LITHIUM MANGANESE IRON PHOSPHATE (LMFP) BATTERIES RECEIVING RENEWED ATTENTION IN CHINA —EXPECTED TO BE INSTALLED MAINLY IN MIDDLE-CLASS EVS —

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SUMMARY

- LMFP battery is a type of lithium-ion battery that is made based on lithium iron phosphate (LFP) battery by replacing some of the iron used as the cathode material with manganese. It has the advantage of achieving higher energy density than LFP while maintaining the same cost and level of safety.
- In China, where cost-effective LFP batteries account for 60% of the EV battery market share, initiatives toward mass production of LMFP batteries, which show promise as a successor, are gaining momentum.
- Moving forward, LMFP batteries are expected to be installed mainly in middle-class EVs, and their market share is expected to increase as they become differentiated from the currently mainstream LFP batteries and ternary lithium-ion (NMC) batteries.

1. WHAT IS LMFP BATTERY?

Currently, the two main types of batteries installed in electric vehicles (EVs) worldwide are lithium iron phosphate (LFP) batteries, which use lithium iron phosphate ($LiFePO_4$; hereinafter LFP) as the cathode material, and ternary lithium-ion (NMC) batteries, which use a compound consisting primarily of nickel, manganese, and cobalt. LFP batteries are safer and less expensive because they use fewer rare earths such as cobalt, but they have the disadvantage of a lower energy density[1], which shortens the cruising range of EVs. On the other hand, although NMC batteries have a higher energy density, they are not as safe as LFP batteries while also being more expensive because they use cobalt and other rare earths. LFP batteries and NMC batteries are differentiated based on their respective properties, with the former generally used for low-priced EV models with cruising ranges of 300 km to 500 km and the latter for middle-class and higher-priced EV models with cruising ranges of 400 km to 700 km. Although NMC batteries currently account for the majority of the global market share, in recent years, LFP batteries, which offer better cost performance, have been gradually gaining in market share, especially in China, as they improve in performance.

The term “LMFP battery” as discussed in this report refers to lithium manganese iron phosphate (LMFP), a type of lithium-ion battery whose cathode is made based on LFP by replacing some of the iron with manganese. LMFP batteries are attracting attention as a promising successor to LFP batteries because they provide roughly 15% to 20% higher energy density while maintaining approximately the same cost and level of safety as LFP batteries. Initiatives toward mass production of LMFP batteries are accelerating, especially in China, where LFP batteries account for 60% of the domestic market share. This report discusses the background, latest trends, and future prospects.

[1]Battery energy per unit mass, or the amount of energy that can be extracted per unit volume. Expressed in units such as Wh/kg or Wh/L.

2. THE CHARACTERISTICS OF LMFP BATTERY

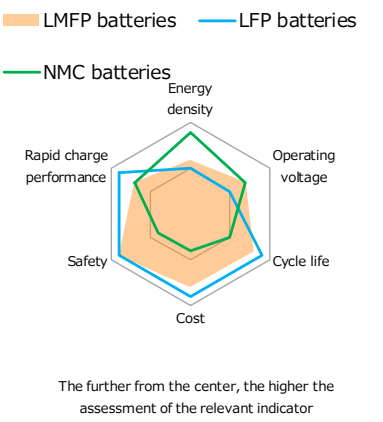
LMFP has a highly stable olivine-type[2] crystal structure, similar to LFP, which ensures less deformation during the charging and discharging processes, yet provides an equivalent level of safety. LMFP surpasses NMC, which has a layered rock-salt structure[3], in thermal stability and cycle life in particular. Although the theoretical capacity of LMFP is similar to that of LFP, its energy density is roughly 15% to 20% higher than that of LFP because the operating voltage is roughly 0.5 V higher than LFP`s 3.2 V. In terms of cost, due to its high energy density and the fact that it does not use cobalt or other rare metals, the cost per watt-hour following mass production is expected to be equal to or lower than that of LFP.

In addition, although there are technical issues such as low electrical conductivity and the dissolution of manganese during charge and discharge cycles, improvements have been made in recent years through advancements in technologies for nano-scale cathode materials and carbon coating the particles, and now that the cycle life exceeds 2,000 cycles, it could be considered on track for practical application.

Main performance data for LFP, LMFP, and NMC batteries are shown in Figure 1.

