act devoted USD 369 billion in subsidies through grants, loans and tax credits to public and private entities to incentivise local investment in clean technologies, including production for EVs, EV batteries and battery raw materials. The subsidies cover the various elements of the battery supply chain from raw material extraction to completed vehicle sale and, at each stage, adds requirements for production to take place in the US. It also sets a minimum threshold for the raw materials in a battery that need to come from countries with which the US has a free trade agreement, with the threshold set to increase over time. In total, the various subsidies on offer for domestic battery manufacturers are estimated to be able to cover up to a third of the total battery manufacturing price [211].

The IRA has spurred significant investment and increased global competition. Between August 2022 and March 2023, major EV and battery makers announced cumulative post-IRA investments of at least USD 52 billion in North American EV supply chains – of which 50% is for battery manufacturing, and about 20% each for battery components and EV [212]. Some battery manufacturers have announced their intent to move manufacturing sites to the US to take advantage of the incentives offered [213].

EU

In early 2023, the EU issued its response to the IRA with its EU Green Deal Industrial Plan [214]. The plan has four key pillars related to progress on net zero-related projects: faster permitting for production facilities (particularly important for gigafactories), financial support, enhanced skills, and open trade. It also introduced the Net Zero Industry Act and Critical Raw Materials Act. These set ambitions for nearly 90% of the EU's annual battery demand to be met by EU battery manufacturers by 2030, and also introduced rules to achieve minimum and increasing thresholds for extraction, processing and recycling in the battery supply chain. The EU also introduced its Carbon Border Adjustment Mechanism (CBAM) which from 2023 will levy an import tax on emissions embedded in imported goods, such as metals produced outside the EU.

UK

The UK already offered extensive support for the automotive sector, including a multi-faceted grant landscape for research, innovation, and scaling emerging technologies. However, the UK has not yet responded with a broader strategy similar to the EU's Green Deal or the IRA in the US. A response to these policies is expected and many argue much needed, to signal the UK's position in the global competition. The Chancellor has said he will respond by the

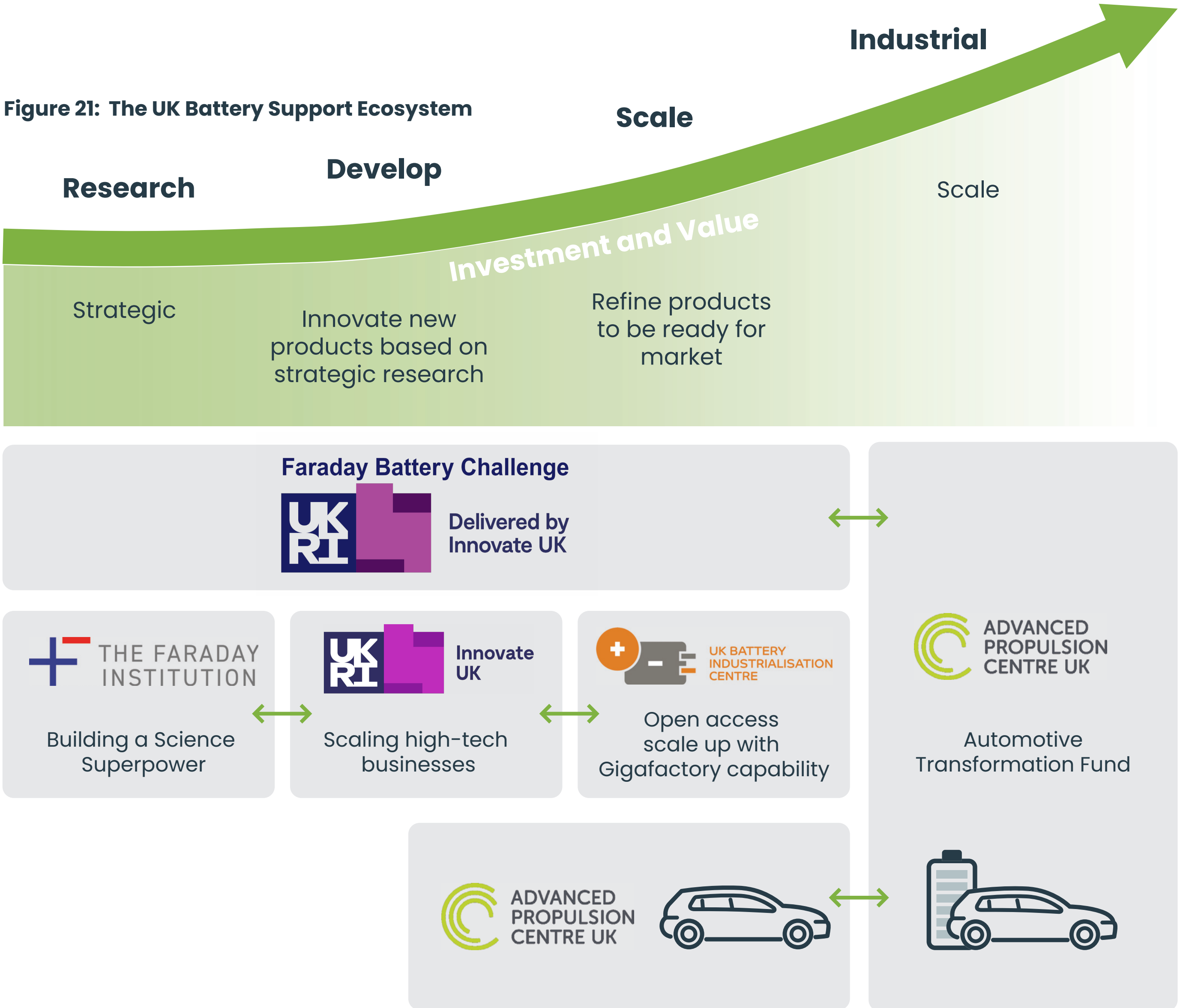
Autumn Statement [215], and industry hope for a full Industrial Strategy. Although the UK Government has not announced a flagship policy, it has taken interventions to support the battery supply chain. This includes the updated Critical Minerals Strategy, designed to build a resilient and sustainable critical minerals supply chain to support green industries and the energy transition in the UK – with materials for batteries forming a central part of this.

