Thermo Fisher
SCIENTIFIC

Chemicals

Sustainable battery material for lithium-ion and alternative battery technologies

What is the battery material for future lithium-ion and alternative battery technologies? Learn about promising cathode and anode battery chemistries for a sustainable battery value chain and manufacturing.

Author
Julian Renpenning, PhD, CM for Science & Technology

Sustainable battery materials for lithium-ion batteries and alternative chemistries

Batteries are becoming an indispensable part of today's global energy storage ecosystem and will play a critical role in facilitating a safe, affordable and clean energy transition. In the transportation sector, they are an essential enabler for the growing number of electric vehicles (EVs) being sold each year. In energy storage, batteries are playing an increasingly important role in utility-scale and behind-the-meter applications as their cost declines and the deployment of solar and wind power expands.

Sustainability in battery materials and the battery supply chain will be critical for optimizing storage capacities, integrating renewable energy sources, and accelerating our transition to electric mobility. However, this involves taking a look at the entire battery lifecycle, including the material supply chain, battery chemistries, and long-term environmental impacts. Recent advances in battery technology aim to further enhance the sustainability of lithium-ion batteries and alternative battery chemistries by improving the availability and safety of battery cathode and anode materials. At the same time, critical raw materials will be eliminated from future battery chemistries.

Some encouraging examples include the increasing market adoption of lithium-iron-phosphate (LFP) batteries, the commercialization of sodium-ion batteries, and the rapid development of next-generation battery technologies, such as the solid-state battery or lithium-sulfate battery chemistry. Traditional lithium-ion batteries are still a key component of modern economies and have reshaped electronic devices, electric mobility, and are on the rise in power systems. However, new battery chemistries under development may challenge traditional lithium battery dominance in the years ahead.

thermo scientific

Growing demand for battery storage capacity

Battery use is expanding significantly across the energy storage sector, with new highs in electric vehicle sales and record additions of battery storage in the power sector. Today, one in five cars sold in the global market are electric (**ref**), while in China, about half of car sales are electric (**ref**). In addition, a growing number of solar and wind power projects are using stationary battery storage capacity. As a result, numerous new battery cell manufacturing facilities have been announced worldwide, driven by political support in various regions.

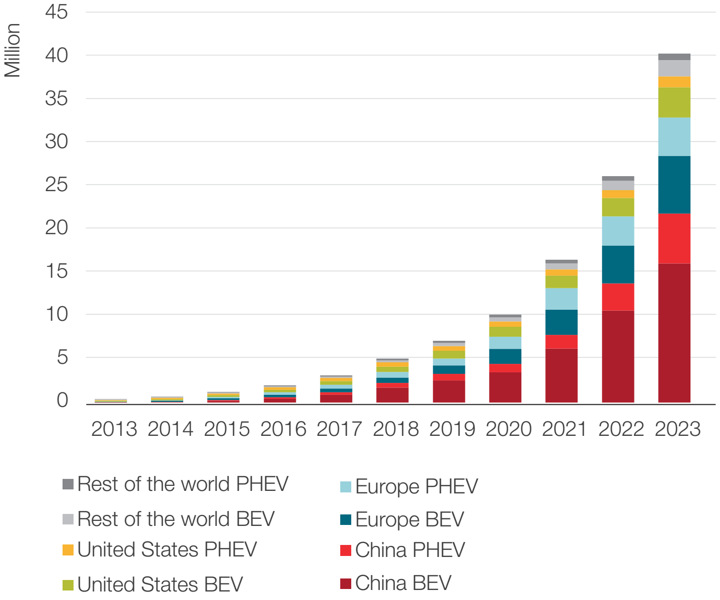

Figure 1. EV battery storage capacity. Source: IEA, **Global EV Outlook 2024, trends in electric cars**

The lithium-ion battery industry has experienced rapid growth over the past five years. From 2018 to 2023, the installed capacity of LIBs for energy storage applications increased by more than 2,000 GWh — a staggering fourfold increase. This brought the total volume to more than 2,400 GWh by the end of 2023. Over the past decade, lithium batteries have outperformed other energy storage technologies due to their superior energy density and cycle life. At the same time, advances in battery chemistry and manufacturing processes have reduced average battery costs by an impressive 90% from 2010 levels.

Battery material and supply chain risks

Today's global rechargeable battery supply chain is incredibly complex and involves many steps. China was an early mover in this sector and now holds a dominant position in virtually every stage of the downstream battery supply chain. The country accounts for more than half of the world's raw material processing for critical battery minerals such as lithium, cobalt and natural graphite. With a 90% share of the world's graphite mining operations, China effectively controls the entire graphite anode supply chain. The country also has nearly 85% of the world's battery cell manufacturing capacity. Its industrial base is also responsible for 90% of the world's cathode active material production.

