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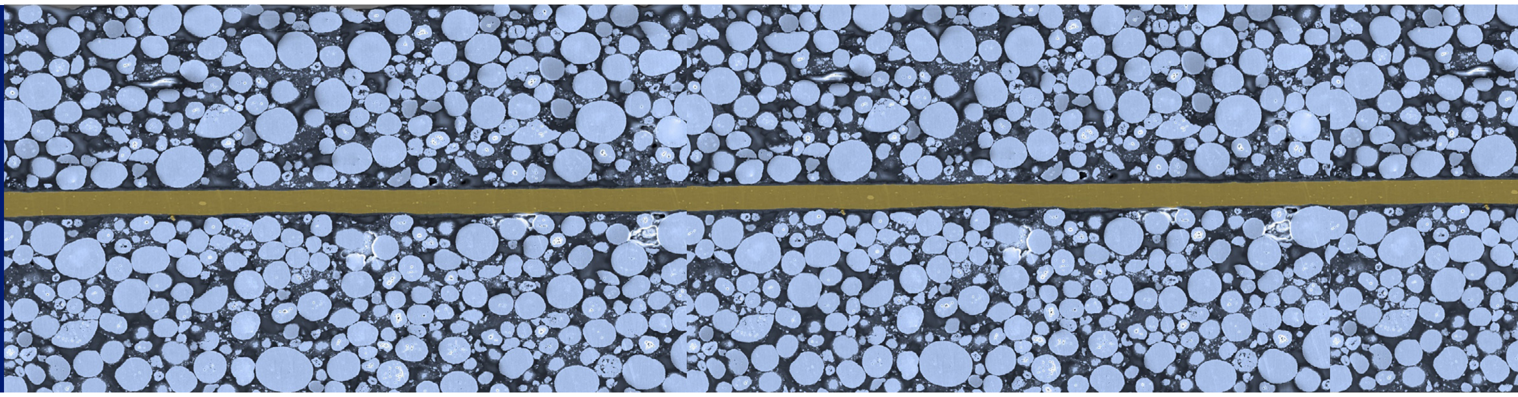
Developments in Lithium-Ion Battery Cathodes



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Commercial battery chemistries are rapidly evolving, driven by market demands, improved cathode materials and electrification of transport. Existing cathode chemistries such as lithium iron phosphate and lithium nickel manganese cobalt batteries continue to fulfil market requirements. However, with continued research and investment, next-generation lithium-ion batteries are likely to occupy a substantial segment of the battery market beyond 2030, bringing significant improvements in performance and/or cost.

Introduction

The cathode used in lithium-ion batteries strongly influences the performance, safety and the cost of the battery. Around one-half of the costs of a battery cell are accounted for by the cathode materials.[1] At the cell level, the performance of lithium-ion batteries is currently limited by the capacity of the cathode active material, which lags behind that of the anode. As such, there is considerable interest from the automotive industry, and other sectors, to increase the capacity of cathode materials.

Battery technology continues to evolve at a fast pace as relative performance of different cathode chemistries changes with research breakthroughs and developments in manufacturing techniques. This Insight outlines the benefits, challenges, likely research directions and production innovations of various battery cathode chemistries, with a particular focus on lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP) type cathodes in electric vehicles (EVs). In addition, beyond lithium-ion battery technologies, which could reach the mass market in the 2030s, will be discussed briefly.

The Insight also outlines key global trends in commercial use and offers two possible scenarios for the market uptake of new cathode technologies. The cost of raw materials has a significant influence on the cathode chemistry of choice, with recent spikes in global commodity prices (including lithium) causing a revival in lower-cost chemistries such as LFP. The report also examines the sensitivities of a variety of cathode chemistries to changes in raw material prices.

A glossary of terms is provided at the end of the document, and summary of key characteristics of various different cathode chemistries are given in Box 1.

Lithium-ion Battery Cathode Chemistries

Key cathode chemistries used in lithium-ion batteries today include LFP, NMC, lithium nickel cobalt aluminium oxide (NCA), and lithium manganese oxide (LMO). Each cathode chemistry offers unique combinations of cost, energy density, power density and cycle life performance benefits, with these changing regularly in response to technological developments and the evolution of supply chains (Box 1).

Cell energy density is a common metric by which commercial viability is assessed. It is an important factor to consider in applications where size and weight are critical, such as in portable devices or EVs. This can be described in two ways: specific energy and volumetric energy density, which are described by the following equations:

Image: SEM cross-sectional image of an NMC cathode (lithium nickel cobalt manganese oxide) produced using the IWS dry film process. © Fraunhofer IWS Dresden

[1] Institute for Energy Research (April 2022). Electric Vehicle Battery Costs Soar.

Box 1: Characteristics of Different Cathode Materials

The table below provides a brief overview of the key characteristics of some of the most important lithium-ion battery cathode chemistries.

Material formula	Abbreviation	Cost	Energy density	Thermal stability	Cycle life
$LiCoO_2$	LCO	High	Moderate	Poor	Good
$LiFePO_4$	LFP	Low	Low	Good	Good
$LiMn_2O_4$	LMO	Low	Moderate	Good	Poor
$LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$	NMC622	High	High	Moderate	Good
$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$	NMC811	High	High	Poor	Moderate
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	NCA	High	High	Poor	Moderate
$Li_{1.2}Mn_{0.48}Ni_{0.16}Co_{0.16}O_2$	LMR-NMC	Moderate	High	Moderate	Poor

Source: Faraday Institution.

$$\text{Cell specific energy (Wh/kg)} = \frac{\text{Cell capacity (Ah)} \times \text{Cell voltage (V)}}{\text{Cell mass (kg)}}$$

$$\text{Cell volumetric energy density (Wh/L)} = \frac{\text{Cell capacity (Ah)} \times \text{Cell voltage (V)}}{\text{Cell volume (L)}}$$

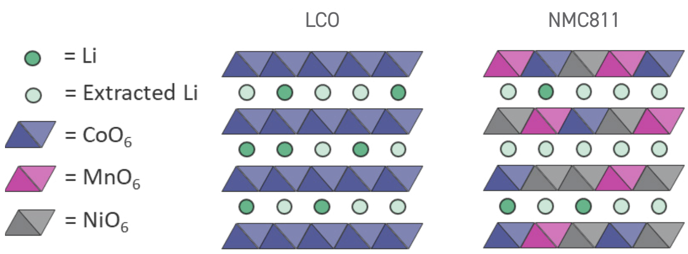
By considering this relationship, if the available capacity or the operational voltage of a particular cathode material is increased, the overall energy density of the cell also increases.

LCO (lithium cobalt oxide) is the original lithium-ion cathode and has been in use for over three decades.[2] Possessing a good theoretical capacity and high average discharge voltage, LCO can deliver high energy densities. However, its practical use is limited due to structural degradation occurring at high states of charge (SOC), which limits its useable capacity to half its theoretical capacity (Figure 1). Mainly used to power portable consumer electronic products, such as digital cameras, mobile phones, and laptops, LCO's market share is likely to reduce further due to ethical and supply chain concerns with the use of cobalt and its unsuitability for EV applications.[3]

NMC oxides are layered cathode materials that were first developed through the optimisation of LCO, with a typical composition of $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC111). This optimisation involved the partial substitution of cobalt with nickel and manganese, aiming to improve the structural stability of the material during cycling. As a result, increasing the ratio of nickel to cobalt within the structure enables higher capacities at the same voltages when compared to LCO, allowing higher energy densities to be reached. This high energy density makes them particularly attractive candidates for EV applications. Since their inception, the composition of NMC cathodes has been refined in pursuit of higher practical energy density. New NMC compositions have been created by varying the ratio of the constituent transition metals, pushing the structure toward more nickel-rich compositions. These compositions include NMC622 ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$) and NMC811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$) which are widely used in battery production for EVs today. Future NMC type materials include lithium- and manganese-rich cathode materials (LMR-NMC), promising higher energy densities. Due to the constrained and volatile supply chains of nickel and cobalt, NMC oxides are more expensive than LFP type chemistries, but less expensive than LCO.

