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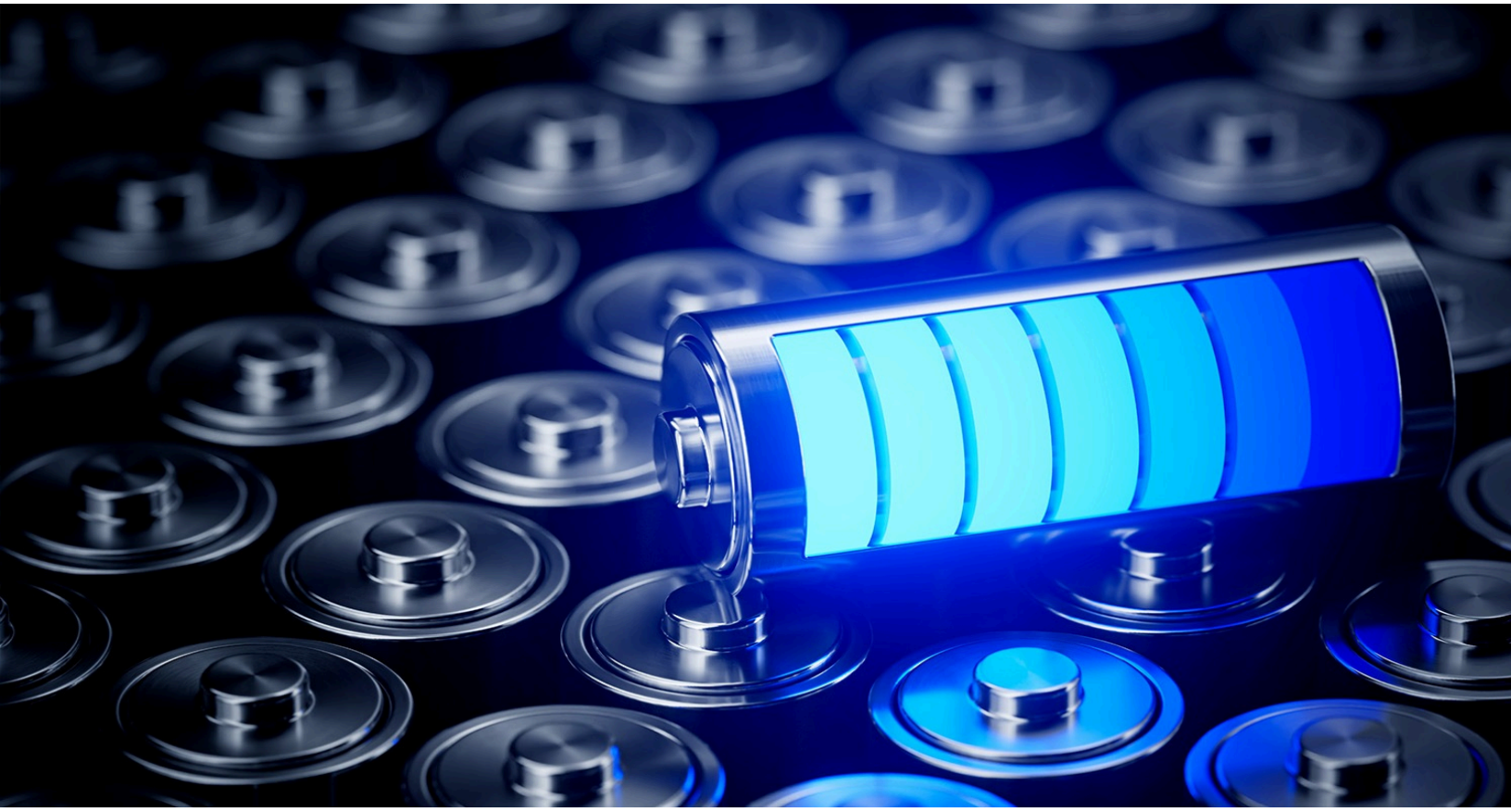
The battery chemistries powering the future of electric vehicles

Battery chemistry for electric vehicles is evolving rapidly, leading to repercussions for the entire value chain.

