MARKET INTELLIGENCE REPORT

# COBRA

## KEY TECHNICAL, POLICY AND MARKET DEVELOPMENTS INFLUENCING THE ELECTRIC VEHICLE BATTERY LANDSCAPE


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VALUE FROM SCIENCE AND TECHNOLOGY


**CATHODE MATERIALS MARKET**

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# INTRODUCTION

Cobalt-free cathodes are being developed rapidly. While they still haven't reached the energy density of the most used NMC cathodes, some OEMs have already switched to compositions like LFP in new EVs, cutting the costs of raw materials and reducing the risk of cobalt shortages. In fact, this has already contributed to the reduction of cobalt prices to the pre-2021 level, ending another period of its volatility.

The cathode market for EVs is evolving which raises several questions: **What cathode chemistry will dominate the market in 2030**? What's the future of LNMO, and what applications can it be most useful for? Who are the key suppliers of cathode materials? How are the cathode and battery cell markets influenced by increasing competition on subsidies between the EU, the US and China? This Market Intelligence Report aims to give answers to these questions.

We present leading battery cathode chemistries, compare their properties, and analyse their market dynamics. Moreover, this edition's contributor Cerpotech (a partner in the COBRA project), provides insights into **advanced ceramic oxide powders**, the key ingredient of cathodes. Production challenges are also presented alongside innovations that help to improve the performance of cobalt-free cathodes.

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# CATHODE CHEMISTRIES CLASSIFICATION

## ROLE OF CATHODES IN EV BATTERIES

A Li-ion battery uses the movement of lithium ions between the anode and cathode to generate electrical energy. During discharge, lithium ions move from the positively charged cathode to the negatively charged anode through the electrolyte, generating a flow of electrical current. During charging, the reverse reaction occurs, and the lithium ions move back to the cathode (Figure 1). The cathode material and its structure determine the speed and efficiency of ion migration, which in turn, affects the battery's performance and life span.

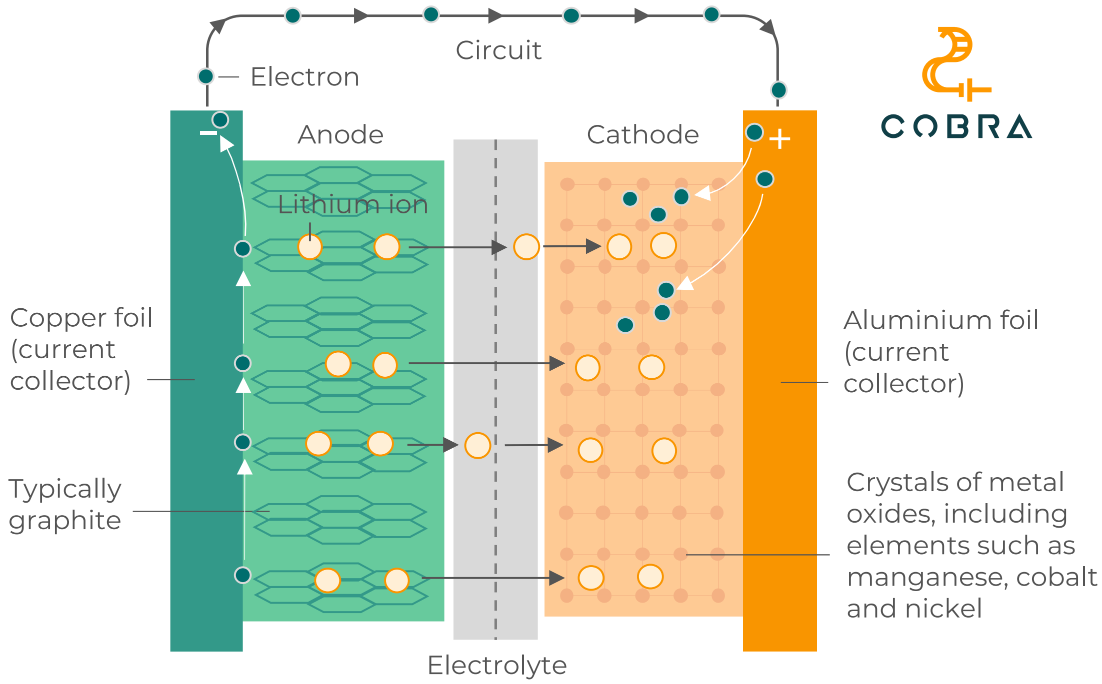


*Figure 1: Battery cell charging process – the role of cathodes (adapted from **[1]**)*

## METAL CONTENT OF CATHODE MATERIALS

Each Li-ion battery cathode consists of a lithium transition metal oxide (e.g., LCO, NMC). Lithium usually accounts for approximately 5-10% of the cathode's mass, while oxides of other elements such as nickel, manganese, cobalt, iron, and phosphorus constitute the rest (Figure 2). Although **cobalt ensures a high charging rate and cycle life, it is undesirable due to its scarcity and unethical conditions of mining**, as explained in one of our previous reports **[2]**. That's why cobalt-rich chemistries such as NCA, LCO and NMC111 are being phased out and replaced by compositions with a higher percentage of nickel and a lower percentage of cobalt (NMC 811) or with more manganese and no cobalt (LMO, LNMO, LFP). The LFP cathode currently appears to be the most sustainable option since its ingredients (iron and phosphorus) are abundant around the world.