Additionally, Jaguar Land-Rover and Tata are believed to be in talks with UK government to secure financial support to assist with building a UK-based gigafactory.

2. What support is available for companies in the battery supply chain in the UK?

There are several organisations which offer support to companies across the supply chain. Together these organisations form a support network for companies at various stages of their development, as shown in **Figure 21**.

Figure 21: The UK Battery Support Ecosystem



Faraday Battery Challenge (FBC)

In recognition of the need for a battery supply chain, UK government established the Faraday Battery Challenge (FBC) in 2017. Delivered by Innovate UK as part of UK Research and innovation (UKRI), the FBC through a GBP 541 million investment between 2017 and 2025, aims to support a world-class scientific, technology development and manufacturing scale-up capability for batteries in the UK. The FBC programme is split into three elements:

- **The Faraday Institution**, a GBP 200 million investment comprised of 500 researchers undertaking application-inspired battery research across 27 UK universities. It is an independent institute for electrochemical energy storage research, skills development, market analysis and early-stage commercialisation. It also acts as a collaborative research community, connecting university groups across the UK.

- Collaborative research and development programmes focused on mid-technology readiness levels and run by **Innovate UK**, part of UKRI. Along with grant funding, Innovate UK provides business-focused interventions including collaborative research and development, skills, and programmes helping to connect businesses with investors through their Investor Readiness Programme, and The Cross-Sector Battery Systems Innovation Network, delivered by the KTN, the Knowledge Transfer Network.

- The £130m **UK Battery Industrialisation Centre** (UKBIC) is the UK's national battery manufacturing development facility, which helps companies to scale and commercialise battery technologies, and to upskill workers in battery manufacturing. Still the only one of its kind in Europe, the open access facility allows companies to reduce risk and increase investor or customer confidence in new technologies without the massive capital cost of entry barriers that often hinders successful progress. It provides the missing link between battery technology which has proved promising at laboratory or prototype scale, and successful mass production [216].

Advanced Propulsion Centre (APC)

The Advanced Propulsion Centre (APC) was set up by the UK government and the automotive industry in 2013 to enable organisations to develop cutting-edge technologies, build supply chains and invest in the facilities required to transition to green transport. The APC offers support to companies at different stages.

- For companies at an earlier stage, the APC offers a Technology Developer Accelerator Programme, which accelerated 100 low-carbon transport technology businesses, approximately 40% of which are battery focussed.

- For those undertaking mid-to-late stage innovation, the APC has R&D competitions, through which companies can attract between GBP 300,000 and GBP 20 million grant funding towards technology development and industrialisation projects. The APC's R&D programme has provided over GBP 140 million in grants to battery focussed projects.