This article is a collaborative effort by Timo Möller, with Clemens Cepnik, Marcelo Azevedo, Nicolò Campagnol, and Yunjing Kinzel, representing views from McKinsey's Automotive and Assembly Practice.



December 2024

Battery technology has evolved significantly in recent years. Thirty years ago, when the first lithium ion (Li-ion) cells were commercialized, they mainly included lithium cobalt oxide as cathode material. Numerous other options have emerged since that time. Today's batteries, including those used in electric vehicles (EVs), generally rely on one of two cathode chemistries:

— lithium iron phosphate (LFP), which was invented by Nobel Prize winner John Goodenough in the late 1990s and commercialized in the early 2000s

— lithium nickel manganese cobalt mixed oxide (NMC), which evolved from the first manganese oxide and cobalt oxide chemistries and entered the market around 2008[1]

LFP is based on a phosphate structure with only iron as its transition metal, and researchers have also developed a new iron and manganese form, termed LMFP, which was commercialized this year (for more information on cathodes and other battery components, see sidebar, "How energy is stored and released"). Although LFP has some advantages over NMC, including a more favorable safety profile and lower cost, automotive OEMs have preferred NMC chemistry for the past ten years because its higher energy density (the amount of energy that can be stored in a given mass or volume) provides a longer driving range.

The balance could soon shift globally in favor of L(M)FP batteries, however, because technological improvements over the past few years have increased energy density at pack level and therefore increased vehicle driving range. All major OEMs have launched, or are about to launch, LFP-equipped vehicles to lower costs, which are now a major hurdle to adoption. This chemistry could become the preferred option for electric cars and trucks globally. Since mobility applications account for about 90 percent of demand for Li-ion batteries, the rise of L(M)FP will affect not just OEMs but most other organizations along the battery value chain, including mines, refineries, battery cell producers, and cathode active material manufacturers (CAMs).

The new chemistry on the block . . . is an old one

According to a recent McKinsey survey, consumers want midsize passenger EVs to have a driving range of about 465 kilometers (km) before needing to recharge.[2] For years, NMC batteries were the only technology that allowed EVs to meet this expectation, but LFP batteries are now catching up.

One of the most important LFP innovations was introduced in 2021, when the Chinese OEM BYD began using elongated LFP battery cells (blade cells) in its Han model and integrated them into the battery pack structure, instead of treating them as structurally passive components. This design innovation which contributes to the battery pack's stiffness, takes advantage of the intrinsic safety of well-designed LFP cells and allows for a higher packaging density without additional module housing. Consequently, battery packs are lighter, extending vehicle driving

[1] Aluminum is sometimes used in place of manganese. The nickel cobalt aluminum (NCA) form has the same crystallographic structure as NMC and is similar in performance. It was commercialized about four years before NMC.
[2] Mobility Consumer Insights, McKinsey Center for Future Mobility (MCFM); Annual MCFM Mobility Consumer Survey, February 2024, global n = 36,954.

How energy is stored and released

Cells, one of the major components of battery packs, are the site of electrochemical reactions that allow energy to be released and stored. They have three major components: anode, cathode, and electrolyte. In most commercial lithium ion (Li-ion cells), these components are as follows:

— anodes, typically consisting of carbon (graphite) coated on a copper foil, serve as the main driver for charging speed

— cathodes, most often containing lithium iron phosphate (LFP) or lithium nickel manganese cobalt oxide (NMC) coated on aluminum foil, are the main driver for cell cost, emissions, and energy density

— electrolytes, either liquid or (semi) solid, which control the flow of ions between anodes and cathodes and are critical to battery safety and cycle life

Most common cells have another key component called the separator, which is often a polymer-based film physically separating anodes and cathodes. Separator is not needed when solid state electrolytes are used, as in the case of solid-state Li-ion batteries or commercial high-temperature sodium nickel or sodium sulfur batteries.