Figure 1: Comparison of main performance data between LFP, LMFP, and NMC batteries

Main performance item	LFP batteries	LMFP batteries	NMC batteries
Molecular formula of active material in cathode	$LiFePO_4$	$LiMn_xFe_{(1-x)}PO_4$	$Li(Ni_xMn_yCo_z)O_2$ (x+y+z=1)
Cathode crystal structure	Olivine type	Olivine type	Layered rock-salt type
Cathode theoretical capacity (mAh/g)	170	170	280
Maximum cell energy density (Wh/kg)	170	230	350
Operating voltage (V)	3.2	3.7	3.7
Cycle life (No. of cycles)	2,000 to 6,000	2,000 to 3,000	800 to 2,000
Electrical conductivity (S/cm) (Note)	10^{-9}	10^{-13}	10^{-3}
Safety	High	High	Average
Cost	Low	Low	High



Note: Electrical conductivity is a physical property that expresses the ease with which electric current flows through a material. The unit is Siemens per meter (S/m).

Source: Compiled by MGSSI based on IDTechEx (https://www.idtechex.com/ja/research-article/volkswagens-long-term-high-manganese-cathode-strategy/23431), HCM (https://www.hcmaterial.com.tw/en/lmfp), TYCORUN ENERGY "LMFP industry special report in 2022" (https://www.takomabattery.com/lmfp-industry-special-report-in-2022/), Battery Design (https://www.batterydesign.net/lithium-ion/) (accessed July 27, 2023)

LMFP production methods, similar to those of LFP, are classified into solid-phase synthesis and liquid-phase synthesis methods. Although the liquid-phase synthesis method, which synthesizes from a mixture of materials in a solution, is a more complex process than that of the solid-phase synthesis method, which synthesizes by grinding solids into smaller pieces, the liquid-phase synthesis method is a better means of producing high-performance LMFP because it enables a more uniform synthesis of materials.

[2]The term olivine-type structure refers to a crystal structure with tetrahedral sites occupied by phosphorus and octahedral sites occupied by lithium, iron, and manganese in a hexagonal close-packed framework of oxygen. As phosphoric acid (PO_4) forms the framework structure, it possesses excellent thermal stability. It is named after the fact that it has the same structure as natural olivine. (Source: Nikkei xTECH, "Development Competition Begins for Li-Ion Battery Part 2: Exploring Candidate Cathode Materials," last accessed on August 1, 2023; Sumitomo Osaka Cement Co., Ltd. website)

[3]The term layered rock-salt structure refers to a crystal structure in which lithium layers and metal oxide are regularly arranged to form 2D planes that appear stacked. (Source: Nikkei xTECH, "Development Competition Begins for Li-Ion Battery Part 2: Exploring Candidate Cathode Materials," last accessed on August 1, 2023)

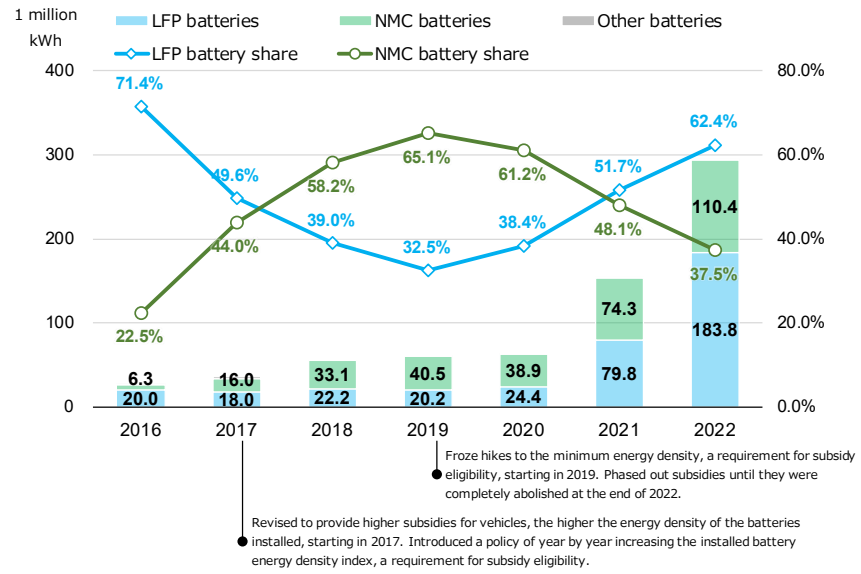
LMFP batteries have the potential to replace LFP batteries in the future due to being so highly cost-effective, as well as the potential to gain some of the NMC battery market share. In addition, mixing LMFP cathode materials with NMC cathode materials of nearly the same operating voltage is expected to increase the safety of NMC batteries, so the combined use of LMFP cathode materials is another expected application.