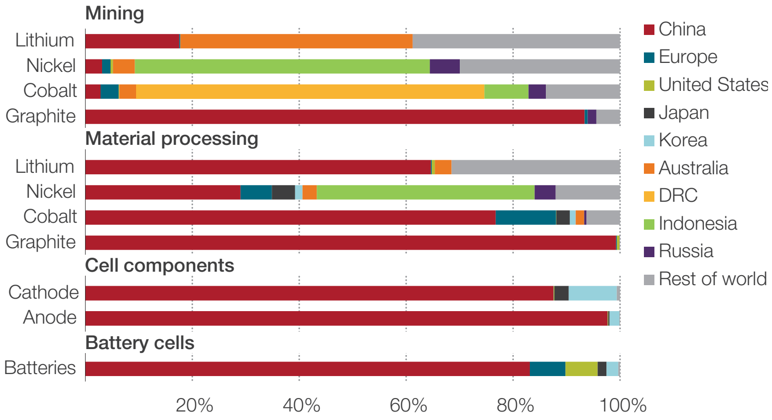

Figure 2. Geographical distribution ofthe globalbattery supply chain. Source: IEA, **Batteries and secure energy transitions**

China's dominant role in the entire battery supply chain, from processed raw materials to finished components and cells, is undeniably significant and currently difficult for other nations to match. Only Korea (9%) and Japan (3%) have significant cathode active material manufacturing capacity outside China today. However, different battery chemistries require different supply chains. This may allow us to find opportunities to reduce supply chain dependencies and find more sustainable ways to move forward with our ambitions in the energy storage and electric mobility sectors.

Evolution of lithium-ion battery material and chemistries

The elemental composition of the cathode material - the positive electrode, where lithium ions are stored during the charge and discharge cycle - influences the battery performance. Therefore, batteries are classified and named based on the applied cathode active material. The most prevalent lithium-ion battery chemistries are:

- lithium nickel manganese cobalt oxide (NMC)
- lithium nickel cobalt aluminum oxide (NCA)
- lithium iron phosphate (LFP)
- and lithium cobalt oxide (LCO)

The varying combinations and proportions of the electrode material in each battery chemistry confer distinctive characteristics. LCO is one of the most established chemistries and finds primary application in portable electronics due to its high-energy density and technological maturity. Today, NMC, NCA, and LFP chemicals are the most popular types of batteries for electric vehicles (EVs). However, recently, alternative technologies and materials for lithium-ion batteries or entirely other chemistries, such as solid-state and sodium-ion batteries, have gained significant attention as potential successors.