Figure 1: Comparing lithium extraction between LCO and NMC811 cathodes at the same voltage.

More lithium can be extracted from NMC811 than LCO, giving NMC811 a higher energy density.



[2] Li_xCoO_2 $(0<x<-1)$: A new cathode material for batteries of high energy density, J. B. Goodenough et al., Mat. Research Bulletin, 1980.
[3] Faraday Insight 7 - Building a Responsible Cobalt Supply Chain.

NCA has the same structure as NMC, except aluminium replaces manganese, with a typical composition of $LiNi_{0.85}Co_{0.15}Al_{0.05}O_2$. NCA was first deployed in EVs by Tesla. Due to its high nickel content, NCA can yield high energy densities like NMC. However, the lack of manganese in the structure limits its thermal stability. New materials such as $LiNi_{0.89}Co_{0.05}Mn_{0.05}Al_{0.01}O_2$ (NMCA), comprised of lithium, nickel, manganese, cobalt and aluminium, offer promise for selectively tuning performance with respect to NMC and NCA.[4] Given the similarity in chemistry, NCA and NMCA both suffer from many of the same challenges as NMC, in particular the accelerated material degradation occurring at high SOCs.[5]

LFP cathode materials are iron-based olivines, derived from low-cost, and relatively non-constrained commodities (iron ores and phosphates), with the composition $LiFePO_4$. LFP was originally discovered in 1950 but its electrochemical viability as an active cathode material was not reported until 1997.[6,7] Although LFP offers lower cell-level energy density than NMC-type cathode materials, due to its operating at a lower voltage and lower specific capacity, it has a superior cycle life. LFP has traditionally occupied a smaller share of the global EV market, but uptake of this chemistry has doubled since 2020 and is expected to continue to rise due to ongoing supply chain issues affecting competitor chemistries, enhancement of LFP performance, and the elapsing of key US and European patents.[8,9] LFP type cathodes can be improved by doping (i.e., introducing other elements or impurities) the parent structure with elements such as manganese leading to LMFP type materials.

LMO is a spinel-type material with a material composition of $LiMn_2O_4$ that is used in consumer electronics, power tools and, to a lesser extent, EVs. LMO operates at much higher voltages than other cathode materials (>4.0V). In addition, lithium can be rapidly extracted due to the three-dimensional lithium channels present in the structure. However, due to its low capacity, LMO is often optimised for high-power applications because the high lithium mobility enables the release of energy at much faster rates. LMO batteries are relatively cost competitive because manganese, the dominant component, is cheap. Advances in spinel-type materials include lithium manganese nickel oxide (LMNO), a nickel containing analogue, that provides an increase in energy and power density.

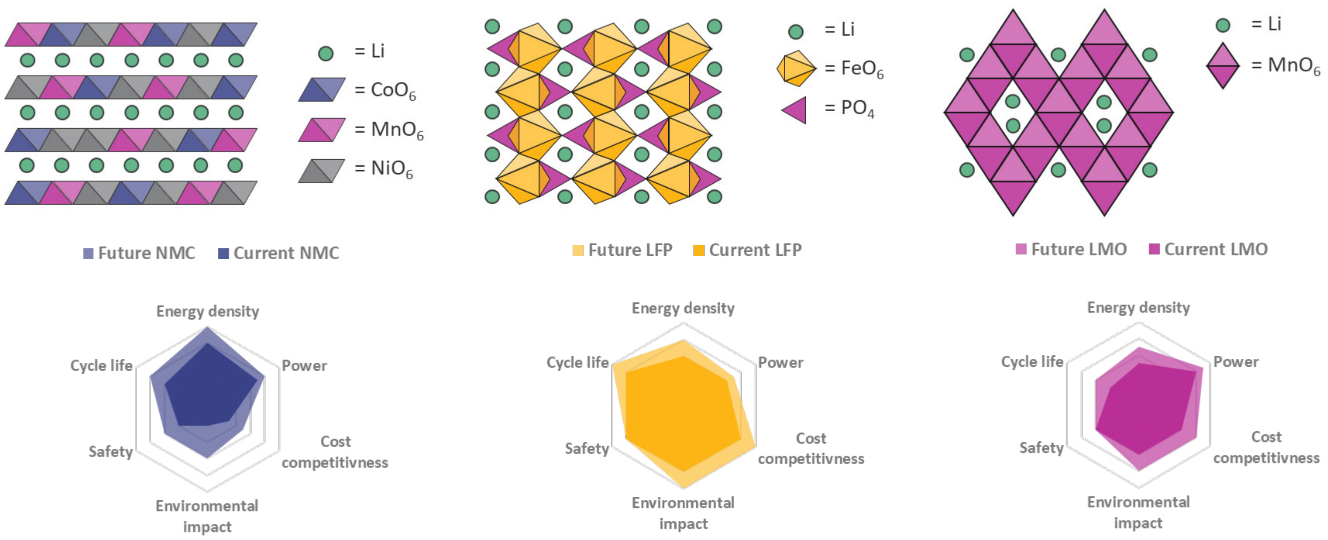
The performance of NMC, LFP, and LMO chemistries (both current and future performance) across key performance characteristics such as energy density, power, cost, safety, environment and cycle life are illustrated in Figure 2. Different chemistries are typically attractive to different EV market segments as follows:

- Low cost / adequate performance: Chemistries such as LMO, LFP and LMFP are used to drive down cost while still securing acceptable levels of energy density at the cell level.
- Mid-cost / mid-performance: Products offer greater performance, but at a mid-range cost price point, using chemistries LMNO and low-nickel content NMCs.
- High cost / high performance: Chemistries such as NCA and the high-nickel content NMCs.

Changes in Battery Chemistries Deployed

While the types of battery chemistries manufactured in the next 2 to 3 years can be anticipated from EV sales and the announced plans and strategies of the automakers and battery manufacturers, the outlook over longer time horizons is much more uncertain. A new battery chemistry typically takes 5 to 10 years to move from academic research to industry. Estimating the market penetration of next-generation battery technology is therefore particularly

Figure 2: Comparison of performance of major cathode classes (current and future)



[4] Quaternary Layered Ni-Rich NCMA Cathode for Lithium-Ion Batteries, Un-Hyuck Kim et al., ACS Energy Lett. 2019.
[5] Oxygen Loss in Layered Oxide Cathodes for Li-Ion Batteries: Mechanisms, Effects, and Mitigation, Hanlei Zhang et al, Chem. Rev. 2022
[6] Effect of Structure on the Fe^{3+}/Fe^{2+} Redox Couple in Iron Phosphates, A. K. Padhi et al 1997 J. Electrochem. Soc. 144 1609.
[7] Phospho-olivines as Positive-Electrode Materials for Rechargeable Lithium Batteries, A. K. Padhi et al 1997 J. Electrochem. Soc. 144 1188.
[8] Global Supply Chains of EV Batteries – IEA 2022.
[9] Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles, Xiao-Guang Yang et al, 2021 Nature Energy.

challenging since success will depend on the timing of numerous research breakthroughs that are currently unknown or undefined. For the purposes of this report, next-generation technologies are batteries with next-generation cathodes, including lithium-ion batteries with lithium-rich cathodes, lithium-sulfur batteries and sodium-ion batteries.