- For companies looking to scale, the APC, alongside the Department for Business and Trade and Innovate UK, operates the Automotive Transformation Fund (ATF). The ATF is a long-term programme designed to enable the UK to build the world's most comprehensive and compelling electrified vehicle supply chain. The ATF is designed to support large-scale industrialisation through large capex grants to companies building gigafactories and associated supply chains. Companies can attract grants of a few hundred thousand pounds to undertake economic scale-up feasibility projects, through to significant grant support to invest in production capabilities in the UK.

Innovate UK and universities

Innovate UK, part of UKRI, offers various other support mechanisms [217]. Companies in the battery sector can apply for SMART Grants, which provide up to GBP 25 million for innovations that can 'significantly impact the UK economy' [218]. Recently, as part of its critical minerals strategy, the UK Government also announced GBP 15 million Innovate UK R&D programme to focus on creating a resilient supply chain of rare earth elements [219].

There is also support through UK universities such as Warwick Manufacturing Group, part of the University of Warwick. This includes the Energy Innovation Centre [220], the High Value Manufacturing Catapult (established by the Catapult network, funded by Innovate UK), and the national battery scale-up facility in Coventry. Together these provide a range of technology development and cell manufacture specialist support.

3. What more can be done to crowd finance into the battery supply chain?

Despite the extensive grant landscape, UK companies looking to scale up report challenges accessing finance at certain stages of development. All new companies or products can face 'Valleys of Death' in their evolution. This refers to the gap in finance availability in the scale up journey, where the risks and capital required do not match available investor appetite. There are multiple valleys in a company's scale up journey. Earlier valleys occur when companies are seeking to scale with feasibility studies, technological assessments, and early-stage piloting and manufacturing. These tend to occupy the space between venture capital and wider equity investment. Later valleys scale up their existing operations further. This tends to be more debt focused as companies move from early cash flows towards stable revenue.

The GFI has developed a Battery Investment Facility, which aims to de-risk specific investments for private sector financiers and help to unlock the scale of capital required for companies to succeed. For more information, see greenfinanceinstitute.co.uk

4. What does the battery supply chain need from investors?

To secure battery supply in a competitive global environment, capital is needed at pace and scale to enable the growth in manufacturing capacity needed to meet growing demand. As this Guide has set out, the size and breadth of the investment required presents an enormous opportunity for a wide range of investors, both those already familiar with, and those new to the sector. While there are established players, and much competition globally within the battery supply chain, the sector is of such strategic importance that governments around the world are developing new policies to attract aspects of the supply chain. This supply chain is diverse, and as this Guide has set out, this means there are various opportunities for investors within this sector in the UK.

9. Appendix:
Case Studies

Case Studies

Supporting technolgies for raw material extraction: Williams Advanced Engineering takeover by Fortescue

In 2022, WAE Technologies (formerly named Williams Advanced Engineering, a spinoff of the Williams F1 team) was acquired by Fortescue Metals Group for GBP 164 million. Fortescue plans to use the subsidiary to develop heavy duty mining vehicles with fully electric powertrains and large batteries, both to be produced domestically in the UK with at least one UK production site already announced [221].

Raw material processing: Green Lithium

2021: Received a grant from the Automotive Transformation Fund to support development activity around its plan to build and operate a large-scale lithium refinery.

2022: Secured GBP 1.6 million in Seed round funding to take the project to the next stage of development through raw material laboratory test-work analysis, planning and environmental scoping and baseline surveys and ground investigation.

Battery management systems: Dukosi

Dukosi, a battery management startup based in Scotland, has developed a BMS chipset which uses near field communication technology. With a single antenna, the design is able to monitor and process data directly on the individual cells of the battery and wirelessly communicate this data to the central BMS. This technology enables suppliers to re-architect batteries in EVs, removing over 95% of the cables currently required, resulting in lighter and, ultimately, more energy dense battery packs.

EOL battery applications: Zenobe

In some cases, companies are integrating multiple business models to generate alternative and diversified revenue streams. For example, Zenobe in the UK is providing several different complimentary services:

Fleet management – They provide fleet operators with support obtaining grid connections, charging infrastructure design and battery repair/ replacement.

Network infrastructure – Enabling grid operators to move to renewable electricity, for example their 100MW Capenhurst project is the first to have a commercial contract for reactive power services and is the largest battery directly connected to the transmission network in Europe.