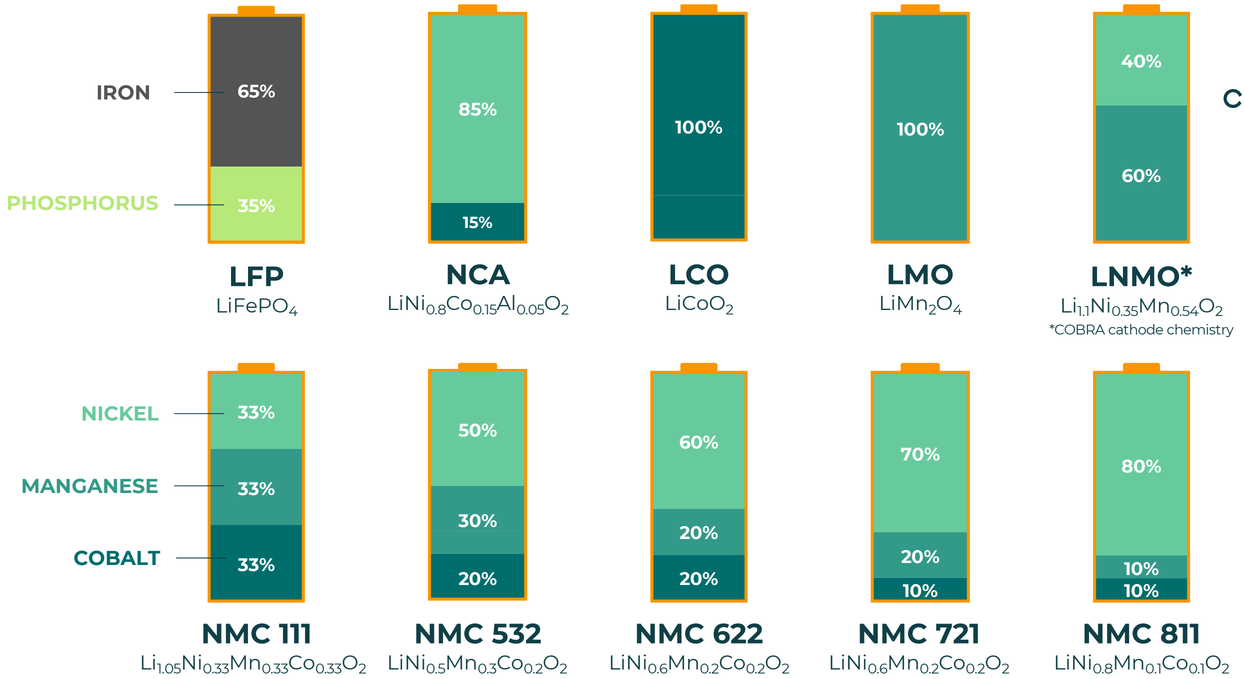


*Figure 2: Li-ion battery cathode chemistries and their content (excluding lithium and oxygen)*

# PRODUCTION OF CATHODE MATERIALS

## METHODS OF POWDERS SYNTHESIS

Factories producing battery cells receive cathode-active materials in the form of powders. To synthesise these powders, precursor materials (such as metal oxides or salts) are usually mixed in a specific ratio, milled to produce a homogenous mixture, calcinated to obtain the desired crystal structure, characterised, and enhanced, e.g., through coating [3]. There are several methods differing mainly in how the mixing and calcination are performed. The **solid-state** method involves heating a mixture of metal salts and a flux agent at high temperatures. The **co-precipitation** synthesis involves mixing stoichiometric transition metal salts with a basic precipitating agent and a complexing agent to produce a mixed-transition metal ion precursor to the final lithiated oxide product. The **sol-gel** processing method involves mixing metal salts and organic solvents to form a gel-like solution, which is then dried and calcinated. The **microwave** processing method involves using microwave energy to heat a mixture of precursors. The **hydrothermal** reaction uses high pressure and temperature in an aqueous solution to produce the cathode material. **Spray pyrolysis** works by spraying a solution of precursors onto a substrate that is heated to a high temperature. Each method requires different conditions and influences the properties of the material. These differences are presented in Table 1.

*Table 1: Comparison of synthesis methods* **[3]**, **[4]**, **[5]**

| | SOLID-STATE | CO-PRECIPITATION | SOL–GEL | MICROWAVE | HYDRO THERMAL | SPRAY PYROLYSIS |
|---|---|---|---|---|---|---|
| Purity | Low | Moderate | High | Moderate | High | High |
| Particle size | Big | Medium | Small | Small | Big | Small |
| Agglomeration | Yes | Yes | No | Yes | No | No |
| Equipment complexity | Simple | Simple | Simple | Simple | Complex | Complex |
| Reactive period | Long | Moderate | Moderate | Short | Long | Short |
| Energy consumption | High | Moderate | Moderate | Low | High | Moderate |
| Reaction control | Easy | Difficult | Easy | Difficult | Easy | Moderate |
| Industrialisation | Moderate | Easy | Difficult | Difficult | Difficult | Easy |
| Performance | Low | Moderate | Good | Moderate | Moderate | Good |