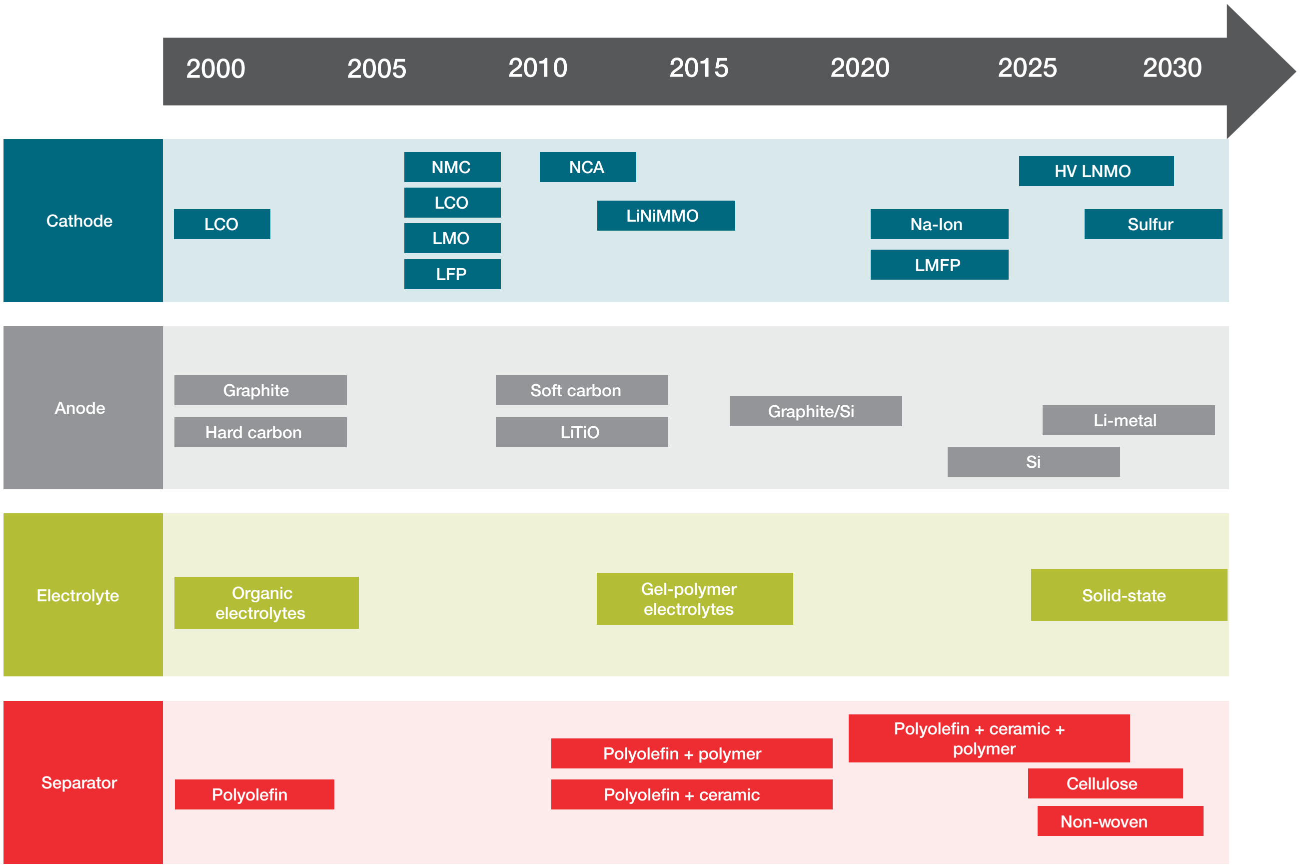

Figure 3. Timeline of battery cellchemistry development. Source: Volta Foundation, Annual Battery Report 2023

Sustainable next-gen battery cathode and anode materials

Cathode material

The cathode material plays an important role in batteries. They facilitate the storage and release of lithium ions during charge and discharge cycles, allowing the movement of electrons, and ensuring a stable and consistent current energy supply. However, there are numerous challenges related to the performance of cathode materials. These may include limited energy storage capacity, slow ion diffusion rates, and higher material costs compared to other battery components due to the use of expensive minerals such as nickel, cobalt, and lithium hydroxide/ carbonate. There are also issues related to sustainability and availability to consider. Overcoming these cathode-related challenges is critical to improving energy density, performance, cost, cycle life, and safety of lithium-based batteries and alternative battery chemistries. But also to meet our sustainability goals and reduce supply chain dependence. So, what are our options for the upcoming five to ten years?

Lithium-iron-phosphate batteries

Lithium iron phosphate (LiFePO4, LFP) is a widely used cathode material for lithium-ion batteries. It currently holds about 40% market share by volume. Since LFP does not contain nickel or cobalt, it has a more sustainable and stable chemical footprint. Compared to nickel-rich cathode chemistries, LFP is less flammable and has a longer cycle life. However, the trade-off is that LFP has a significantly lower energy density, typically 20-30% lower than high-nickel cathodes at the battery cell level. Despite this lower energy density, the application of LFP in electric vehicle batteries has greatly increased in recent years.

From an environmental and sustainability standpoint, LFP benefits from the high availability of iron and phosphate resources. Lithium is the only critical cathode active material it contains, making LFP cheaper than NMC and NCA cathode materials. As a consequence, LFP chemistry provides a more sustainable and resilient option for battery manufacturing. This helps improve the long-term viability of the EV and energy storage industries. LFP cathodes are very popular in China, with over two-thirds of new EV battery installations there expected to use LFP by 2023. At the same time, more automotive and battery companies outside China are also producing or adopting LFP batteries for EVs, recognizing the advantages of this cathode composition.

Lithium-manganese-iron-phosphate batteries

A promising improvement in LFP cathode chemistry is the addition of manganese to form lithium manganese iron phosphate (LiMnxFe1-xPO4, LMFP). The main advantage of LMFP over regular LFP is its higher operating voltage, which results in higher energy density. At the same time, LMFP maintains the low cost of LFP by avoiding expensive materials other than lithium. This means LMFP is expected to have a similar low-cost structure to LFP, while also providing sustainability and supply chain benefits.

One of the challenges associated with LMFP is its shorter cycle life than LFP due to manganese dissolution, as well as a higher sensitivity to moisture and water. However, the battery industry addressed these issues, and a number of companies are actively investing in the development of LMFP cells. Several battery manufacturers have announced their progress in developing or producing LMFP batteries. According to their reports, CATL, a leading battery manufacturer, has already started mass production of its so-called M3P batteries with LMFP cathode chemistry in 2023.