Given these uncertainties, the Faraday Institution has developed two scenarios, instead of a single point forecast, to illustrate how battery technology might evolve in the European EV battery manufacturing market:

- Scenario 1 (Gradual transition): An extension of recent trends and developments with lithium-based chemistries dominating the outlook to 2040; and
- Scenario 2 (Beyond lithium-ion breakthrough): A more optimistic view of the speed of breakthroughs, with new battery technologies taking nearly half of the market by 2040.

Under scenario 1, NMC (including NCA) and LFP (including LMFP) lithium-based cathode chemistries dominate the European EV market over the next decade, with next-generation technologies only beginning to get a modest foothold. By 2040, NMC chemistries decline to around 38% as the use of cheaper LFP chemistry becomes more widespread, with LFP chemistries accounting for a 32% market share and LMO/other chemistries for the remainder (Figure 3).[10] Under this scenario, the development of next-generation technology is gradual with a market share smaller than existing chemistries.

Under scenario 2, significant research breakthroughs in next-generation technologies occur at pace and commercialisation is successful in bringing the technologies to market. By 2040, next-generation technologies take 50% of the European EV battery manufacturing market, with NMC and LFP retaining sizeable market shares of 25% and 21% respectively (Figure 4).

Figure 3: European EV battery manufacturing by chemistry to 2040 – 'Gradual transition' scenario

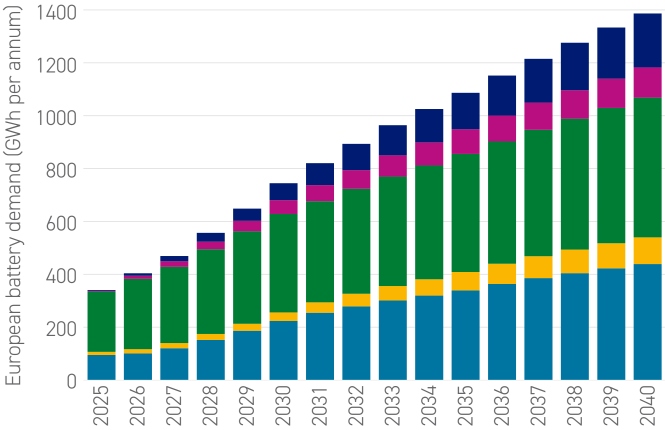
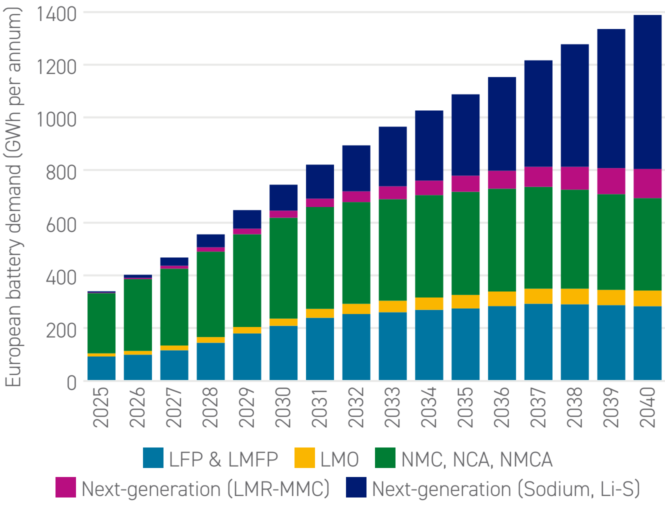


Figure 4: European EV battery chemistry manufacturing to 2040 – 'Next-generation breakthrough' scenario



Source (Figs 3 & 4): Faraday Institution. Numerical data for figures.

Developments in NMC

Key properties

In this section, the term 'NMC' will be used to refer to both NMC and NCA type cathodes, as they share similar structures and composition. The baseline NMC111 composition (33% nickel / 33% manganese / 33% cobalt) exhibits modest discharge capacities and relatively good thermal stability. By varying the ratio of the constituent transition metals and increasing the nickel content of the cathode, new compositions were formed (NMC532, NMC622, NMC811 etc) leading to higher energy densities, while simultaneously decreasing the reliance on cobalt.

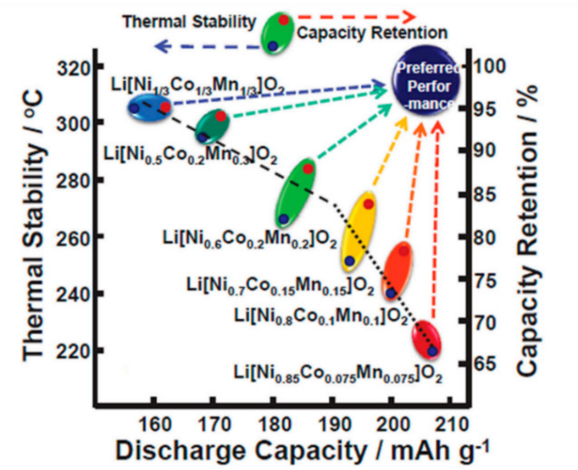
The high energy density of NMC materials enables longer ranges to be reached for EVs, making them the cathode material of choice for many sectors of the automotive industry. NMC type cathodes have higher power capabilities than LFP type cathodes, making them more appropriate for high end luxury and performance EVs. At the cell level, NMC type cathodes can typically reach 300 Wh/kg and above 700 Wh/L.[11] Innovations in battery pack design, such as the introduction of cell to pack technology, are being applied to NMC cells. For example, CATL's Qilin NMC pack offers an energy density of 250 Wh/kg, significantly higher than LFP based chemistries.[12]

Increases in energy density using NMC type materials will largely be achieved by moving to higher nickel content cathodes. However, nickel-rich NMCs also face numerous challenges, such as lower capacity retention and lower thermal stability (Figure 5). At the same voltage, nickel-rich cathodes show higher levels of degradation than lower nickel content cathodes. This is in large part due to the plethora of oxygen loss inducing surface reactions that occur with the electrolyte, causing structural degradation and gas evolution,

[10] It should be noted that LFP takes a much larger share (42%) of the global market in 2023 due to the high penetration of LFP in China and the relative importance of the Chinese market, which accounts for 74% of batteries manufactured globally.
[11] Push EVs: CATL achieves 304 Wh/kg in new battery cells - 2022.
[12] CATL - Innovative Technology.

which in turn effects performance. The Faraday Institution's Degradation project[13] aims to develop a comprehensive mechanistic understanding of the relationship between external stimuli (such as temperature and cycling rate) and the physical and chemical processes occurring inside the battery that lead to degradation.

Figure 5: The thermal stability, discharge capacity, and cycle life of NMC cathode materials[14]



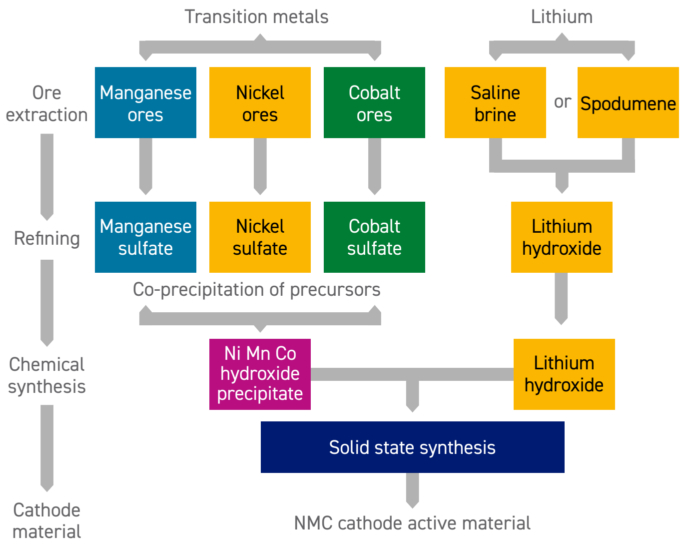
Nickel-rich cathodes also have decreased structural and thermal stability, raising potential safety concerns. Finally, nickel-rich cathodes are also more sensitive to air and moisture damage and require specialist equipment and manufacturing. Improvements and innovations in materials production are needed as the nickel content of NMC cathodes increases.