## ENHANCING THE PERFORMANCE OF CATHODE MATERIALS

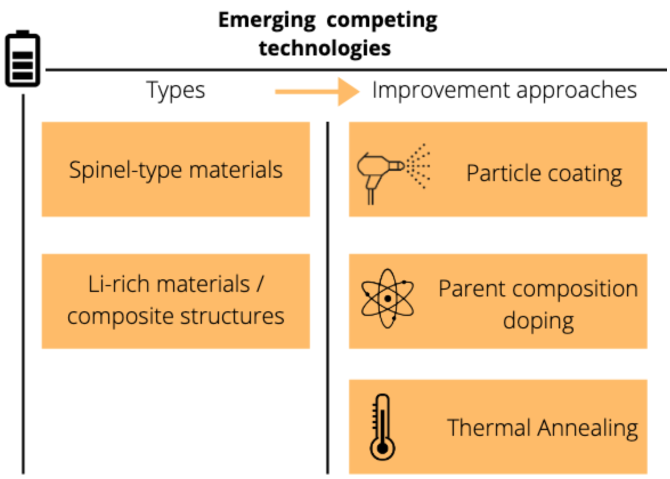


*Figure 3: Cathode enhancement methods* **[6]**

The cathode performance is not only influenced by the chemical composition and production methods but can be additionally enhanced using innovative approaches. These include particle coating, parent composition doping and thermal annealing. **Chemical doping** can help increase the performance of an LNMO cathode – in COBRA we achieved an initial discharge capacity of 159 mAhg-1 at a C/3 rate and a corresponding capacity retention of 94.3% after 150 cycles **[7]**. The **thermal annealing** approach induces the formation of gradient structures with improved performance in terms of cycle life and C-rate capability. These approaches were explained in more detail in one of our previous reports on battery cathodes **[6]**.

## CHALLENGES AND INNOVATIONS IN THE PRODUCTION OF ADVANCED CATHODE MATERIALS

### CONVERSATION WITH ANNE DALAGER DYRLI

CEO AT CERAMIC POWDER TECHNOLOGY AS (CERPOTECH)

### What is Cerpotech's role in the COBRA project?

In this project, Cerpotech has been mainly involved with the development of cathode materials. Using lab results of the LNMO cathode chemistry composition, we have optimised our spray pyrolysis method and subsequent powder morphology to achieve desired production properties. The cathode powder we produced will be used in the final cobalt-free COBRA battery cells.

### Why do you use spray pyrolysis to synthesise advanced powders?

Spray pyrolysis is an economically feasible method to produce high-quality advanced materials with particles in the nano/submicron range. The powders synthesised in this way exhibit excellent sinterability due to their small particle size, large specific surface areas, and high chemical and phase purity. Additionally, spray pyrolysis can produce a vast selection of materials given stable precursor solutions.

### What are the main challenges in the cathode production process?

Storage and transportation of the cathode materials prove to be quite challenging. Powders easily react with moisture and CO2 in the air which deteriorates the shelf life of materials. That's why we investigated various conditions and found several solutions to reduce the time when our powders are exposed to atmospheric conditions during packaging and storage. Another challenge is the cost of the manufacturing process – higher automatisation and new procedures would be needed to reduce manual hours. High product quality and flexibility are what distinguish us from our competitors.

### How will you use COBRA's results? What are your plans for the upcoming years?

We are considering applying learnings from LNMO manufacturing to scale up the production of battery cathode powders for applications requiring high quality. LNMO cathode is not the only battery material for which we can apply our process – NMC cathode and solid-state electrolyte materials are also within our production capabilities which we proved in other EU projects: LASIBAT, ADVAGEN and SPINMATE. Apart from battery materials, we have strong expertise in solid oxide cells (SOFC/SOEC) and lead-free piezo materials (injectors, sensors, transducers etc.) – we are open to collaboration in these fields with interested companies and research institutes.

Cerpotech is a spin-off company from the Norwegian University of Science and Technology (NTNU) founded in 2007 and produces high-quality complex oxide powders via spray pyrolysis from environmentally friendly aqueous precursors. Since 2013, the company has been operating at semi-industrial production facilities with the ability to serve both academia and industry. Cerpotech's current facility has an annual production capacity of several tonnes with a further increase planned.

# CATHODE MARKET ANALYSIS

## KEY CATHODE PROPERTIES

Cathodes are responsible for several key properties of battery cells. **Volumetric energy density** expresses how many watthours of electrical energy can be stored per volume of battery cells. This property is important in applications with space constraints in their design, such as mobility and consumer electronics. **Power density** is the amount of power that can be delivered per unit of weight or volume. A higher power density means a battery that can deliver more power for a given size. Highly demanding applications like electric cars will require more power than less demanding applications such as e-scooters. **Cycle life** is the number of charge-discharge cycles a battery can undergo before it reaches its end of life. A higher cycle life means a longer-lasting battery. This property is most important for applications where the battery cannot be easily replaced, such as satellites and medical monitoring devices. The **safety** of the battery includes its stability under different conditions and its resistance to thermal runaway. A safer battery is less likely to cause fires or other hazards. The **cost** of batteries is usually expressed in US dollars per kilowatt-hour and is mainly influenced by market prices of raw materials, manufacturing processes used, and the scale of production. The cost of batteries is usually compared and estimated at the GWh production scale or above (even though some chemical compositions like LNMO have not been produced at this scale). Figure 4 compares these key properties of the five most common battery chemistries on the market: NMC811, NCA, LFP, LCO and LNMO.