Re-use – They use second-life batteries to create temporary power sources which run as a clean energy alternative to local diesel generators. These are arranged into banks, which can typically provide enough power to charge five cars.

Key to its success is the company's ability to raise finance. Zenobe was founded in 2017 and has since raised an estimated GBP 370 million [222] in convertible debt and equity funding, including GBP 50 million from private investors, management and NYC based private equity house Tiger Infrastructure Partners. The company has raised circa GBP 1 billion of debt, most recently a GBP 235 million long-term project debt facility with an accordion of GBP 400 million provided by a conglomerate of five banks, structured by NatWest. The company will use the funding to develop its next two grid-scale, battery project storage assets in Scotland which will provide stability services to the National Grid by storing energy from off-shore wind generators [223].

Battery health: Elysia

Part of William's Advanced Engineering, Elysia's software uses a battery digital twin and telematics data to track battery condition to provide automakers, fleet operators and battery asset financiers with information, such as when there might be safety issues, to inform decision-making. For example, batteries at risk of not meeting certain durability targets can be automatically flagged, with specific recommendations for each vehicle. This can help asset owners preserve the residual value of their batteries.

New recycling technologies (direct recycling):

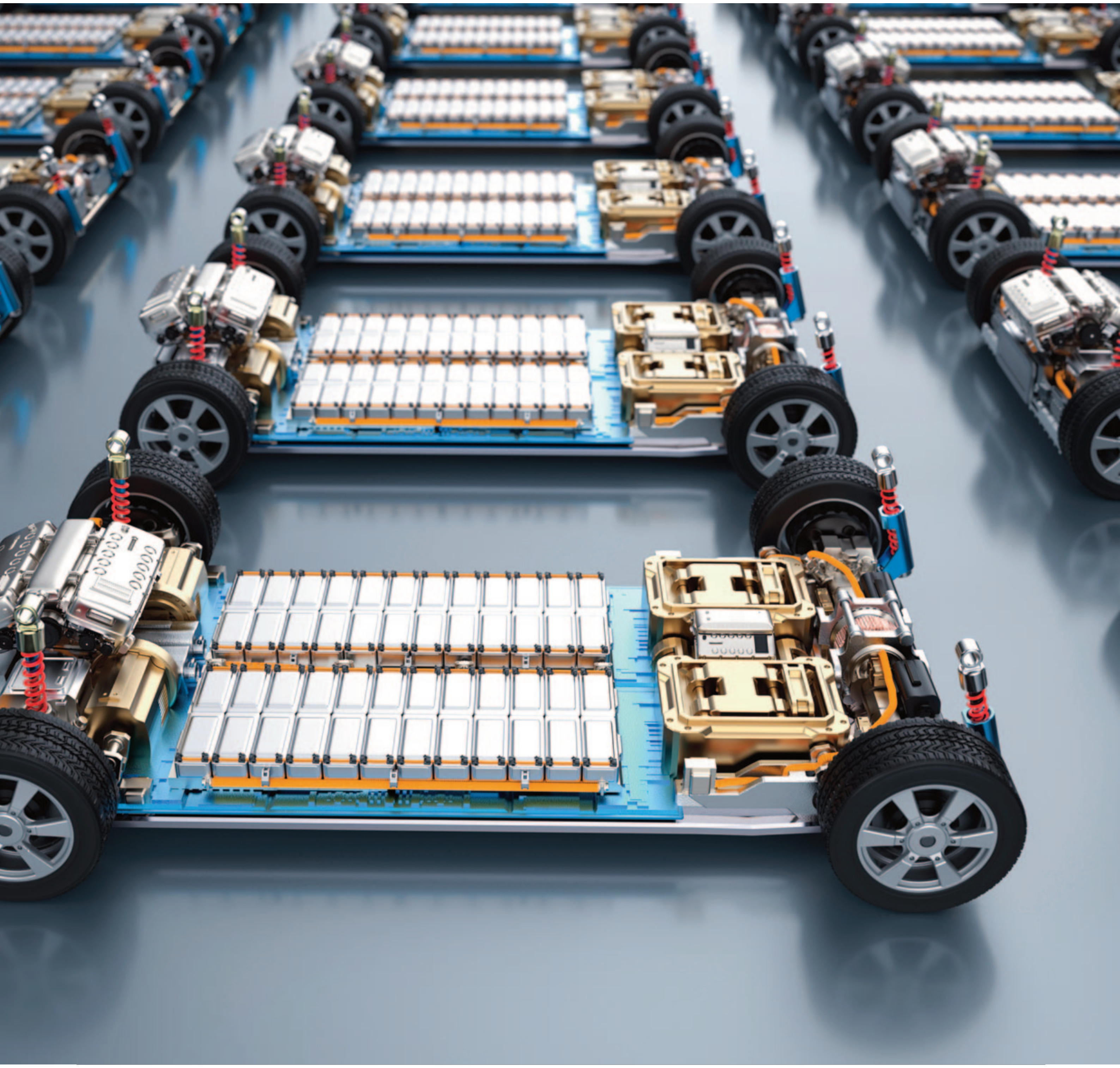
ReLib

ReLiB in the UK are using ultrasonic delamination to enable complete recovery of active materials with low energy and acid consumption to develop an economic method of recycling LFP batteries.

Supply chain management & lifecyle assessment:

Infyos

The Infyos platform allows companies to gain visibility into materials and suppliers across the supply chain, assess and report impact and a range of risks including human rights concerns, and help build internal tools to stay on top of company net-zero goals and customer requirements and comply with carbon and battery legislation.



Glossary

Term	Definition/Explanation
Anode	The negative electrode in a battery cell
Battery	A device containing an electric cell or a series of electric cells storing energy that can be converted into electrical power
Battery chemistry	Refers to the specific chemistry of the materials contained within the battery cells
Battery safety	Protecting the cell from out of limits operating conditions, either from the loads imposed by the intended application or abuse by the user or from unsuitable charging regimes
Cathode	The positive electrode in a battery cell
Cell	The electrochemical unit that provides a source of electrical energy by direct conversion of chemical energy