Innovations in NMC cathode production

Currently, the industrial production of NMC cathodes requires a two-step process (Figure 6). The first step involves co-precipitation of the transition metal precursors to regulate particle size, morphology and surface composition of the final NMC cathode material. This is then followed by a solid-state reaction with lithium hydroxide that leads to the final NMC cathode material. Materials made this way typically have a spherical morphology, with the larger secondary particles being made up of thousands of smaller primary particles. This high surface area morphology limits the cycle life of high nickel content NMC cathodes due to the formation of cracks between these particles. These cracks expose bulk active material to the electrolyte, where parasitic side reactions can occur.

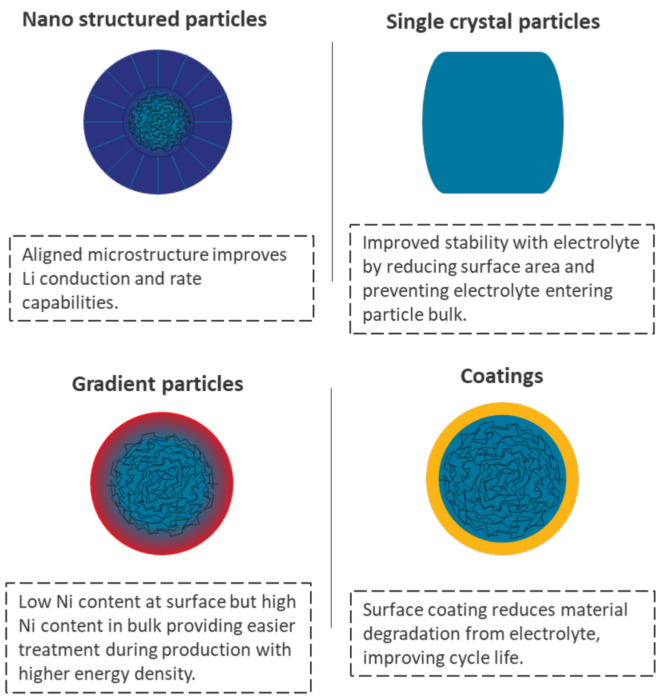
To improve the performance of nickel-rich cathodes, innovations in the cathode material production are being pursued to manipulate particle homogeneity, elemental distribution and structure. Innovations in cathode production seek to address the issues of structural and surface instability by using protective surface layers or manipulation

Figure 6: Overview of the industrial production processes for NMC cathode materials



of particle structure to improve stability and performance (Figure 7). For example, nano-structured particles have been shown to improve the movement of lithium during the charge discharge cycle and increase the rate capability of the material. Another avenue for innovation is the development of single crystal NMC cathode materials, which could help prevent the formation of cracks between primary particles, thus mitigating degradation. This can be achieved by synthesising a single continuous crystal structure within the whole particle – single crystal NMC particles.[15]

Figure 7: Innovations in NMC cathode synthesis



[13] The Faraday Institution Degradation project website.

[14] Comparison of the structural and electrochemical properties of layered $Li[Ni_xCo_yMn_z]O_2$ (x = 1/3, 0.5, 0.6, 0.7, 0.8 and 0.85) cathode material for lithium-ion batteries, Hyung-Joo Noh et al., Journal of Power Sources, 2013.

[15] A Wide Range of Testing Results on an Excellent Lithium-Ion Cell Chemistry to be used as Benchmarks for New Battery Technologies, Jessie E. Harlow et al 2019 J. Electrochem. Soc.

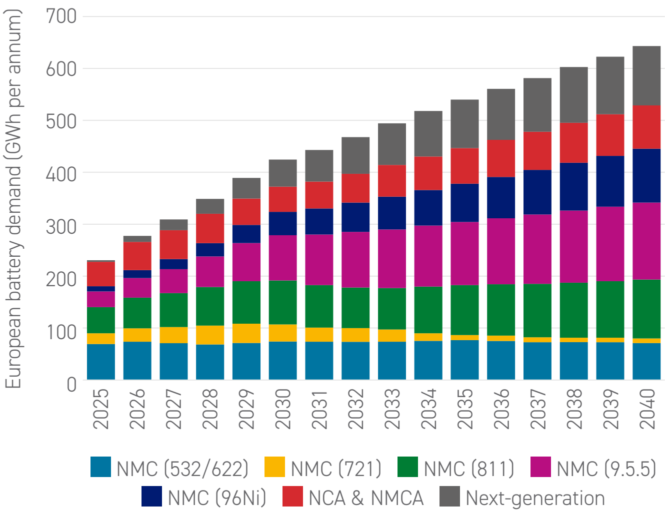
Other advancements focus on the development of surface modifications. This includes the synthesis of gradient articles with a nickel concentration gradient increasing from a low nickel concentration at the particle surface to a high nickel concentration within the bulk structure. Using a NMC811 bulk structure encased by a NMC622 surface layer, for example, produces a cathode which not only has increased energy density but also a more stable surface. Coatings (e.g., Al_2O_3) are another important innovation, as they prevent long-term degradation and increase the cycle life by reducing the surface reactivity of the cathode.

Market trends in NMC cathodes

NMC cathode materials are predominately used in the automotive industry, as they offer much higher energy densities than other materials. This demand for NMC cathodes will continue to increase as the transport sector continues to electrify, but there are several developments that are set to determine which cathodes will become dominant.

The key trend in the NMC market is a move towards cathodes with higher nickel content (Figure 8) and this trend will be driven by current and future innovations. From 2025 onwards, NMC532 or NMC622 cathodes will continue to be replaced by NMC811, NMC9.5.5 cathodes ($LiNi_{0.9}Mn_{0.05}Co_{0.05}O_2$) and ultra-high nickel content cathodes (i.e., Ni% > 96%). The increased popularity of high nickel content cathodes has also been driven by advances in materials manufacturing as described in the previous section. Large automotive companies such as VW, Tesla and Renault have announced that high nickel content cathodes are a key part of their battery development strategies.[16] Battery manufacturers including Panasonic and SVolt are actively researching and producing cobalt free cathode formulations.[16,17]

Figure 8: Breakdown of NMC chemistries to 2040 under scenario 1



Source: Faraday Institution. Numerical data for figures.

NCA type cathodes will continue to have an important market share towards 2040 thanks to the development of NMCA type materials. NCA cathodes were originally developed by Tesla and Panasonic and have remained exclusively in use by Tesla for its early EV models. However, as the demand for EVs has grown, automotive manufacturers have found themselves needing a greater supply of batteries, which in turn has pushed the demand for different cathode chemistries. For example, both Tesla and GM are now trialling NMCA cells for automotive applications.[16,18]

Finally, a new material class named lithium-rich NMC cathode materials are expected to become commercially available from the middle of the decade. These materials represent are a key development in the evolution of NMC cathodes, and will be discussed in more detail later in the "next-generation" section.

Developments in LFP

Key properties

The baseline composition of LFP cathodes is $LiFePO_4$. LFP is non-toxic and is less susceptible than other chemistries to catch fire during battery misuse or after sustaining structural damage to the cell. However, LFP has poor electrical conductivity and sluggish lithium-ion mobility due to its FeO_6 octahedral network, which limits charge/discharge efficiency at fast rates.[19] Improvements to cycle efficiency have been achieved through several strategies, including:

- the use of highly conductive carbon nanofibers in the electrode composite;
- the alteration of surface chemistry by means of direct surface coatings to improve conductivity;
- the introduction of other elements or impurities, referred to as doping.