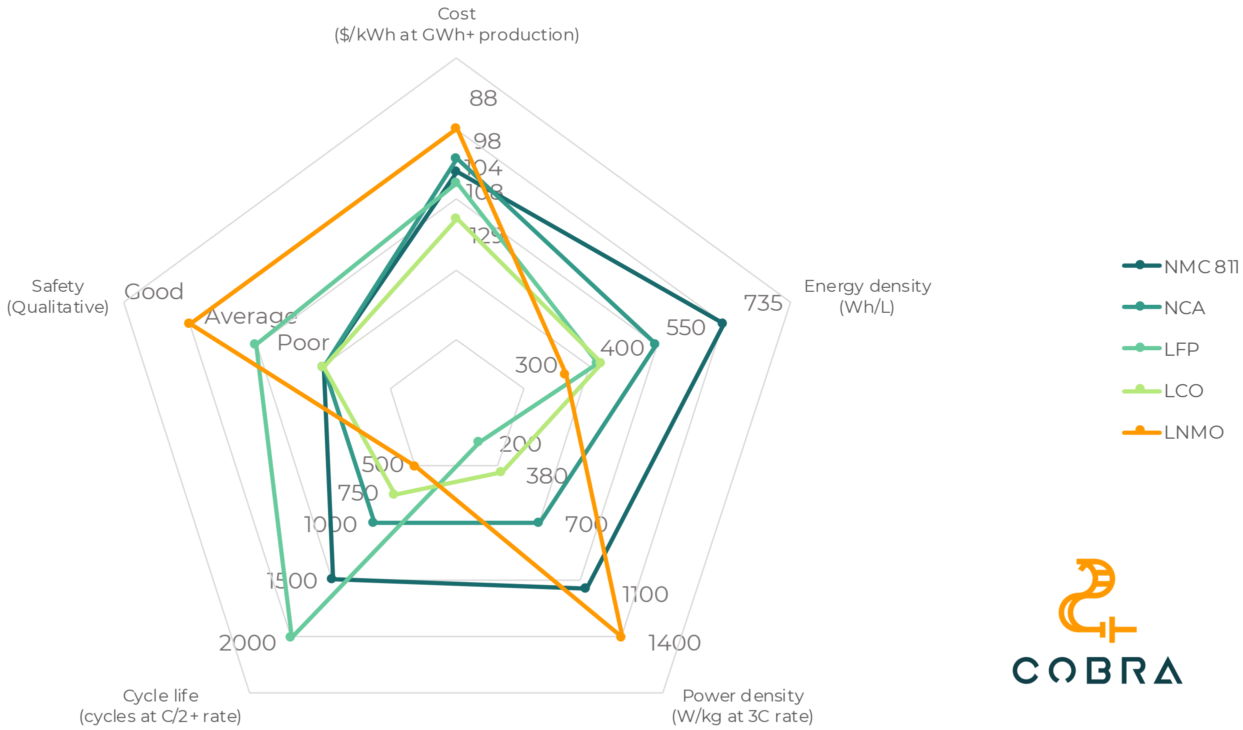


*Figure 4: Comparison of SoTA Li-ion chemistry properties on a cell level (based on* ***[8]****)*

## SUITABILITY FOR APPLICATIONS

In the past, Li-ion batteries were used mostly in consumer electronics, like smartphones. With the growing necessities of the energy transition, increasing performance and production costs going down, the applications range has grown. Currently, **71% of produced batteries power electric vehicles**, 15% are used in consumer electronics (smartphones, power tools, e-bikes), 4% in stationary energy storage systems, and 10% in other applications (medical devices, military, etc.) [9]. The battery industry is going to focus even more on the automotive sector which by 2030 is expected to constitute 89% of the market share, while grid applications will continue to grow fast, quadrupling its current market size to $10,8 Bn. Battery developments may also unlock new applications such as electric aircraft which could become the new fastest-growing battery market in the long term.

How do these applications work with battery chemistries analysed in this report? Most **electric vehicles** require high energy density, decent cycle life and reasonable cost of batteries – these conditions are best met by NMC811 and LFP. The low cycle life and limited energy density of LNMO do not make it a good choice for high-performance automotive applications – if these two properties can be improved LNMO can still compete in the automotive market thanks to its low cost, especially in the mass sedan segment.

Batteries for **stationary storage systems** should have a high level of safety/reliability, low cost per cycle and long cycle life. These needs are best addressed by LFP cathode which has an exceptionally good cost per cycle – in grid applications this chemistry is expected to overtake NMC in market share by 2030 [10].

The **consumer electronics** market has been dominated by the LCO cathode which was the first widely adopted Li-ion chemistry, due to a decent energy density and a reasonable cost. Environmental/ethical concerns and limited performance can encourage manufacturers to switch to another chemistry. LNMO offers a good fit thanks to a high rate (required in power tools), low cost and high safety (especially in mobile devices).

The **aerospace industry** requires a very high gravimetrical energy density (>400 Wh/kg) due to the weight constraint of aircraft. Currently, the closest chemistry to meet these demands is the high-performing NMC, but the true revolution can be brought by new chemistries, e.g., lithium-metal which is not yet commercialised.

Applications in **medical devices** are more niche and include the likes of defibrillators, surgical tools, monitoring devices and pacemakers. The first two applications require a high-power rate and safety which can be met by the LNMO cathode. For the other two, a high cycle life is necessary which makes LFP or NMC a better choice.

Finally, in **military** applications (infantry, backup power, missiles, drones) energy density, reliability, and rate are most important. NMC seems to be the best fit thanks to its high gravimetric and volumetric density.

The summary of cathode chemistry suitability for applications is presented on Figure 5.