Sodium-ion batteries

Research on sodium-ion batteries (SIBs) has a long history, dating back to the mid-20th century, and significant progress has been made since then. In recent years, various companies and start-ups have approached the commercialization stage or have already started commercialization of SIBs, including Faradion, Altris, Northvolt, Natron Energy, Tiamat, BYD, CATL, and HiNa. Sodium-ions (Na^+) compared to lithium-ions (Li^+) result generally in lower gravimetric and volumetric energy densities for SIBs. Current real-world energy densities, such as those reported by CATL, are in the range of 140-160 Wh/kg, but future cell generations are expected to exceed 200 Wh/kg. SIBs cycle life today is in the range of 500-1,000 cycles. However, these values are dependent on the specific cell chemistry and have been reported to be as high as 4,000 cycles.

Compared to some other Li-ion battery materials, SIBs offer significant sustainability and cost advantages that are worth considering. They use less expensive materials than lithium-based batteries, resulting in a 20-30% cost reduction compared to LFP batteries. In addition, SIBs require fewer critical minerals than the battery chemistries currently dominating the global battery market, making them more economical to produce. There are many ways to make SIBs. Layered oxides, which usually have nickel, manganese, or both, and Prussian white, which has sodium, iron, nitrogen, and carbon, are the most common. Notably, sodium-ion technology is currently the only viable non-lithium battery technology available.

In addition to material cost advantages, SIBs can use aluminum anode collectors, whereas lithium-ion batteries require copper anode collectors. This substitution further reduces the copper usage associated with SIB production, contributing to their overall sustainability profile. The combination of lower battery material costs, reduced dependence on critical minerals, and the potential to reduce the use of copper, positions sodium-ion batteries as a promising alternative for sustainable and cost-effective energy storage solutions, particularly in the stationary energy storage market.

Solid-state batteries

While current LIBs are based on liquid electrolytes, solid-state batteries (SSBs) are based on solid electrolytes and promise improvements in several KPIs. The most important KPI improvements that SSBs offer are in energy density and safety. However, there isn't just one type of SSB. Different materials are considered for SSB components. Lithium metal and silicon are among the most promising anode active materials (AAMs).

Currently, three groups of solid electrolyte materials appear to be the most promising: oxide electrolytes, sulfide electrolytes, and polymer electrolytes. All SSBs have a high potential to outperform state-of-the-art LIBs in terms of energy density. According to calculations, SSBs with all three solid electrolyte materials could reach volumetric energy densities of up to 1150 Wh/l and gravimetric energy densities of up to 350 to 500 Wh/kg when combined with lithium metal anodes.

As SSBs move closer to practical applications and commercialization, they will need to demonstrate performance improvements over state-of-the-art liquid electrolyte LIBs. The safety of SSBs is expected to be high, even at the cell level, as they do not contain flammable liquids. Depending on the materials used, SSBs may also be more sustainable. But the main reason to go for SSB in many applications is its superior energy density.

Metal-sulfur batteries

Sulfur is an abundant, low-cost and lightweight material for cathodes, which is why metal-sulfur batteries are being intensively researched. Various metals like lithium, sodium, potassium, magnesium, calcium, and aluminum are being studied in combination with sulfur cathodes. Among these, lithium-sulfur (Li-S) batteries are the most technologically advanced.

Li-S batteries aim to take advantage of sulfur's high theoretical energy storage capacity of 1,672 mAh/g, which is far higher than current lithium-ion cathodes. Prototype Li-S batteries have demonstrated energy densities of 300-400 Wh/kg by combining the high capacities of lithium and sulfur anodes and cathodes. However, their cycling stability is lagging behind state-of-the-art lithium-ion batteries, and key components face research and development challenges.

Nevertheless, Li-S batteries could target applications requiring high-energy density per weight or high cost-sensitivity. From a raw material standpoint, the low cost of sulfur means that Li-S batteries could potentially be cheaper than lithium-ion batteries, if manufacturing challenges can be overcome.

Battery anode material

Graphite is still the state-of-the-art anode material for LIBs and is likely to remain so for the foreseeable future. Global production capacity for graphite as an anode active material is heavily centered in China, which has significant natural graphite deposits, resulting in strong supply chain dependencies. Graphite can be produced either from natural sources through mining (natural graphite, NG) or synthetically (synthetic graphite, SG or AG) through high-temperature processes using organic precursors such as tar. Despite its advantages of low cost and good storage capacity, there is an increasing demand for higher energy density and faster charging capabilities, which cannot be easily achieved with graphite or require significant compromises.