When electrons move from anodes to cathodes—for instance, to move a vehicle or power a phone to make a call—the chemical energy stored is transformed into electrical energy as ions move out of the anode and into the cathode. When a battery is charging, electrons and ions flow in the opposite direction. As it is generally easier to remove ions from a material than to insert them, cathodes are the main drivers for discharge speed and anodes largely determine charging speed.

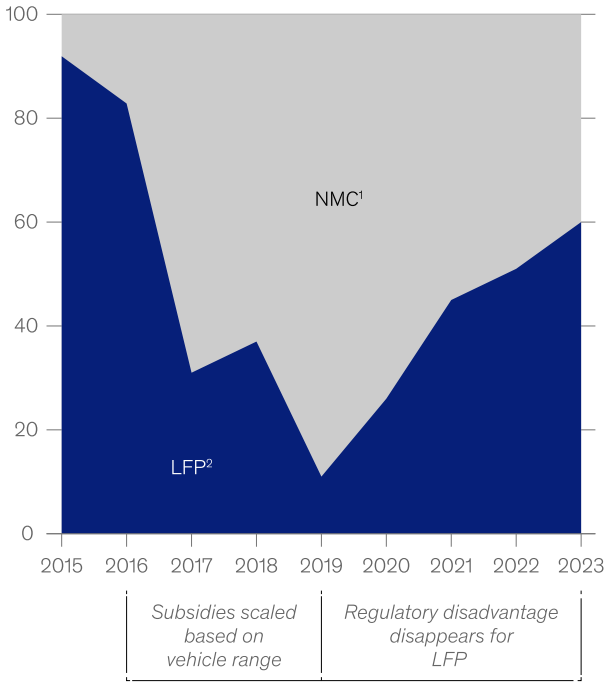
range to more than 520 km (as measured by the WLTP, or Worldwide Harmonised Light Vehicle Test Procedure)—comfortably above the minimum threshold that consumers specified in the recent McKinsey survey. Some companies hope to extend their range to 1000 km.

To appreciate how battery performance and cost have evolved, consider the Chinese market, which leads in EV sales. In the 2010s, all batteries were five to ten times more expensive than they are today, and Chinese OEMs used LFP chemistry in about 90 percent of their EVs because it was more affordable than NMC (Exhibit 1). Given LFP's range limitations, the EVs that they manufactured tended to be small and designed for short commutes. In 2015, however, the Chinese government decided to scale its EV subsidies based on vehicle range. The market thus began to shift in favor of NMC, despite its higher cost, because it had a range advantage over LFP. By 2019, NMC had approximately 90 percent share of the Chinese market.

Exhibit 1

LFP is once again the dominant battery chemistry in Chinese electric vehicles.

Market share of passenger car batteries by chemistry, mainland China, %



[1]Nickel manganese cobalt, or NMC, is a type of lithium-ion battery with a nickel, cobalt, manganese mix oxide-based cathode active material.
[2]Lithium iron phosphate, or LFP, is a type of lithium-ion battery with an iron phosphate-based cathode active material.
Source: McKinsey Battery Insights

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In 2020, Chinese OEMs began to transition back to LFP. This trend occurred partly because of innovations in EVs as a whole and LFP batteries in particular. Range improvement in LFP-equipped EVs was particularly impressive, with the average pack energy density of top-selling LFP vehicles going from about 80 watt-hours (Wh) per kilogram (kg) in 2014 to approximately 140 Wh/kg in 2023—an increase of 75 percent. China's decision to phase out scale-based subsidies also helped LFP gain market share. By 2023, LFP was once again the dominant chemistry in China.