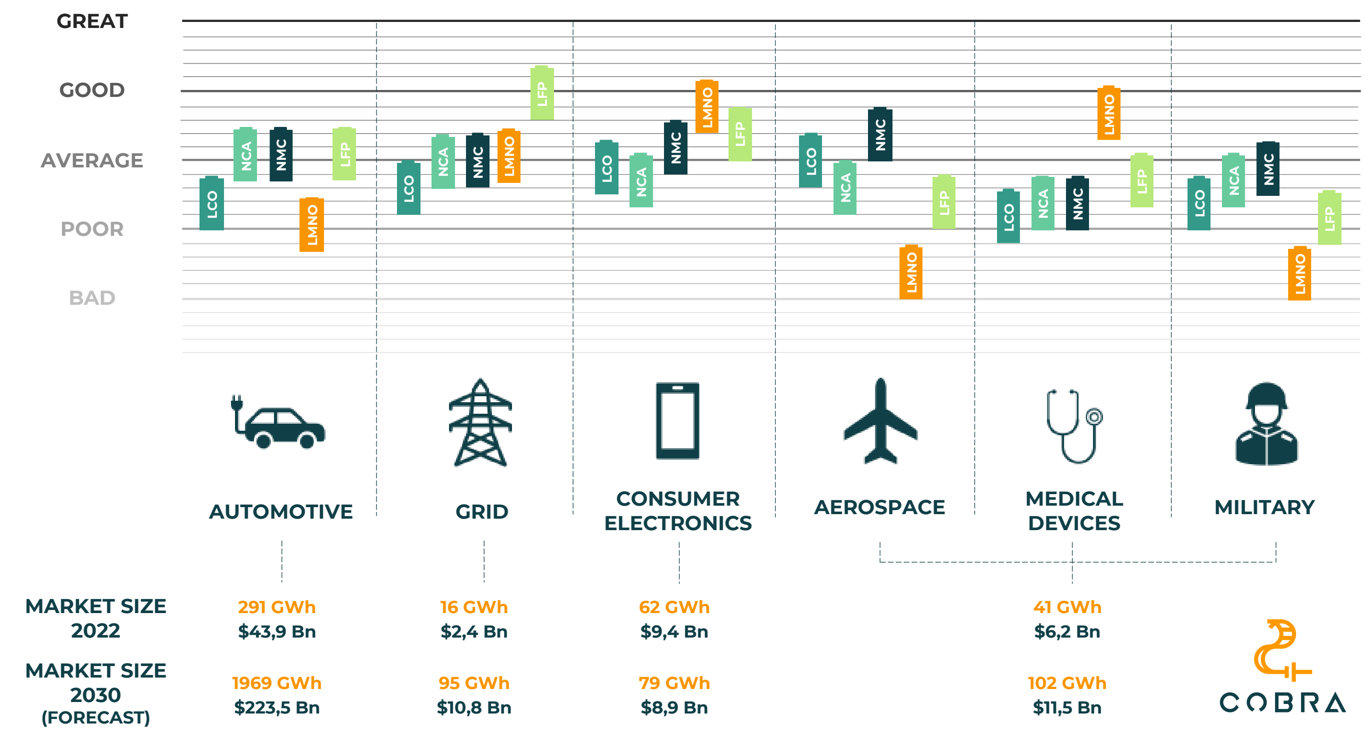


*Figure 5: Battery applications: chemistry fit and market (based on **[8]**, **[9]** and own analysis)*

## DEMAND FOR CATHODE MATERIALS

Several factors determine the forecast of demand for cathode materials: **market size** for battery applications, **chemistry-application suitability**, **performance development**, **environmental/ ethical concerns** regarding the use of critical raw materials, and **political dynamics** connected with the domestication of supply chains. The first two aspects were explained in the previous chapter, and they are the main driving forces of the demand for NMC and LFP cathode chemistries which are expected to dominate the battery market. Environmental and ethical concerns limit the demand for cobalt-rich batteries, such as older NMC compositions, NCA, and LCO. Recent improvements in LFP's energy density allowed this chemistry to compete with NMC in the biggest market of high-volume cars, while our researchers are still investigating how to boost the cycle life of LNMO which would enable increasing its range of applications.

The prices of raw materials currently seem to be the result of the demand for battery cathodes rather than its cause. After a spike in 2021-2022, cobalt prices started decreasing again to the 2020 level **[11]**, while lithium and nickel are still on the rise, mainly due to the high growth of demand for nickel-rich Li-ion batteries. Nevertheless, **if prices for nickel and lithium continue to rise, this may push manufacturers to switch to chemistries with more abundant materials like LFP and LMNO,** or even lithium-free sodium-ion which has recently been invested in by some of the largest cell manufacturers like CATL **[12]**. Figure 6 presents the historical and forecasted demand for batteries per chemistry and Figure 7 shows the resulting demand for battery cathodes.