3. RECOVERY OF THE LFP BATTERY MARKET SHARE IN CHINA TRIGGERED RENEWED INTEREST IN LMFP BATTERY

First of all, LMFP battery is not a new technology. In 2014, Wang Chuanfu, the founder of BYD, China's largest EV manufacturer, announced that the company was developing LMFP batteries as the successor to LFP batteries. However, in addition to facing the aforementioned technical challenges, ever since 2017, the Chinese government has been favoring batteries with high energy density in its EV subsidy program, so the market share of LFP batteries, which had been systematically disadvantaged, has declined year by year, and LMFP batteries never made it to the point of installation.

Later, moves to correct the preferential treatment under these systems for high-energy-density batteries began in 2020, and such treatment was fully abolished in 2023. This once again increased demand for highly cost-effective batteries, and the share of LFP batteries in the EV battery market has recovered significantly, with LFP batteries accounting for 62.4% of all batteries installed in EVs in China in 2022 (see Figure 2).

Figure 2: Trends in volume of LFP and NMC batteries installed in EVs in China (2016 to 2022)



Source: Compiled by MGSSI based on materials released by the China Automotive Power Battery Industry Innovation Alliance and the Chinese government

According to the IEA[4], due to making great strides in the domestic Chinese market, LFP batteries accounted for 30% of the global EV battery market in 2022, which is the highest record in the past decade. Roughly 30% of all batteries installed in EVs sold by Tesla are LFP batteries, and Ford also plans to launch production in the US in 2026, showing that LFP batteries are becoming increasingly popular in other parts of the world as well.

While the market share of LFP batteries is thus steadily expanding, primarily in China, and its low energy density, which is considered a drawback, is improving year by year, advancements are approaching their limits due to the chemical nature of the materials. Against this backdrop, LMFP batteries are once again attracting attention

[4]International Energy Agency

for the significant progress that has been made in overcoming the technological issues hindering their practical application.

4. CHINESE COMPANIES ACCELERATE INITIATIVE TOWARD MASS PRODUCTION OF LMFP BATTERY

Taking the lead in achieving practical application of LMFP batteries will help Chinese companies, which account for 90% of the global production of LFP batteries, maintain competitiveness moving forward, so ever since 2022, battery manufacturers and battery cathode material manufacturers have been accelerating their initiatives toward mass production.

Figure 3 shows the performance indices of LMFP batteries for EVs developed by the various Chinese battery manufacturers. In August 2022, the major automotive battery company CALB announced an LMFP battery with a package energy density of 180 Wh/kg. Soon after, several other battery manufacturers announced prototypes one after the other. The expected cruising ranges of EVs equipped with LMFP batteries currently under development by the various companies are between 500 km and 1,000 km, which suggests that they are targeting middle-class or higher models. Most recently, in May 2023, Gotion High-Tech, the fourth-largest shipper in China, announced an LMFP battery with a 1,000 km range and plans to launch mass production in 2024. Most other prototypes, however, are still under development or undergoing performance testing by EV manufacturers, and the timing of mass production has yet to be determined.

Figure 3: LMFP batteries for EVs under development by Chinese battery manufacturers

Battery manufacture	Timing of announcement	Cell energy density		Cell shape	Estimated cruising range	Mass production schedule and other performance indicators
		Wh/kg	Wh/L		km	
CALB	August 1, 2022	200	n/a	Square	700	Timing of mass production unknown. Scheduled to have a life of 2,500 cycles, a battery package energy density of 180 Wh/kg, and to be compatible with both rechargeable and replaceable batteries.
Frasis Energy	September 1, 2022	240	n/a	Pouch	500	Scheduled to release first generation product before the end of 2023.
SVOLT	December 1, 2022	220	503	Rectangular	900	Used in combination with NMC cathode material. Has rapid charge capabilities with a C rate of 2.2 (note), and better low-temperature performance than LFP. Mass production scheduled for 2024.
REPT BATTERO	March 1, 2023	n/a	500	Rectangular	800	Scheduled to be announced in 2023 or 2024.
JEVE	April 1, 2023	220	555	Rectangular	500～600	Timing of mass production unknown. A life of at least 2,000 cycles (25°C).
Gotion High-Tech	May 1, 2023	240	525	Rectangular	1,000	Mass production scheduled for 2024. Has a battery package energy density of 190 Wh/kg, and a life of 2,000 cycles (25°C, 0.5C).

