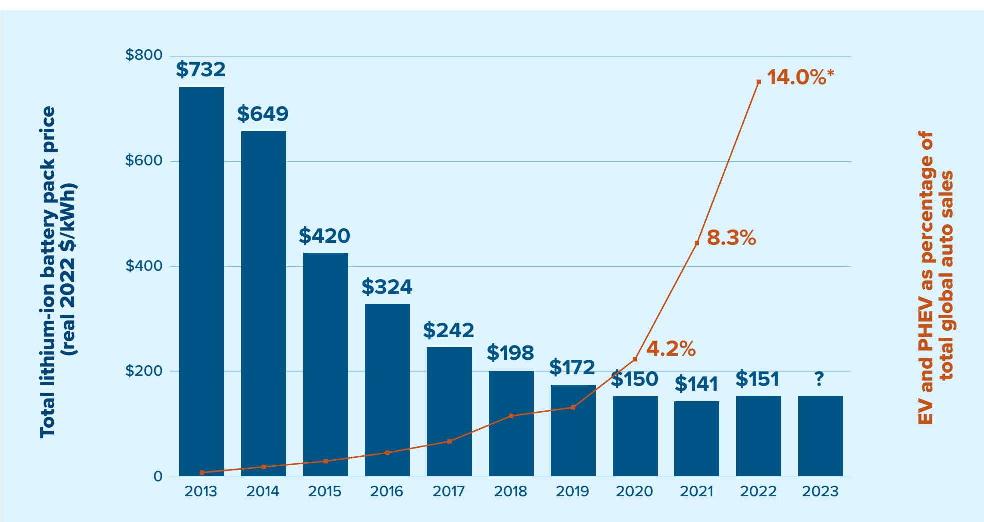
MACKENZIE Investments

The race for a better EV battery

Last year an astonishing 10.5 million electric vehicles (EVs) were sold globally, about 14% of all cars and light duty trucks. Some believe EVs will account for as much as 50% of the market by 2040. There is zero chance we'll meet these targets, however, without better batteries – much better.

First, they will need to cost less. For almost a decade, declining prices were the norm but last year inflation also hit battery manufacturers hard – for the first time in ten years, battery pack prices increased, with average battery pack prices rising from $141 per kilowatt hour (kWh) in 2021 to $151/kWh in 2022. Sector analysts generally agree that, at current gasoline prices, batteries need to cost less than $100/kWh for EVs to be economically competitive with gasoline powered cars. The second improvement needed is battery density, or the maximum driving range for a given battery pack weight. The final challenges are related to charging: safety, speed of charging, and number of charges before functional degradation (currently around 3,000 cycles).

FIGURE 1 – FOLLOWING A DECADE OF BATTERY PRICE DEFLATION, COSTS INCREASED IN 2022



Source: Bloomberg, BNEF Lithium-ion Battery Pack Prices Rise for First Time to an Average of $151/kWh | BloombergNEF (bnef.com). BNEF. Automoblog: The Auto Industry's Big Challenge, January 11, 2023.
* Mackenzie Greenchip estimates for 2022

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Major automobile companies, governments, and investors are all betting that innovation, scaled manufacturing, and new resource mining will improve all these characteristics. To date, engineering batteries has mostly been a game of whack-a-mole. Improving one characteristic, so far, has led to a deleterious effect on others.

Energy dense lithium-ion batteries were invented by Sony in the 1990s. The world has been manufacturing high energy density batteries at scale for decades already. Billions in research has been showered on the space and meaningful breakthroughs have been disappointing. This paper explores technologies that *might* change the game.

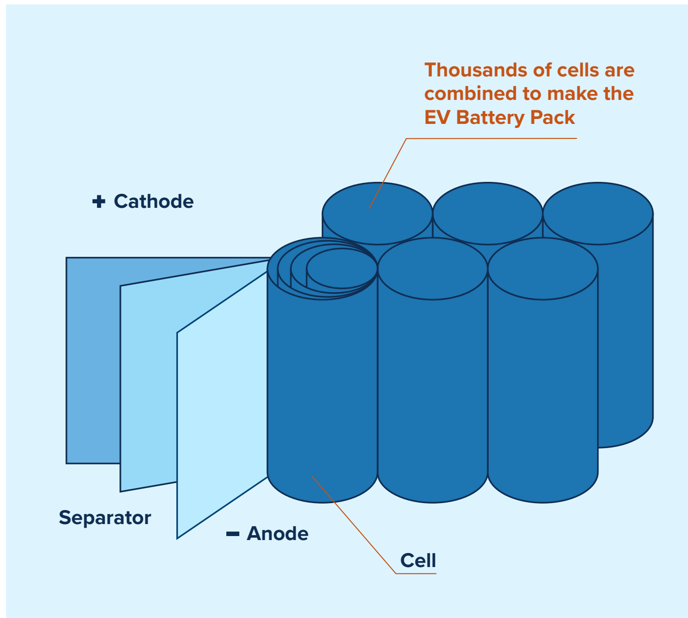
EV Battery Basics

A review of battery structure is necessary to understand the opportunities to make them better. Today's lithium-ion EV batteries are composed of four main parts:

1. **Anode,** usually a current collecting copper foil coated in graphite powder;
2. **Cathode,** a current collecting aluminum foil coated with nickel, manganese, and cobalt oxides (NMC is the most common, though several metallic combinations are used);
3. **Electrolyte** that enables charged particles to flow between the anode and cathode; and
4. **Semi permeable separator** which keeps the anode and cathode from touching.

It is easiest to think of the anode, cathode, and separator as thin sheets or foils that can be rolled, folded, or stacked in "cylindrical" (see Figure 2), "prismatic", or "pouch" shapes respectively. These are then wrapped in a plastic housing which allows a liquid electrolyte to douse the components without leakage. Together it creates a battery "cell". In an EV, these cells are then arranged together to create "modules", and the modules are strung together in series to create a "battery pack". The original 85KW Tesla Model S battery pack contained over 7000 battery cells and weighed 550kg.

FIGURE 2 – PARTS OF A LITHIUM-ION EV BATTERY



Each of these components has its own cost and performance metrics. One of the great challenges of battery design is that increasing the performance of one metric often means sacrificing another. For example, it is possible to get the cost of battery cells down using sodium instead of lithium as the electrolyte. Sodium is much cheaper but three times heavier than lithium.

FIGURE 3 – MACKENZIE GREENCHIP'S BEST ESTIMATE OF BATTERY PERFORMANCE CHARACTERISTICS

Different battery chemistries come with unique attributes. Increasing the performance of one metric often means sacrificing another. Figure 3 and Table 1 represent Mackenzie Greenchip Team's estimates.

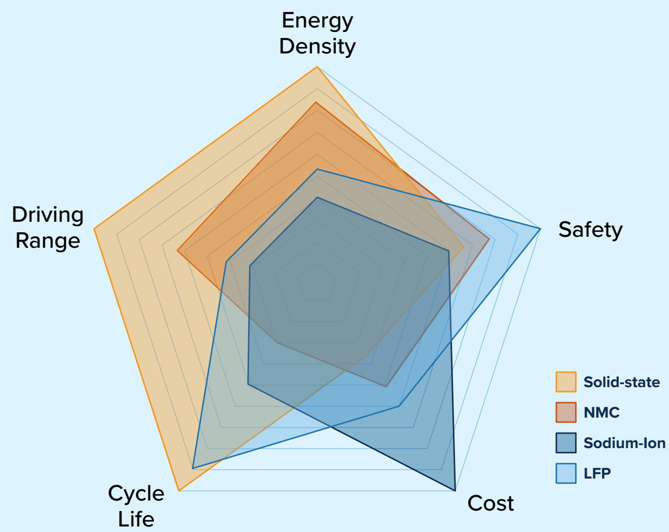


TABLE 1 – MACKENZIE GREENCHIP TEAM'S BEST ESTIMATE OF BATTERY PERFORMANCE CHARACTERISTICS

Performance Metric	Lithium iron phosphate (LFP)	NMC*	Sodium-Ion	Solid-State
Energy Density (Wh/kg)	160	255	120	300
Safety (Thermal Runaway in ^{O}C)	270	210	162	177
Cost ($/kWh)	131	151	77	227
Cycle Life (# Cycles)	9,000	2,500	4,500	10,000
Driving Range (km)	300	450	230	724

* NMC is short for Lithium-Nickel-Manganese-Cobalt-Oxide ($LiNiMnCoO_2$)

Electrode Chemistry

The Cathode

Lithium-ion batteries are traditionally differentiated by their cathode chemistry, as the use of a graphite-based anode is typically universal across conventional lithium-ion battery types. Nickel-rich cathodes, such as NMC and nickel, cobalt, and aluminum (NCA), are the prevailing form of li-ion batteries found in EVs, as they provide higher energy density and longer driving range. However, volatile raw material prices, supply chain constraints, and ESG concerns relating to nickel and cobalt sourcing have led to an uptake in the adoption of lower-cost cathodes, such as lithium iron phosphate (LFP), primarily in shorter-range entry-level EVs.