Commercially available LFP batteries offer considerably longer cycle life and longer calendar life than most NMC batteries. LFP batteries also offer excellent round trip efficiency.[20] In addition, LFP is also cobalt free, providing substantial socio-economic and environment benefits. However, LFP has much lower energy density than NMC and NCA cathodes and as a result, has only been used outside of China in the low-cost EV market segment.

LFP is widely used in China due to favourable licensing arrangements, city driving requirements and regulatory considerations. This has incentivised Chinese companies to focus on improving the energy density of LFP. Consequently, significant improvements have been made at the material, cell and pack levels over the past decade, including:

- An increase in the cell level energy density of state-of-the-art LFP batteries from 90 Wh/kg in 2010 to 160 Wh/kg in 2022;[21]

[16] Volta Foundation - Battery Report 2021.
[17] IMLB 2022 Talk – Evolution of Battery Technology & Manufacturing in Panasonic to Realize Sustainable Society.
[18] Electrek - Tesla is expected to be first to use LG's new NCMA nickel-based battery cells.
[19] The Progress and Future Prospects of Lithium Iron Phosphate Cathode Materials, Chunyu Chen et al., Highlights in Science, Engineering and Technology, 2022.
[20] Degradation of Commercial Lithium-Ion Cells as a Function of Chemistry and Cycling Conditions, Yuliya Preger et al 2020 J. Electrochem. Soc.
[21] Takoma Battery LMFP industry report - 2022.

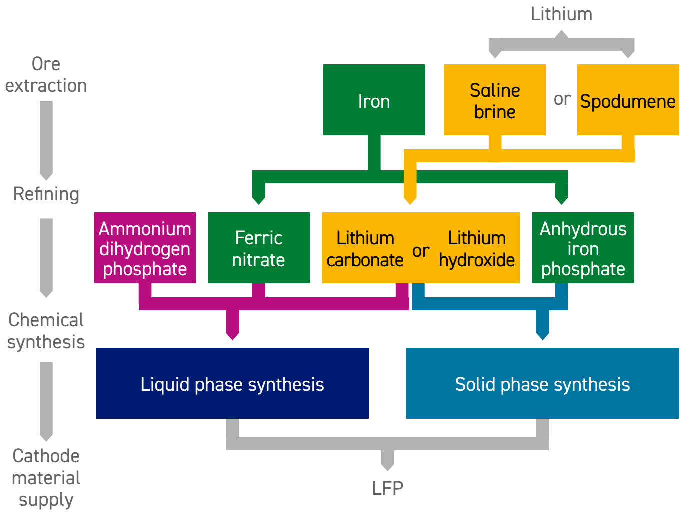
- Increases in pack level energy density achieved through pack level engineering and innovation, such as BYD's or CATL's novel cell to pack technology,[12] which have narrowed the gap with conventional modular NMC and NCA packs; and
- Requirements for less inactive cell casing materials at the pack-level, due the safer chemistry of LFP.

The increasing competitiveness of LFP packs has recently been recognised by US and European automotive companies. For example, Tesla and Volkswagen have already begun transitioning to LFP for entry-level models.[22] In addition, optimised LFP is highly cost competitive, with LFP cells reaching a cost point of $80/kWh in 2020.[23]

Innovations in LFP cathode production

LFP was initially produced industrially via solid phase synthesis routes, such as high temperature solid phase reactions or carbothermal reduction, using lithium hydroxide derived from saline brine or from spodumene (Figure 9).[24] However, the supply of lithium hydroxide has become relatively constrained due to ever growing EV battery demand. As a result, Chinese manufacturers are transitioning to lithium carbonate and employing liquid phase syntheses, such as liquid phase precipitation, sol-gel or hydrothermal synthesis.

Figure 9: Overview of the industrial production processes for LFP cathode materials



In addition, further improvements in cell level energy density are expected through the introduction of modified LFP chemistries. A relatively new variation of LFP called lithium manganese iron phosphate ($LiMn_xFe_{1-x}PO_4$ or LMFP) is attracting significant attention from battery producers. The substitution of iron with manganese increases the operating voltage of the cell, yielding a greater energy density than that provided by standard LFP. As such, LMFP offers a cell level energy density of around 210-240 Wh/kg, roughly 40% more than LFP.[25,26] Mass-scale LMFP cell production is already underway, with companies in China and the US looking to commercialise this technology.[25,27]

Market trends in LFP cathodes

Over the past three years, the global market has seen a substantial increase in the market share of LFP, thanks to lower raw material costs and improvements in cell and battery pack engineering. The growth in popularity of LFP has so far been driven largely by market developments in China, but LFP has recently started to grow in European markets as well.[28]

While NMC type cathodes are mainly used to power EVs, LFP is well suited to EV applications with shorter range requirements as well as battery energy storage systems (BESS). This is due to the outstanding cycle life, safety benefits and low cost of LFP compared to NMC type cathodes. Its importance within the BESS sector is expected to continue to grow to 2030 and beyond. As such, the share of the battery market occupied by LFP and LMFP is set to continue increasing over the coming decade, rising to 30% in Europe in 2030 under scenario 1.

Developments in LMO Type Chemistries

LMO has the potential to be an alternative cheap cathode material to LFP. LMO operates at a much higher voltage than other cathode materials, enabling it to achieve high power densities, which is useful for applications such as power tools and aerospace. However, LMO type cathodes currently suffer from poor cycle life, due to the instability of the cathode under cycling. Structural Mn^{2+} cations dissolve into the electrolyte during operation, promoting irreversible phase changes that make lithium extraction (and reinsertion) difficult. This lowers the accessible capacity and decreases capacity retention in subsequent cycles. Inhibiting this dissolution through the use of coatings is required to enable efficient LMO use.

Advances in spinel-type materials include lithium manganese nickel oxide (LMNO), a nickel containing analogue of LMO with a typical composition of $LiNi_{0.5}Mn_{1.5}O_4$. The introduction of nickel into the material pushes the operational voltage above 4.5V, providing an increase in energy and power density. However, operating a battery at such an elevated voltage brings with it some challenges. Interfacial side reactions in the cell lead to poor cycle life and potential safety issues. As such, advances in electrolyte formulations are required to enable the full potential of LMNO cathodes to be realised.

[22] Electrek - Tesla is already using cobalt-free LFP batteries in half of its new cars produced.
[23] BNEF - Battery Pack Prices Cited Below $100/kWh for the First Time in 2020.
[24] Xiamen WinAck Battery Technology.
[25] CNEVPOST - CATL said to mass produce LMFP batteries within this year.
[26] Electrive - Gotion High-Tech prepares LMFP cell production.
[27] iM3NY website.
[28] Goldman Sachs - Batteries: The Greenflation Challenge - 2022.

Box 2: Cathode Material Research Led by the Faraday Institution

As a part of its research portfolio, the Faraday Institution funds two research projects focused on the development of new cathode materials - FutureCat[29] and CATMAT.[30] FutureCat employs a coordinated approach to discover, develop, and deploy next-generation cathode materials, with a particular focus on high performance, layered and spinel nickel rich materials, as well as coatings for cathode materials (Figure 7). The project also explores dopants, single crystal materials, and coatings for cathode materials (Figure 7). The Degradation project is exploring the stability of the high nickel material developed by FutureCat.