Composition	Refers to the raw materials used in a particular cell
Cycle life	The number of charge and discharge cycles that a battery can complete before losing performance
Cylindrical cell	A cell enclosed in a rigid cylinder can
Electrolyte	A medium containing ions that is electrically conducting through the movement of those ions, but not conducting electrons
Energy density	Energy density: The measure of how much energy a battery contains in proportion to its weight or volume. This measurement is typically presented in Watt-hours per kilogram (Wh/kg) or Watts-hours per litre (Wh/l)
Format (pack)	The physical structure of a battery pack
Formulation (chemistry)	Mixtures of chemical substances, designed to be used for a particular purpose
Gigafactory	A large factory that makes very large numbers of batteries for electric vehicles
Gigawatt-hours/year (GWh/yr)	The amount of Gigawatt-hours (1GWh = 1,000 MWh) produced per year

Term	Definition/Explanation
Hydrometallurgy	Use of aqueous chemistry for the recovery of metals from ores, concentrates, and recycled or residual materials.
Lithium iron phosphate (LFP)	A type of lithium-ion battery using lithium iron phosphate as the cathode material, and a graphitic carbon electrode with a metallic backing as the anode
Lithium-ion (Li-ion)	A type of rechargeable battery which uses the reversible reduction of lithium ions to store energy
Module	A grouping of battery cells
Lithium-Nickel-Manganese-Cobalt-Oxide (NMC)	A type of cathode
Pack	A set of battery modules within a surrounding enclosure
Pouch cell	A soft battery design where most of the cell components are enclosed in an aluminum-coated plastic film
Powertrain	The mechanism that transmits the drive from the engine/battery of a vehicle to its axle
Prismatic cell	A cell whose chemistry is enclosed in a prismatic rigid casing
Pyrometallurgy	Thermal treatment of minerals and metallurgical ores and concentrates to bring about physical and chemical transformations in the materials to enable recovery of valuable metals.
Separator	A permeable membrane placed between a battery's anode and cathode
Solid state	Deploys solid-state technology using solid electrodes and a solid electrolyte, instead of the liquid or polymer gel electrolytes
Tier 1 manufacturers	With more than 5 GWh of annual cumulative production capacity who are also qualified to supply more than one multinational OEM/EV producer outside of China
Technology readiness level (TRL)	A method for estimating the maturity of technologies during the acquisition phase of a program
Temperature performance	Referring to the performance of a battery under different temperature conditions
Voltage	The difference in electric potential between two points

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Green Finance Institute

CONTACT US

info@gfi.green

greenfinanceinstitute.co.uk