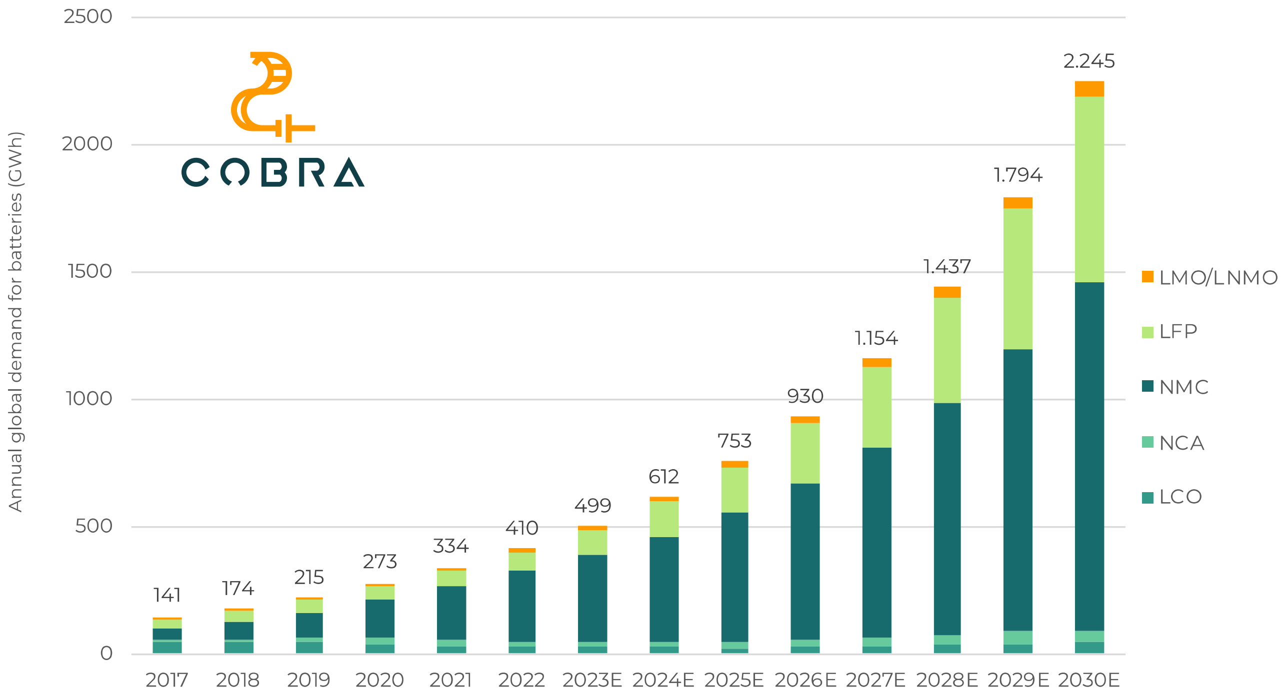


*Figure 6: Annual global demand for Li-ion batteries (based on **[9]**, **[13]** and own analysis)**

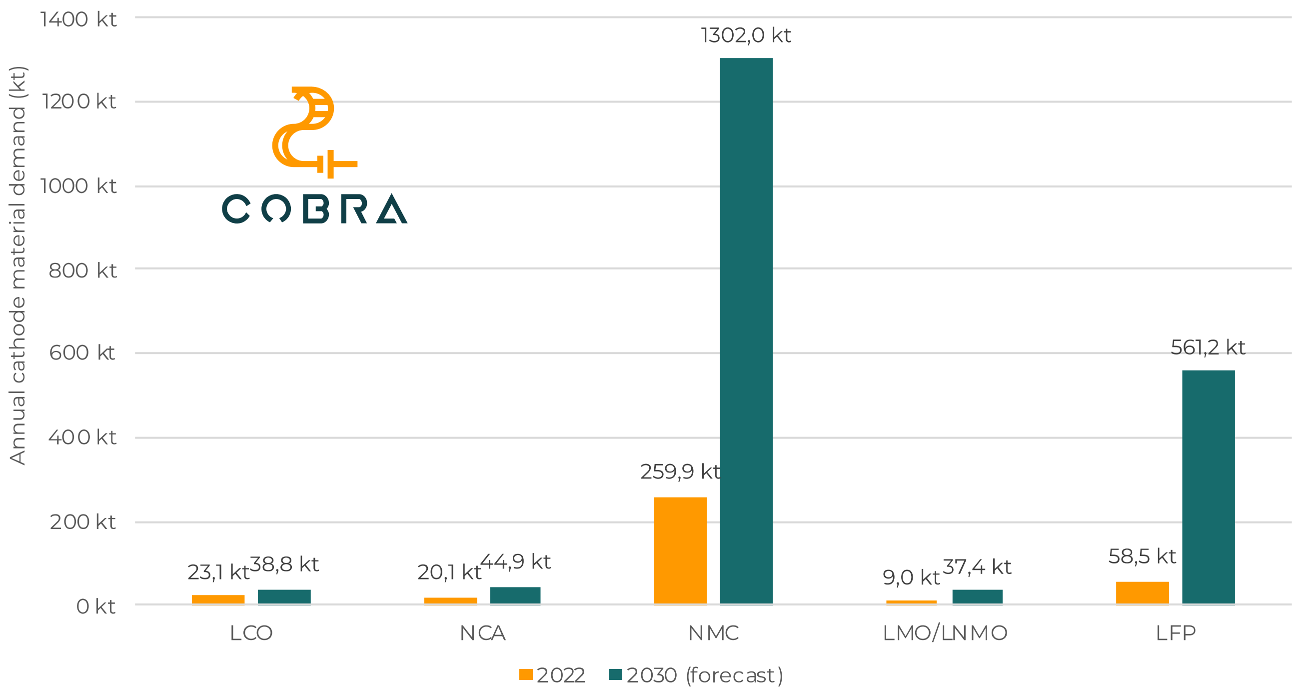


*Figure 7: Annual global demand for cathode materials (based on **[9]**, **[13]** and own analysis)**

** Information on these graphs should not be used as investment advice as they contain forward-looking statements based on assumptions and estimates that may not be accurate.*

## KEY PLAYERS IN THE MANUFACTURING OF CATHODE MATERIALS

China is currently the largest manufacturer of battery cathodes – it produces 68% of the global supply **[14]**, covering each chemistry. Japan and South Korea are the second largest producer, each covering approximately 15% of the market. Some of the biggest Asian companies include XTC, Ronbay Technology, Easpring, Tianjin B&M, LG Energy Solutions and Sumitomo Metal Mining. Although currently none of the non-Asian companies has a meaningful share in cathode material production, the outlook is promising. Umicore (Belgium) recently opened a gigafactory for cathode active materials in Poland, aiming to reach a capacity of 20 GWh by the end of 2023 and 40 GWh in 2024 **[15]**. Germany-based BASF has been manufacturing cathode materials primarily in Japan and China but in 2023 the company will also deploy a 24 GWh plant in its homeland as part of an IPCEI project **[16]**.