CATMAT aims to understand the fundamental mechanisms acting within lithium-rich cathode materials. The project is exploiting this new knowledge to aid the discovery of novel cathode materials using low cost, earth abundant elements. Some of the early-stage materials that the project is working include oxygen redox materials, disordered rocksalt materials and polyanionic charge carrying materials. Oxygen redox cathode materials have the potential to increase both the capacity and operating voltage of cathode materials, however their stability over long term cycling must be increased to enable commercialisation. Disordered rocksalt materials can be made with a wide range of abundant elements and offer exceptionally high capacities. Conversely, these materials suffer from severe capacity fade during cycling, limiting their application. Polyanionic materials are not reliant on cobalt or nickel making them attractive from a cost perspective. However, their energy densities are still too low for practical use.

In a commercial setting, LMO cathodes have already been used for a wide range of applications, including EVs. The Nissan Leaf, launched in 2011, originally had a battery pack that contained LMO as an active material.[31] Another auto OEM, Volkswagen, made announcements at their battery day in 2020 that they would be pursuing manganese-rich cathode material compositions (which includes LMO and LMO derivatives) in their battery development, while CATL have placed LMNO type materials on their battery chemistry roadmap to 2030.[16] Another development with LMO materials include a dual chemistry battery pack created by battery manufacturer Our Next Energy, which combines LMO and LFP and was used to power a modified Tesla 752 miles on a single charge.[32] Due to its high-power capabilities, LMO type cathodes are seen as promising for aerospace applications, including drones, electric vertical take-off and landing (eVTOL) aircraft and satellite applications.

Developments in Next-Generation Batteries

Next-generation batteries and next-generation cathodes are being developed at pace. The specific chemistries of these future technologies that will be commercialised and adopted at scale is uncertain and will depend on research advances, market factors and the development of new manufacturing methods. Promising technologies include sodium-ion, lithium-sulfur, lithium-rich cathode materials, and other next-generation chemistries, such as multivalent chemistries and metal-air batteries.

By 2040, sodium-ion batteries, lithium-sulfur batteries and other next-generation chemistries are expected to take a 23% market share (Figure 3) under the 'Gradual transition' scenario rising to 50% (Figure 4) under the 'Next-generation breakthrough' scenario. The potential market split between sodium, lithium-sulfur and other chemistries (under the Next-generation breakthrough scenario) is illustrated below.

Sodium-ion batteries[33] have the potential to be a low-cost competitor to lithium ion. Reserves of sodium, unlike lithium, are widely distributed with relatively non-volatile supply chains. Numerous countries, including India, are prioritising the development of this technology due to its lower cost and resilience to geopolitical issues. The relatively high-power density and low energy density of sodium-ion batteries make them suitable for low-cost and lightweight e-bikes, scooters, short-range EVs and light EVs, as well as for BESS applications. A key advantage of sodium-ion batteries is that they can be produced on existing lithium-ion battery lines. Although sodium-ion batteries are in their infancy compared to lithium-ion batteries, there have been significant performance improvements in recent years. In terms of cathode chemistry, there are three leading classes of sodium-ion cathodes: polyanion-type materials,[34] prussian blue analogues[35] and sodium layered oxides.[36]

Companies such as CATL, BYD, SVolt, HiNa and Reliance New Energy Solar (RNES),[37,38] are all working in this area. In February 2023, HiNa became the first sodium-ion cell producer to announce the release of an EV with an all sodium-ion battery pack with an expected late 2023 launch date.[39]

Lithium-sulfur cells[40] are batteries that pair a lithium metal anode with a sulfur-based conversion cathode. Sulfur is a low-cost material with an exceedingly high theoretical

[29] The Faraday Institution FutureCat project website.
[30] The Faraday Institution CATMAT project website.
[31] Inside EVs - Nissan LEAF 40-kWh Battery: Deep Dive.
[32] Our Next Energy – Gemini Battery Pack.
[33] For further details see: Faraday Insight 11 – Sodium-ion Batteries: Inexpensive and Sustainable Energy Storage.
[34] Polyanion-Type Electrode Materials for Sodium-Ion Batteries, Qiao Ni et al., 2017, Advanced Science, Wiley Online Library.
[35] Thin Film Electrodes of Prussian Blue Analogues with Rapid Li+ Intercalation, Yutaka Morimoto et al., 2012, Applied Physics Express 5.
[36] High-Voltage Stabilization of O3-Type Layered Oxide for Sodium-Ion Batteries by Simultaneous Tin Dual Modification, Tengfei Song et al., Chem. Mater. 2022, 34, 9, 4153–4165.
[37] Inside EVs - CATL Unveils First-Generation Sodium-Ion Battery.
[38] Electrive - Reliance takes over Faradion for £100 million.
[39] CNEVPOST - Hina Battery becomes 1st battery maker to put sodium-ion batteries in EVs in China.
[40] For further details see: Faraday Insight 8 - Lithium-sulfur batteries: lightweight technology for multiple sectors.

capacity, which could enable lithium-sulfur cells to achieve ultrahigh theoretical energy densities (2,600 Wh/kg). Despite this, few cells currently offer energy density above 500 Wh/kg, with cell cycle life and power density also being an issue. As such, there are considerable challenges that need to be addressed before sulfur cathodes can be seriously commercialised. Lithium-sulfur batteries are most appropriate for applications that require high energy rather than power.

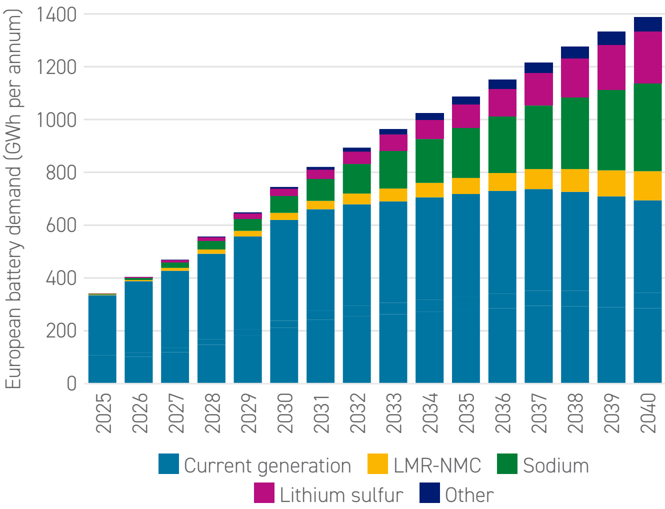
In the long-term lithium-sulfur batteries are expected to find uses in both short-range aviation and niche automotive markets, such as large heavy goods vehicles. This technology is expected to be introduced for commercial use from 2030 although it is not yet available.

Lithium-rich cathode materials are a key development in the evolution of NMC cathodes. LMR-NMC cathode materials promising exceedingly high specific capacities (280 mAh/g for LMR-NMC versus 200 mAh/g for NMC811) due to the large amount of lithium incorporated within the material's structure. As this additional lithium can also be extracted at high voltages, LMR-NMCs yield superb energy densities. In addition, LMR-NMC type cathodes contain a higher proportion of manganese than NMC, moving away from supply chain risks and high costs associated with nickel and cobalt. However, under long-term cycling conditions, LMR-NMCs suffer from severe structural degradation that limits the accessible capacity in successive cycles. Particle coatings and surface modifications may be necessary to help mitigate this degradation, thus enabling the commercialisation of these materials.[41] Umicore, a world leading supplier of cathode active material for lithium-ion batteries, recently announced it will begin industrialisation of LMR-NMC type materials[42] with commercial production and use targeted in EVs by 2026. LMR-NMC type materials are expected to become increasingly important towards 2040.