Long-term prospects for L(M)FP

Now that L(M)FP batteries can enable longer driving ranges that meet most customers' expectations, some OEMs are transitioning to this chemistry, or at least adding it to their portfolio for entry-level models. As of 2024, the difference in energy density between NMC and LFP cells is only about 30 percent (which drops to 5 to 20 percent at pack level, based on vehicles in the market). At the same time, the production cost of an NMC cell is about 20 percent higher than that of an L(M)FP cell in US dollars per kilowatt-hour (kWh), produced under the same conditions.[3]

In many cases, OEMs continue to use NMC batteries in premium vehicles, since it still confers a longer driving range than LFP, even though the performance gap has narrowed. For instance, the Tesla 3 SR+, which has a 55 kWh LFP battery, has a driving range of about 450 km (WLTP[4]), while the LR version, equipped with an 82 kWh NMC battery, has a range of about 630 km (WLTP). Similarly, the new Xiaomi SU7 has an LFP version with 73 kWh and a 700 km range (CLTC[5]), as well as a higher-performance version with 101 kWh NMC and an approximately 800 km range (CLTC). Even though the first supercar with an L(M)FP battery was commercialized in 2024, market trends suggest that vehicles that require high energy densities to maximize range will still be equipped with NMC.

The speed of LFP adoption varies by region. Chinese OEMs are proceeding most rapidly. The percentage of passenger EVs in China with LFP technology rose from 45 percent in 2021 to 60 percent by 2023, as shown in Exhibit 1. In Europe and North America, NMC remains the most common chemistry by far, but these regions may soon see higher adoption rates for L(M)FP vehicles because of market demand for low-cost models. According to our projections, the global battery share for L(M)FP could rise from 11 percent in 2020 to 44 percent in 2025; by 2026, we estimate that eight of the top automotive groups will have at least one L(M)FP-equipped vehicle in the volume and premium segments, up from only a couple of groups in 2023.

While trends are clear in China, Europe, and the United States, several factors may affect the ongoing shift to L(M)FP batteries, including regulations and sunk investments. For instance, the United States introduced import tariffs on batteries in 2024, prompting a company to pause sales of vehicles with LFP batteries that were produced in China. It now focuses on vehicles with NMC cells, which are free of tariffs. Since the technology behind NMC batteries is well established, production yields are high and costs are partially amortized. These factors, combined with subsidies, allow OEMs to offer entry-level vehicles with NMC batteries at affordable prices.

[3] Cost is calculated in dollars per kilowatt-hour.
[4] As measured by the Worldwide Harmonised Light Vehicle Test Procedure (WLTP).
[5] As measured by the China Light-Duty Vehicle Test Cycle (CLTC), a Chinese standard.

Western OEMs will face additional challenges over the next few years as they attempt to transition to L(M)FP batteries because the supply chain is not well established and most cell production capacity is in China. To mitigate risks, these OEMs must build more resilient supply chains and significantly invest in production capacity in various geographies. Improved supply chains and production capacity will also help Western OEMs lower costs and achieve scale. Once companies establish the L(M)FP value chain outside mainland China, and/or if tariffs become less stringent, L(M)FP batteries will be more cost competitive in all regions.

For 2030 and beyond, the outlook for L(M)FP adoption is more uncertain because both the automotive market and battery technologies could evolve in different directions. We investigated three potential scenarios for L(M)FP adoption in 2035 and identified the developments that would have to occur for each one to materialize (Exhibit 2):

— *A continuation of the current trajectory.* In this scenario, the market permanently splits into NMC and L(M)FP segments, with L(M)FP batteries reaching a 60 percent market share worldwide. Most premium vehicles are still equipped with NMC battery packs, allowing for the longest range possible, and other, less-expensive vehicles use L(M)FP. This pattern is already apparent in the market, with sport versions of common vehicles using NMC to differentiate them from less expensive models. This scenario assumes that innovations in NMC technology, such as using a single crystalline material for long cycle life, or cell-to-pack technology to increase range and decrease cost, will become more widespread. These advances would allow NMC to maintain a compelling value proposition, even though L(M)FP is less expensive.