Note: The term C rate refers to the charging and discharging speed. When measuring constant-current charge/discharge, 1C is defined as the amount of current that fully charges (or discharges) a battery's theoretical capacity in one hour. The higher the value, the greater the possible current output and the more quickly the battery can be charged.
Source: Compiled by MGSSI based on information released publicly by Gaogong Industry Institute Co., Ltd. and the companies concerned

Chinese manufacturers of battery cathode materials are hurrying to secure and expand their production capacity in preparation for mass production of LMFP cathode materials as a means of getting a head start in capturing future demand. Dynanonic, which specializes in nanoscale technology, plans to expand production capacity from its current 110,000 tons per year, one of the highest volumes in China, to 440,000 tons by 2025. In July 2022, Ronbay Technology, a major cathode material manufacturer, announced its intention to acquire a 68.25% stake in SKLD, a startup with an annual production capacity of 5,000 tons, to expand its annual production capacity to 300,000 tons by 2025. CATL, the world's largest battery manufacturer, also acquired a 100% stake in Lithitech, a startup with an annual production capacity of 2,000 tons, with plans to produce 3,000 tons annually. As shown in Figure 4, the total production capacity of the various cathode material manufacturers whose operations are either underway or in the planning stages reaches several hundred thousand tons per year. However, at the present time, even plants that are in operation are still producing on a small scale, such as only shipping sample products. In addition, with the exception of a few companies, such as Dynanonic, most of the companies are expected to make use of the solid-phase synthesis method they developed in the course of

manufacturing LFP cathode materials, so the performance of the mass-produced products will have to be assessed.

Figure 4: LMFP cathode material production capacity of battery cathode material manufacturers in China and plans for the future

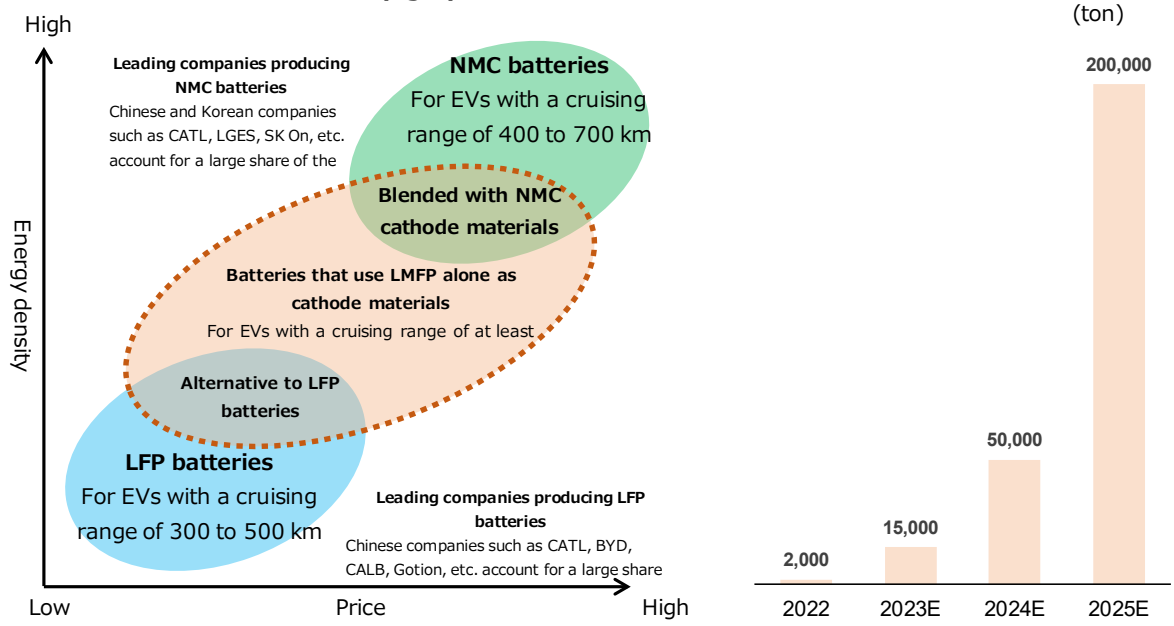
Cathode material manufacturer	Production capacity Tons/year	Operating status	Future plans, etc.
Dynanonic	110,000	In operation	Scheduled to expand to 440,000 tons/year by 2025.
Zhongbei New Material	10,000	In operation	Plans to expand to 100,000 tons/year in the future.
Ronbay New Energy Technology	5,000	In operation	Currently expanding to 10,000 tons/year. Scheduled to expand to 300,000 tons/year by 2025.
HENGTRON Nanotech	5,000	In operation	Scheduled to expand production capacity to 150,000 tons/year over the long term.
Lithitech	2,000	In operation	A subsidiary of CATL, the world's largest battery manufacturer. Planning to upgrade its production capacity by 3,000 tons/year.
Hubei RT Hi-Tech Advanced Materials	40,000	Construction	Scheduled to launch operations by the end of 2023.
EASPRING	120,000	In planning	The aforementioned is the production capacity during Phase 1, and this will be expanded to a total of 300,000 tons/year by 2028.
Qianyun Tech	100,000	In planning	Scheduled to expand to 200,000 tons/year over the long term.
GHTECH	36,000	In planning	The aforementioned production capacity represents the total of LFP and LMFP cathode materials.
Jinquan New Material	25,000	In planning	A subsidiary of EVE Energy, a major battery manufacturer
Cnano Technology	20,000	In planning	The aforementioned is the production capacity during Phase 1. Eventually to be expanded to a total of 100,000 tons/year