Other battery chemistries are also under early-stage development, including multivalent chemistries (calcium, magnesium, aluminium, etc.) and metal-air batteries (lithium-air, zinc-air, aluminium-air, etc.). Given that the demand for ever higher energy storage is likely to grow, especially in aerospace, there is a need to research these batteries and establish if they can be commercialised. They are at a very early stage and as it takes time to move from the laboratory to mass-scale manufacturing, it is unlikely that these technologies will form a significant segment of the battery market until the mid-2030s.

A note on solid-state batteries:[43] This is the other major development in battery chemistry that is expected to have a substantive impact on market shares. Solid-state batteries employ solid electrolytes (ceramics, polymers, etc.) to allow lithium conduction between the electrodes, in contrast to current lithium-ion batteries that use a liquid electrolyte.

Figure 10: Breakdown of technology - Next-generation breakthrough scenario



Source: Faraday Institution. Numerical data for figures.

As such, solid-state batteries are not considered a standalone next-generation lithium-ion chemistry, but rather a specific formulation of either an existing liquid electrolyte lithium technology or a next-generation cathode such as lithium-sulfur. There are numerous types of solid electrolytes (oxide, sulfide, halide, etc.), each offering unique advantages and challenges. The commercialisation of solid-state batteries is likely to be initially through utilising existing lithium-ion cathodes such as NMC or NCA type materials.

Supply Chain Issues

With the demand for battery materials increasing substantially as the energy transition accelerates, there have been supply shortages for some materials. Geopolitical risks and disruption to global supply chains after the pandemic have added to a market that is already under strain. The result has been rising commodity prices across the board, leading to changes in the types of batteries being manufactured, most notably the large shift to LFP.

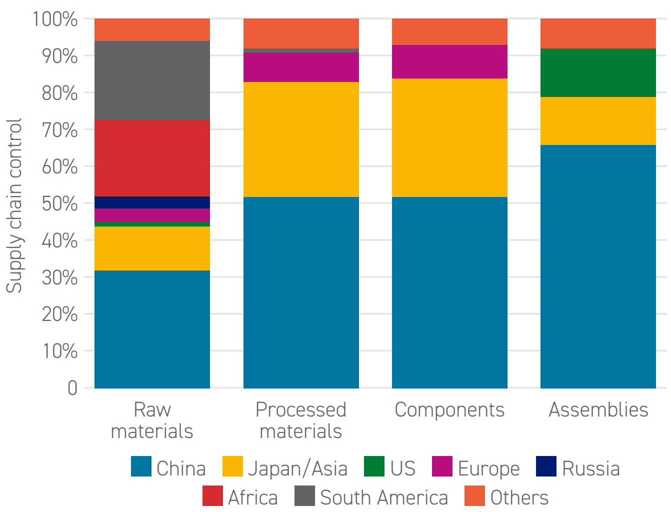
An example of this is the lithium spot price which rose significantly between February 2021 and February 2022, with high prices remaining until the end of 2022. Prices for nickel and cobalt also rose substantially over the same period, causing the average price of lithium-ion batteries to rise for the first time in 2022, defying historical trends.[44] Although the price of lithium has since begun to drop, these price increases demonstrate the impact that raw materials price volatility can have. It should be noted that cell costs are not always aligned to spot prices. For those with large long-term lithium offtake agreements, cathode material costs could be as much as 50-60% lower than those indexed to 100% spot in today's market.

[41] Gradient Li-rich oxide cathode particles immunized against oxygen release by a molten salt treatment, Ju Li et al., Nature Energy, 2019.
[42] Umicore starts industrialization of manganese-rich battery materials technology for electric vehicles - 2023.
[43] For further details see: Faraday Insight 5 - Solid-State Batteries: The Technology of the 2030s but the Research Challenge of the 2020s.
[44] BNEF - Lithium-ion Battery Pack Prices Rise for First Time to an Average of $151/kWh.

The battery supply chain also suffers from a lack of diversification, with China dominating the upstream and downstream stages (Figure 11). China and Japan supply the vast majority of processed materials (accounting for 52% and 31% of global cathode materials respectively), as well as taking a similar proportion of the components market (anodes, cathodes, electrolytes and separators).[45] The top 10 OEM lithium-ion producers are all from China, South Korea and Japan.[16] There is also a geographical split when considering where different battery chemistries are produced. China provides NMC and LCO cathode materials, in addition to leading LFP production globally.[46,47] Japan leads on the supply of NCA material, while South Korea is focused on producing NMC and NMCA type cathode materials.

There has been much discussion around the global short-term availability of lithium. Benchmark Mineral Intelligence (BMI) has predicted that the lithium market will remain in structural shortage until 2025.[48] In contrast, Goldman Sachs recently called the peak of the battery metals a bull market with an expected over supply surge occurring in 2022-2025, with lithium supply rising by 33% per annum, cobalt by 14% per annum and nickel by 8% per annum.[49]

Figure 11: Overview of the global lithium supply chain

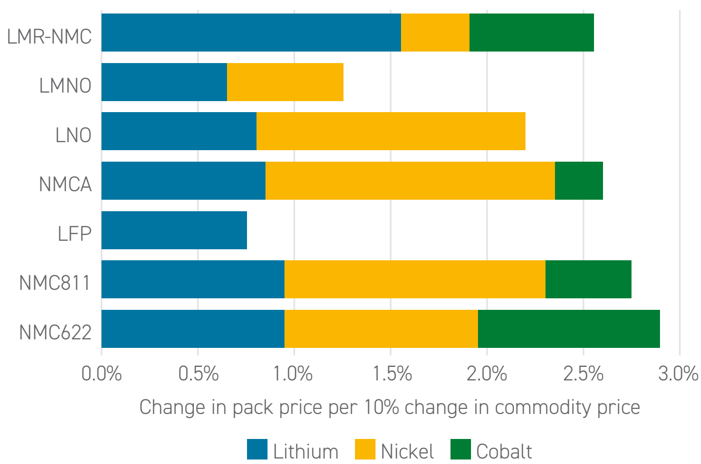


Source: European Commission (2020). Critical Raw Materials for Strategic Technologies and Sectors in the EU. Numerical data for figures.

In addition to scarcity issues, raw materials for batteries are also concentrated in a small number of areas, with South America and Australia being the most important sources of lithium, and Africa and Indonesia holding large reserves of cobalt and nickel respectively.[45] The EU, US and UK are therefore heavily dependent on other countries for significant parts of the battery supply chain. However, recent Government led spending in the EU (the Green Deal Industrial Plan),[50] and the US (the Inflation Reduction Act and the Bipartisan Infrastructure Law)[51,52] have helped support the establishment of supply chains for battery production in these markets towards the end of the decade.[53]

Supply chain risks, bottlenecks, price spikes and volatility will all affect cell price. The price sensitivity of battery chemistries to changes in commodity prices differs significantly by battery chemistry (Figure 12). NMC cathodes in particular have experienced a large increase in price due to a spike in the nickel price as a consequence of sanctions on Russia (Russia had previously been responsible for producing 20% of the world's battery grade nickel). Although LFP is derived from low-cost minerals with resilient supply chains, it is worth noting that LFP is highly susceptible to lithium prices, although it is less affected by raw material price volatility than NMC type chemistries. As an example, research from Exawatt shows that the cell level cost for an LFP cell would increase from $60/kWh to $81/kWh due to an increase in lithium price of 70%.[54]

Figure 12: Impact of a 10% commodity price change on the battery pack price by chemistry



Source: IEA (July 2022). Global Supply Chains of EV Batteries. Numerical data for figures.