— *More aggressive adoption of L(M)FP resulting from technology breakthroughs.* This scenario, in which L(M)FP reaches an 80 percent market share, hinges on several other developments. For instance, aggressive adoption would require OEMs to switch most of the small to midsize vehicles to L(M)FP batteries. Meanwhile, 70 percent of NMC-planned gigafactories in the European Union, and a similar percentage in North America, would have to switch to L(M)FP production to meet local demand. To ensure resilience, elements of the value chain, such as CAM production, would need to be less geographically concentrated. Other uncertainties that could affect this scenario relate to the chemistry and underlying technology. New variants of LFP, such as LMFP, are still entering the market and have not yet revealed their full potential. What's more, anodes and electrolytes are evolving and the new variants might make L(M)FP a safer, more effective cathode.

— *A slowdown in L(M)FP adoption because of innovation at both ends of the energy density spectrum.* Researchers are now developing solid-state batteries (SSBs), which use different

electrolytes than most commercial Li-ion batteries and promise a step-change increase in energy density, which could potentially enable longer driving ranges or smaller batteries. Smaller, high-performing batteries might eventually also be more cost competitive at the system level, compared with today's standard costs. The cost-performance ratio in SSBs could be better for NMC than L(M)FP, which might increase NMC demand if SSBs become common. Changes in raw-material prices, such as an increase in the cost of lithium, could also tip the balance in favor of NMC over the long term.

Further, the potential rise of sodium-ion (Na-ion) technology might limit demand for L(M)FP cells. This is especially true if various factors, such as a high lithium market price, make Na-ion less expensive than LFP. OEMs might decide to use Na-ion technology in batteries for entry-level cars or if developers use this technology for grid-storage applications. Finally, the growth of charging networks and acceleration of charging speeds might convince more people to buy cars with a shorter range. If that happens, smaller batteries might become more common. Since smaller batteries have a lower impact on overall vehicle cost, the price advantage of L(M)FP would be less pronounced, leading NMC to gain traction.

To summarize, we believe that both NMC and L(M)FP demand will grow through 2030. After that point, demand for one of these chemistries might stagnate or decline, and multiple scenarios are possible.

The potential impact of L(M)FP growth along the value chain

A shift to greater L(M)FP use would have major repercussions for OEMs. For instance, they might change the battery-pack and electrical/electronic design, or even its architecture, because L(M)FP variants differ from NMC in voltage, safety, cooling profile, and other characteristics. The trend of shifting from modular packs to cell-to-pack architectures with larger cell form factors might accelerate because they are better suited to L(M)FP batteries, which have lower energy density.

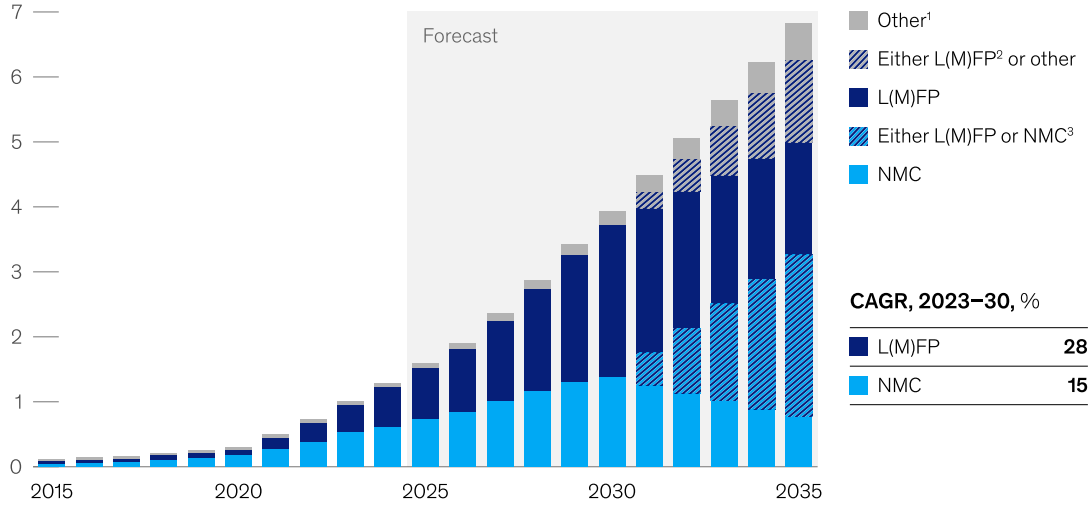
If OEMs begin to prefer L(M)FP, EVs may become more affordable. The price drop could increase demand for them, as well as for L(M)FP cells and components, and the impact would likely ripple through the value chain. Consider miners and refiners: nickel producers might have to focus on other end sectors, such as stainless steel and specialty alloys, if demand from the automotive sector grows at a much slower pace than initially anticipated. But diversification may not entirely offset lower automotive demand, given the large nickel capacity that has recently become available.