*Table 2: Key global manufacturers of cathode materials (based on **[8]** and own analysis)*

| LCO | NCA | NMC | LFP | LNMO |
|---|---|---|---|---|
| XTC<br>CHINA | BASF We create chemistry<br>GERMANY | 天津巴莫科技有限责任公司 Tianjin B&M Science and Technology Co.,Ltd<br>CHINA | Dynanonic<br>CHINA | HALDOR TOPSOE<br>DENMARK |
| 天津巴莫科技有限责任公司 Tianjin B&M Science and Technology Co.,Ltd<br>CHINA | 杉杉科技 Shanshan Technology<br>CHINA | 容百科技 RONBAY TECHNOLOGY<br>CHINA | 富临精工 FULIN P.M.<br>CHINA | nanoOne<br>CANADA |
| 杉杉科技 Shanshan Technology<br>CHINA | umicore<br>BELGIUM | umicore<br>BELGIUM | BTR Better our world<br>CHINA | TARGRAY<br>CANADA |
| GEM 格林美 资源有限 循环无限 Recycling for future!<br>CHINA | L&F Co., Ltd.<br>SOUTH KOREA | LG Energy Solution<br>SOUTH KOREA | 融通高科先进材料 RT Advanced Materials<br>CHINA | NEI NEI Corporation<br>USA |
| MGL NEW MATERIALS<br>CHINA | SUMITOMO METAL MINING<br>JAPAN | ZEC 振华新材料 ZHENHUA E-CHEM<br>CHINA | Pulead<br>CHINA | GELON<br>CHINA |
| Pulead<br>CHINA | 当升科技 EASPRING<br>CHINA | XTC<br>CHINA | BYD<br>CHINA | TOB<br>CHINA |
| 当升科技 EASPRING<br>CHINA | TODA KOGYO<br>JAPAN | GEM 格林美 资源有限 循环无限 Recycling for future!<br>CHINA | VSPC<br>AUSTRALIA | TMAX BATTERY EQUIPMENTS SINCE 1995<br>CHINA |
| KH<br>CHINA | EcoPro<br>SOUTH KOREA | 当升科技 EASPRING<br>CHINA | nanoOne<br>CANADA | MERCK<br>USA |

# TECHNICAL DEVELOPMENTS

## MICROWAVE-ASSISTED LFP COATING OF LNMO SPINEL PARTICLES

A new coating method with $LiFePO_4$/C (LFP/C) olivine was discovered to enhance the electrochemical stability of LNMO spinel particles. Since it is extremely challenging to conduct this process during atmospheric conditions, researchers proposed a simple route to prepare **LFP/C-coated LNMO using microwave irradiation**. This provided sufficient physical interaction between both materials while avoiding side reactions. LFP/C-coated LNMO electrode exhibited a higher discharge capacity at 25°C and 60°C, **superior cyclability (up to 500 cycles)** at 25°C and better C-rate capability at 60°C than uncoated LNMO spinel.

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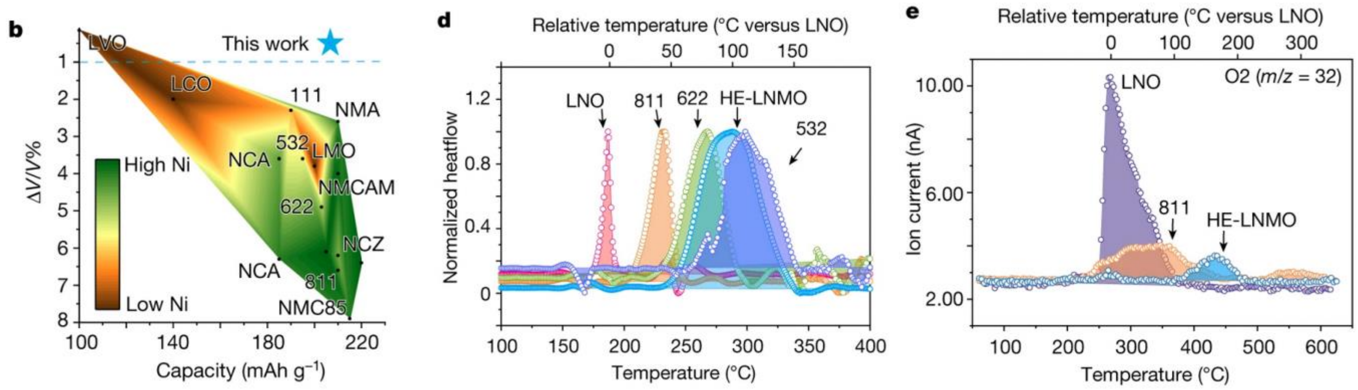
## HIGH-ENTROPY DOPING FOR HEAT TOLERANCE AND STABILITY

A novel high-entropy doping strategy was developed to address thermal and chemo-mechanical instabilities and insufficient cycle life of cobalt-free cathodes. Combining X-ray diffraction, transmission electron microscopy and nanotomography, it was found that the LNMO cathode exhibits **nearly zero volumetric change**, resulting in greatly reduced lattice defects and local strain-induced cracks. Experiments revealed that the thermal stability of the new cathode is significantly improved, reaching the level of the ultra-stable NMC-532. Owing to the increased thermal stability and the zero volumetric change, the cathode exhibits greatly **improved capacity retention**.