Part of the solution to these supply chain risks and bottlenecks is additional mining and refining capacity. BMI predict that over 300 new mines will be needed to meet 2035 demand.[55] They also note that current investment and construction in the pipeline will not deliver these numbers. It takes at least five years to bring new mining production online, so there is immediate pressure on mining companies

[45] European Commission (2020). Critical Raw Materials for Strategic Technologies and Sectors in the EU.
[46] Inside EVs - The West Needs to Build LFP Battery Capacity.
[47] British Geological Survey - Global material flows of lithium for the lithium-ion and lithium iron phosphate battery markets.
[48] Benchmark Mineral Intelligence (June 2022). Lithium oversupply not likely.
[49] Goldman Sachs (May 2022). Battery Metals Watch: The end of the beginning.
[50] European Commission - The Green Deal Industrial Plan.
[51] McKinsey - The Inflation Reduction Act: Here's what's in it.
[52] McKinsey - The US Bipartisan Infrastructure Law: Breaking it down.
[53] Centre on Global Energy Policy - The IRA and the US Battery Supply Chain: Background and Key Drivers.
[54] Exawatt market research.
[55] Benchmark Minerals Intelligence (September 2022). More than 300 new mines required to meet demand by 2035.

to decide whether to expand production capabilities to meet projected demand.

As the UK battery supply chain begins to take shape, there are important policy factors that must be taken into consideration, in particular with regards to the Trade and Cooperation Agreement signed by the UK and the EU. Locating cathode active material production in the UK will become important once rules of origin regulation become active if any UK-based battery producers wish to have access to the EU market. There is a six-year phase-in period to a permanent state from 2027 for EVs, plug-in hybrid EVs (PHEVs), hybrid EVs and EV batteries. From 2027, the UK can export any number of EVs and PHEVs into the EU market at a zero tariff under the following conditions (based on cost):

- EVs must have 55% UK/EU content and must have an originating battery pack.
- An originating battery pack must have either 65% UK/EU content for the cell or 70% for the battery pack.

Given that the cathode material represents the single largest cost component, the production of cathode materials (and other cell components) will need to be located in the UK or the EU in order to qualify under these rules.[56] This will require shifting the production or active materials and other cell components, as well as cell production, from China to the EU/UK.

Conclusion and Implications

With commodity prices soaring across the world, the market for EV batteries has tilted towards lower cost chemistries in order for EVs to remain competitive. NMC-type cathodes are still likely to continue to take the lion's share of the European EV market, but lower-cost chemistries such as LFP and LMO derivatives are now expected to take a much greater share of the market than previously expected. While next-generation technologies have the potential to displace current lithium-based technologies, substantial research, investment and scale-up will be needed for them to reach mass-market deployment.

There is also now a much greater appetite to focus research and manufacturing efforts on reducing cost, but the challenge is to reduce the cost without reducing energy density. Establishing local supply chains is another key development, with the US and the EU allocating large sums of funding towards building domestic resilience given that the current supply chain for lithium batteries is overwhelmingly concentrated in Asia. There are important factors for the UK to consider in this area. The Department of Business and Trade recently launched a new independent Critical Minerals Taskforce to identify supply chain vulnerabilities and promote resilience and diversity, strengthening the competitiveness of the UK and helping grow the economy.[57] However, more work is needed to make the UK an attractive location for battery manufacturing to take place. In a positive step towards establishing a local battery supply chain, Imerys announced in June this year that it was acquiring an 80% stake in British Lithium to establish a lithium mine in Cornwall, which could have the capability to meet roughly two-thirds of Britain's demand by 2030.[58]

Various lithium-ion battery cathode chemistries offer unique combinations of cost, energy density, and performance benefits. Factors such as technological developments, supply chain constraints and market demands will influence the evolution and adoption of these chemistries in EVs and other applications. Ongoing research and innovation in battery technologies will continue to shape the future landscape of energy storage solutions.

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[56] CER - A Tale of Batteries, Brexit and EU Strategic Autonomy.
[57] UK Government. Government ramps up supply chain work with first independent Critical Minerals Taskforce meeting.
[58] British Lithium - Joint Venture announcement.

Glossary of terms

Anode	The battery community commonly refers to the negative electrode in a rechargeable battery as the anode, regardless of whether the battery is being charged or discharged. This convention is used throughout this document.
Cathode	The battery community commonly refers to the positive electrode in a rechargeable battery as the cathode, regardless of whether the battery is being charged or discharged. This convention is used throughout this document.
Cell level energy density	The amount of energy stored in a battery cell per unit mass.
Doping	The process of intentionally introducing impurities or elements into a material to modify its properties.
Electrolytes	The electrolyte in a lithium-ion battery (LIB) is a combination of organic solvents containing a dissolved lithium salt. The solvents are most commonly carbonates.
Layered oxides	A type of crystal structure made up of repeating layers of transition metals and lithium. NMC and NCA cathodes are examples of layered oxide materials.
LCO	Lithium cobalt oxide is a class of cathode active material used in LIBs. This cathode material is mainly used in consumer electronics.
LFP / LMFP	Lithium iron phosphate ($LiFePO_4$) is a cathode material used in LIBs. LFP is widely used in EVs today. Next-generation LFP type cathodes include lithium iron manganese phosphate.
Li-S	Lithium-sulfur batteries are a next-generation battery technology with a potentially higher energy density than LIBs. These batteries combine a lithium metal anode with a sulfur-based conversion cathode, aiming for ultrahigh energy densities.
Lithium carbonate equivalent (LCE)	A unit of measure used to compare the mass of lithium in different chemical compounds.
Lithium-rich materials	A type of lithium-ion cathode where the ratio of lithium ions to transition metals is greater than 1:1.
LMO / LMNO	Lithium manganese oxide is a class of cathode active material used in LIBs. LMO is characterised for its low-cost and high voltage but poor cycle life. Next-generation LMO type materials include lithium manganese nickel oxide spinel materials (LNMO).
Multivalent chemistries	Battery chemistries using ions with multiple positive charges (e.g., calcium, magnesium, aluminium) for improved energy storage.
NCA / NMCA	Lithium nickel cobalt aluminium oxide is a class of cathode active material used in LIBs. NCA batteries are used in several high cost, high performance EVs. Next-generation NCA-type cathodes include lithium nickel cobalt manganese aluminium oxides (NMCA).
NMC / LMR-NMC	Lithium nickel manganese cobalt oxide is a class of cathode active material used in LIBs. NMC is often the battery chemistry of choice for high-end luxury vehicles and current-generation EVs. Next-generation NMC-type cathodes include lithium and manganese-rich materials (LMR-NMC).
Olivines	A type of crystal structure made up of repeating units of metal oxide octahedra and tetrahedral polyanionic groups. LFP type cathodes are examples of olivine materials.
Polyanionic materials	A material which contains more than one anion in its base composition.
Primary particles	Smaller particles making up larger secondary particles in a material.
Rate capability	The rate capability of a material refers to the ability of a cathode or anode material to be charged rapidly while maintaining a certain battery voltage limit
Sodium-ion batteries	Sodium-ion batteries are a next-generation battery technology using sodium ions instead of lithium ions. Sodium-ion batteries will have a lower energy density than LIBs but also lower cost, making them suitable for low-cost and lightweight EVs and BESS applications.
Solid-state batteries	Solid-state batteries employ a solid electrolyte instead of a traditional liquid electrolyte, offering potential improvements in energy density, safety and longevity.
Specific energy	The specific energy of a cell relates to the amount of energy stored in a cell divided by the cell mass. Specific energy is measured in Wh/kg.
Spinels	A type of crystal structure formed by metal ions sitting in octahedral and tetrahedral sites in the lattice. LMO type cathodes are examples of spinel materials.
State of charge (SOC)	The current capacity of a battery expressed as a percentage of its maximum capacity.
Volumetric energy density	The volumetric energy density of a cell relates to the amount of energy stored in a cell divided by the cell volume. Volumetric energy is measured in Wh/L.

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