Consequently, a major focus of industrial development is the use of silicon-based materials as anode alternatives. Compared to the established graphite production facilities and planned expansions, the development of silicon production as an anode material is on a smaller scale. Currently, silicon is used as an additive to improve graphite-based anodes, but its importance is expected to grow in the future. For high energy LIBs, silicon offers high-capacity and favorable voltage compared to anode materials. However, the main challenges with silicon anodes are its high chemical reactivity with common electrolytes and large volume changes during lithiation and delithiation.

Several start-ups, particularly in the US, are working on novel silicon-based anode materials, some of which may require new manufacturing processes. Improvements in silicon anode applications could lead to higher energy density, higher voltage batteries and reduced dependence on the graphite anode supply chain.

Redox flow batteries

Redox Flow Batteries (RFBs) are emerging as another alternative battery technology for sustainable and cost-effective energy storage, with the potential to integrate seamlessly with the electrical grid and renewable energy sources. RFBs differ from conventional batteries in that they store energy in the electrolyte rather than in the electrode material. With their affordability, reliability and safety in stationary applications, RFBs are now poised to overtake lithium-ion as a major player in renewable energy storage.

Most commercial RFBs use vanadium-based electrolytes, typically a mixture of vanadium sulfate and sulfuric acid. The electrolytes are stored in external tanks that can be as large as shipping containers. During discharge, the electrolytes are pumped across electrodes separated by a membrane. Ions from one electrolyte migrate through the membrane to the other electrolyte, releasing electrical energy in the process. Charging the battery reverses this flow, with ions moving back across the membrane, driven by an external power source.

One of the key advantages of RFBs is their scalability. By increasing the volume of the electrolyte tanks, the energy storage capacity can be easily increased without the need to modify the electrochemical components of the cell. RFBs also have a lower risk of short circuit, thermal runaway and environmental impact due to electrolyte separation and the use of nonflammable materials. In addition, individual components can be selectively replaced. Low cost and flexibility in storing energy makes RFBs well suited for applications that require long discharge times, such as grid-scale energy storage.

Battery research and technology roadmap

Conventional lithium-ion batteries have long been considered a versatile solution for various applications because of their excellent performance. However, with growing concerns about the supply of raw materials, costs and environmental impact, there is now a rising interest in exploring different alternatives for battery materials. While certain battery technologies like lithium manganese iron phosphate (LMFP) or sodium ion batteries (SIBs) are already on the market, others are still in the early stages of research and development.

If the research challenges can be overcome, the cost of these promising next-generation battery types, such as zinc-ion batteries (ZIBs), zinc-air batteries (Zn-Air), or sodium-sulfur batteries (Na-S), can be significantly reduced to as little as half the cost of LIBs. Similarly, aluminum-ion batteries (AIBs), magnesium-ion batteries (MIBs), and lithium-sulfur (Li-S) batteries could also achieve significant cost advantages over LIBs.

Opportunities in battery manufacturing and energy storage

Battery manufacturing has a significant environmental footprint due to the materials used and the complex manufacturing processes and supply chains involved. In many cases, the technologies used to optimize the environmental impact of battery manufacturing are also beneficial for cost optimization. Also, battery recycling, which was not discussed in this article, will play an increasingly important role in sustainability and cost reduction in the future.

The growing focus on alternative battery systems beyond lithium-ion is driven by the fact that relying on a single technology may not be sustainable in the long term. The threat of raw material constraints and the need to address environmental and economic concerns require a more diversified approach to storing energy.

To mitigate risks, reduce costs and improve overall energy storage sustainability, the industry must diversify battery chemistries and technologies. This diversification strategy has the potential to lower supply chain risks, reduce environmental impacts, and optimize the economics of battery manufacturing and recycling processes in the long run.

References

1. IEA Report: Global EV Outlook 2024
2. IEA Report: Batteries and Secure Energy Transitions
3. Fraunhofer-Gesellschaft: Alternative Battery Technologies Roadmap 2030+
4. Fraunhofer-Gesellschaft: Solid-State Battery Roadmap 2035+
5. Nature Communications: Electric vehicle battery chemistry affects supply chain disruption vulnerabilities
6. Volta Foundation, Annual Battery Report 2023

Learn more about CM for Science & Technology

Browse the complete portfolio of products supporting battery research and manufacturing. For more information visit: **thermofisher.com/battery-chemicals**

Contact us for more information on our chemicals for battery applications

thermo scientific