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## THE US GRANTS $42M TO 12 PROJECTS IN BATTERY DEVELOPMENT

The US Department of Energy selected the best projects submitted for funding under Electric Vehicles for American Low-Carbon Living (EVs4ALL) program, which aims to expand domestic EV adoption by developing batteries that **last longer, charge faster, perform efficiently in freezing temperatures and have better overall range retention**. The projects are led by both research institutes and industrial companies and have budgets ranging from $2 million to $5 million. Some of the new battery types to be developed include **sodium metal, solid-state LNMO, potassium-ion** and **sulphur composite**.

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# MARKET DEVELOPMENTS

## MORROW BATTERIES PARTNERS UP TO DEVELOP NEXT-GEN LNMO

A Norwegian battery manufacturer Morrow Batteries is developing two battery products based on next-gen LNMO cathodes. The **LNMO-X** battery combined with the niobate anode will offer **high cycle life and very fast charging capabilities** while keeping a similar energy density and voltage to LFP. This product is planned to be launched in 2025 and will be dedicated to heavy mobility (trains, trucks, ferries) and long-life energy storage systems. A year later the company aims to kick off the first deliveries of **LNMO-C** batteries for automotive applications. The cell combined with a modified graphite anode and special electrolyte will offer **a very high single-cell voltage (4.5V)** while maintaining the energy density of an NMC cell. To begin commercial production of LNMO batteries, Morrow Batteries has signed several agreements: a US membrane manufacturer **Celgard will develop dry-process battery separators** while a Danish supplier of advanced materials **Haldar Topsoe will deliver up to 150 tonnes of LNMO cathode materials** annually.

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## THE US IS CATCHING UP ON CATHODE PRODUCTION CAPACITIES

According to data from BloombergNEF, since 2009 there have been **882 battery manufacturing projects** started or announced in the US, primarily aimed at electric vehicles, representing $108 billion in investment. About a quarter of the projects were unfurled in 2022, which is linked to the Inflation Reduction Act: a new law giving a $7,500-per-vehicle tax credit to customers buying EVs assembled in the US Massachusetts' 6K plans to produce 3,000 tpa of LFP by 2025 and 10,000 tpa by 2026. Redwood Materials, a battery recycling company, announced to build a $3.5 billion facility in South Carolina with an annual production capacity of **100 GWh** of cathode and anode components. Stellantis with Samsung SDI will deploy a **23 GWh** battery plant in Kokomo, Indiana by 2025, while General Motors is planning four new battery factories in the US (also with LG Chem) for a total annual capacity of **140 GWh**.

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## NANO ONE ACQUIRES CANDIAC TO MANUFACTURE LFP CATHODES

In November 2022, the fast-growing Canadian battery manufacturer **Nano One acquired the 2400 tpa facility in Candiac (Quebec) from Johnson Matthey** – the only large-scale manufacturer of LFP cathodes in North America. In January 2023 Nano One announced a successful transformation of the newly bought facility to their patented One-Pot process. Large-scale trials with the One-Pot technology will start in Q1 2023 and results from this work will provide Nano One with insights for the next stage of trials, pilot production, and advanced engineering. Large One-Pot reactors have been designed and ordered, with installation, integration, and commissioning expected in **Q3 2023 for industrial pilot-scale LFP production**.

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# POLICY DEVELOPMENTS

## 10% TAX CREDIT FOR PRODUCERS OF BATTERY COMPONENTS

The US Inflation Reduction Act not only includes tax credits for end users of EVs, but also tax relief on investments in qualifying advanced energy projects. The so-called Advanced Manufacturing Production Credit ("PTC") applies to the production of battery components as well as to critical battery minerals. Provided the production occurs in the US and that the components are sold **between 2023-2030, a 10% credit** (measured as a percentage of the total cost of production) **will be available for the production of electrode active materials**. The credit begins phasing down in 2030 in increments of 25% per year and is not available for components sold after 2032.

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## FIRST PILOTS OF THE GLOBAL BATTERY PASSPORT PRESENTED

Global Battery Alliance (GBA) presented three pilots of the world's first battery passport at the World Economic Forum meeting in Davos. The passport includes information in four categories: **battery** (general information), **materials** (traceability of origins), **ESG** (Environmental, Social and Governance) and **data** (quality of verification and interoperability). GBA also sets out the **Greenhouse Gas rulebook** and the **Child Labour and Human Rights indices**, sharing experience for the deployment of due diligence and carbon footprint requirements which will be part of the New Battery Regulation in the EU.

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## EU RESPONDS TO THE US SUBSIDIES WITH ITS INDUSTRY PLAN

European Commission President Ursula von der Leyen presented the Green Deal Industrial Plan aimed at ensuring the production capacity of key green technologies in Europe. To increase Europe's manufacturing capacity of green technologies, the Commission will propose the **Net Zero Industry Act by mid-March**, which will set targets for the sector until 2030, and cover batteries, windmills, heat pumps, solar, electrolysers, carbon capture and storage technologies. Funding will come primarily from EU member states, with the REPowerEU funding being redirected towards the net-zero industries. A **temporary state aid framework** will be implemented after a public consultation, while a European Sovereignty Fund will provide a structural answer and common European funding for common key technologies.

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