For lithium producers, on the other hand, a shift to L(M)FP might generate higher than anticipated short-term demand, which would partially offset the reduction in price observed

Exhibit 2

Battery demand will increase globally, but L(M)FP is expected to see a more accelerated uptake than NMC.

Global battery cell demand by source, terawatt-hours



[1]Including sodium-ion and other lithium-ion chemistries.
[2]Lithium manganese iron phosphate, or L(M)FP, is a type of lithium-ion battery with a manganese and iron phosphate-based cathode active material.
[3]Nickel manganese cobalt, or NMC, is a type of lithium-ion battery with a nickel, cobalt, manganese mix oxide-based cathode active material.
Source: McKinsey Battery Insights

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from 2023 to 2024. Since long-term demand for lithium is difficult to predict, producers need to plan for a variety of scenarios when designing and building new capacity. Adding to the uncertainty, future product requirements for various technologies are still unknown, and they will also affect lithium demand.

For CAM producers, lower growth in demand for NMC could prove challenging because NMC and L(M)FP require different production processes, production lines, and expertise. Since CAM producers that now specialize in NMC cannot easily convert to L(M)FP production, they might end up with excess inventory and lower profits. Their options to improve the bottom line might involve diversifying—for instance, by investigating Na-ion offerings, or trying to catch up by developing L(M)FP knowledge and skills. Several large Chinese NMC CAM providers now offer L(M)FP, but some other Asian NMC CAM players have instead diversified into other components, such as anode materials, rather than entering the L(M)FP market.

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Cell manufacturers are also affected by these dynamics. While it is possible to produce L(M)FP cells in lines previously designed for NMC, it is often not economically viable. Moreover, cell manufacturers would need to modify parts of the supply chain and acquire expertise specific to L(M)FP. Similarly to CAM producers, NMC cell players will need to decide whether to strengthen their position in the NMC market or jump into the competitive yet fast-growing L(M)FP arena.

Battery technology is on the cusp of a major shift. Our analyses suggest that L(M)FP batteries could become the technology with the largest global market share before 2030, challenging the recent preeminence of NMC chemistry. OEMs and other stakeholders along the EV value chain can either solidify their position in NMC—which is expected to see continued demand growth, albeit at a slower rate than L(M)FP—or pivot to L(M)FP. In either case, companies that can act quickly, monitor market developments closely, and make strategic adjustments nimbly will be best positioned to win in the changing marketplace.

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The authors wish to thank Andreas Gouder, Christian Ahrberg, Denny Thiemig, Henrik Zhao, Johan Bracht, Martin Linder, Michel Van Hoey, Nicolas Goffaux, Patrick Schaufuss, all other members of the McKinsey Battery Insights team, the McKinsey Metals & Mining MineSpans team, and the McKinsey Center for Future Mobility for their contributions to this article.

This article was edited by Eileen Hannigan, a senior editor in the Boston office.

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