Source: Compiled by MGSSI based on information released publicly by the companies concerned and articles by Gaogong Industry Institute Co., Ltd.

5. FUTURE PROSPECTS

LMFP batteries are ranked between LFP and NMC batteries in terms of energy density and price, as shown on the left in Figure 5. During the initial stage of installation in EVs, it is expected that their most common applications will be as a substitute for LFP batteries as well as in mixture with NMC cathode materials. Over the medium- to long-term, as the technology continues to mature, it is thought that LMFP can be increasingly used alone mainly in middle-class EVs as a cathode material, and LMFP batteries will differentiate themselves from the currently mainstream LFP and NMC batteries. According to a forecast released in May 2023 by the Chinese research firm Gaogong Industry Institute Co., Ltd., the volume of LMFP cathode material shipments in China will grow from 2,000 tons in 2022 to 200,000 tons (equivalent to roughly 100 GWh[5] in battery capacity) by 2025, reaching approximately 10 billion yuan (about 200 billion Japanese yen) in monetary value. (Figure 5, right side).

Figure 5: Anticipated applications of LMFP batteries (left) and projected shipment volume of LMFP cathode material in China (right)



Source: Compiled by MGSSI based on information released by Gaogong Industry Institute Co., Ltd. (https://mp.weixin.qq.com/s/xuiLjyW0UlWw4A_j5F1R2g) (accessed August 1, 2023)

[5]GWh＝1 million kWh

According to an analysis by APC[6], an industry-academia consortium in the UK, LMFP batteries will cost less than $100/kWh by around 2030, making them more cost-effective than NMC batteries and fuel cells when installed, for example, in large SUVs with a battery capacity of 150 kWh and a cruising range of at least 800 km.

Outside of China as well, there are other capable companies in the field of LMFP cathode materials. In Japan, Taiheiyo Cement used its proprietary hydrothermal synthesis technology to successfully develop Nanolitia, a high-performance LMFP cathode material, by synthesizing and granulating uniformly-sized particles at the nano level and coating them with carbon. The company is aiming to launch mass production in 2025. In Australia, VSPC[7] has succeeded in prototyping a cell with an energy density of roughly 236 Wh/kg through a manufacturing method that takes advantage of its proprietary nanotechnology, and plans to begin commercialization in 2027. Although it has been pointed out that China's manufacturing technology, which is primarily based on solid-phase synthesis, may be inferior to that of other overseas countries, China is still likely to lead the way in mass production of LMFP batteries thanks to demand from its huge domestic EV market and the presence of so many battery manufacturers actively engaged in development.

In contrast to China, which possesses the world's largest LFP battery manufacturing base and is expected to begin mass producing LMFP batteries, it is believed that Japan, Europe, the US, and elsewhere will face high hurdles in achieving mass production due to the current situation on both the supply and demand sides, in which domestic EV markets remain small-scale with the existing battery manufacturing bases focused on NMC batteries. Under these circumstances, Chinese battery manufacturers are increasing their exports of EV batteries and ramping up overseas expansion into Europe and the US with the possibility of launching exports and local production of LMFP batteries in the future. It would be best to keep a close eye on their future activities in terms of their impact on global competition in the battery industry.

[6]Advanced Propulsion Centre
[7]VSPC Pty Ltd: A wholly-owned subsidiary of Lithium Australia, a battery materials company listed on the Australian Securities Exchange