LFPs outperform NMCs on multiple metrics, including cost, safety, and lifespan. LFPs are around 20-30% cheaper than NMC batteries, owing to the lower raw material costs and abundance of LFP cathode constituents. LFPs also come with increased thermal stability compared to NMC batteries. Theoretically, LFPs can be charged faster and to 100% of their storage capacity. While manufacturers of NMC recommend limiting charging to 80% capacity to reduce performance decay.

LFP-based chemistries already account for about 30% of the market and will dominate the low-cost segment going forward. As manufacturers move towards novel technologies such as cell-to-pack structures, which integrate prismatic battery cells without the use of modules to reduce pack weight, LFPs are becoming more energy dense at the pack level, closing the performance gap with NMC-based chemistries. Led by Tesla, several leading automakers have already shifted to the use of LFPs in their shorter-range vehicles instead of NMCs, including Ford, Volkswagen, and Mustang, while only using NMC batteries for their higher-performance models.

The Anode

As the theoretical performance improvement of nickel-based cathode chemistries plateaus, more research is shifting to the anode. Some companies are adding silicon to graphite-based anodes. Doing so can increase battery energy density and reduce overall cost. Being the second most abundant element in the Earth's crust, surpassed only by oxygen, raw material sourcing for silicon-anode batteries is cheaper and less vulnerable to supply chain disruptions than it is for graphite-based anodes.

The technology has been backed by industry leaders, including Porsche, Mercedes-Benz, and General Motors. Companies like Sila Nanotechnologies, Group 14 Technologies, Wacker Chemie, and Amprius Technologies are developing silicon-based anodes. Claims have been made that the silicon-anode batteries can lower the charge time to between 5 and 10 minutes while increasing battery energy density by 20%. The cost-efficiency, high energy density, and quick charging time of silicon-anode technology could have the potential to transition sectors that have been historically difficult to electrify, such as aviation.

There has been a technical challenge, however, to commercializing anodes with high silicon content. Silicon's capacity to store lithium atoms is so great that the anode physically expands, as much as four times, while charging. Then, during discharge, it contracts back to its original size. Over many cycles, this extreme fluctuation causes the anode to crack, shortening battery life. Currently, silicon is used as an additive to graphite anodes in very small amounts, around 5-10%, to improve energy density while preserving the physical structure of the anode. For example, the first Tesla Model S battery anode was made of 5% silicon. At this point, it seems likely that silicon remains complementary rather than a substitute in battery anodes.

The Electrolyte

Finding an alternative for lithium in the electrolyte is another source of potential cost reduction. Currently, sodium is at the forefront. As the name suggests sodium salts are used in the electrolyte solution instead of lithium. However, they do not seem to require cobalt or nickel in the cathode. And due to the larger atomic size of sodium atoms, hard carbon must be used instead of graphite for the anode.

The competitive advantage of sodium-ion batteries lies mainly in the cost, material sourcing, and safety. They could theoretically cost 10-30% less than even an LFP battery. This is because sodium is far more abundant and can be extracted more easily than lithium. Most estimate we will need nearly 10 times the amount of lithium currently being mined and processed by 2035. Sodium-ion batteries are also potentially safer, having an operating temperature range from minus 30 degrees to plus 60 degrees Celsius, significantly better than lithium.

The drawback to sodium-ion chemistry is the lower energy density. According to Wood Mackenzie, sodium batteries averaged 230 km compared to 450 km and 300 km for similar sized NMC and LFP batteries, respectively. We anticipate sodium-ion will primarily be used for energy grid storage and shorter-range EV applications. Bloomberg New Energy Finance predicts sodium ion batteries will account for less than 5% of the EV market by 2035. Recently, the world's biggest EV battery manufacturer, CATL (Contemporary Amperex Technology Co. Limited), announced plans to create mixed battery packs that combine sodium and lithium cells in the same EV. These mixed packs provide the extended temperature range and cost benefits of sodium batteries while maintaining the longer range offered by lithium cells.

The Game Changer — Solid State

Solid-state batteries use a solid electrolyte made of mostly of ceramic which also acts as the separator. The anode is also different. Rather than a graphite and/or silicon anode, in a wonderous act of chemistry the anode builds itself as a layer of lithium metal during charging. The cell saves the weight of a liquid solvent and a traditional anode and allows for a smaller overall design. Theoretically, solid-state improves energy density, charge times, safety, and lifespan of EV batteries. They could be the game changer.

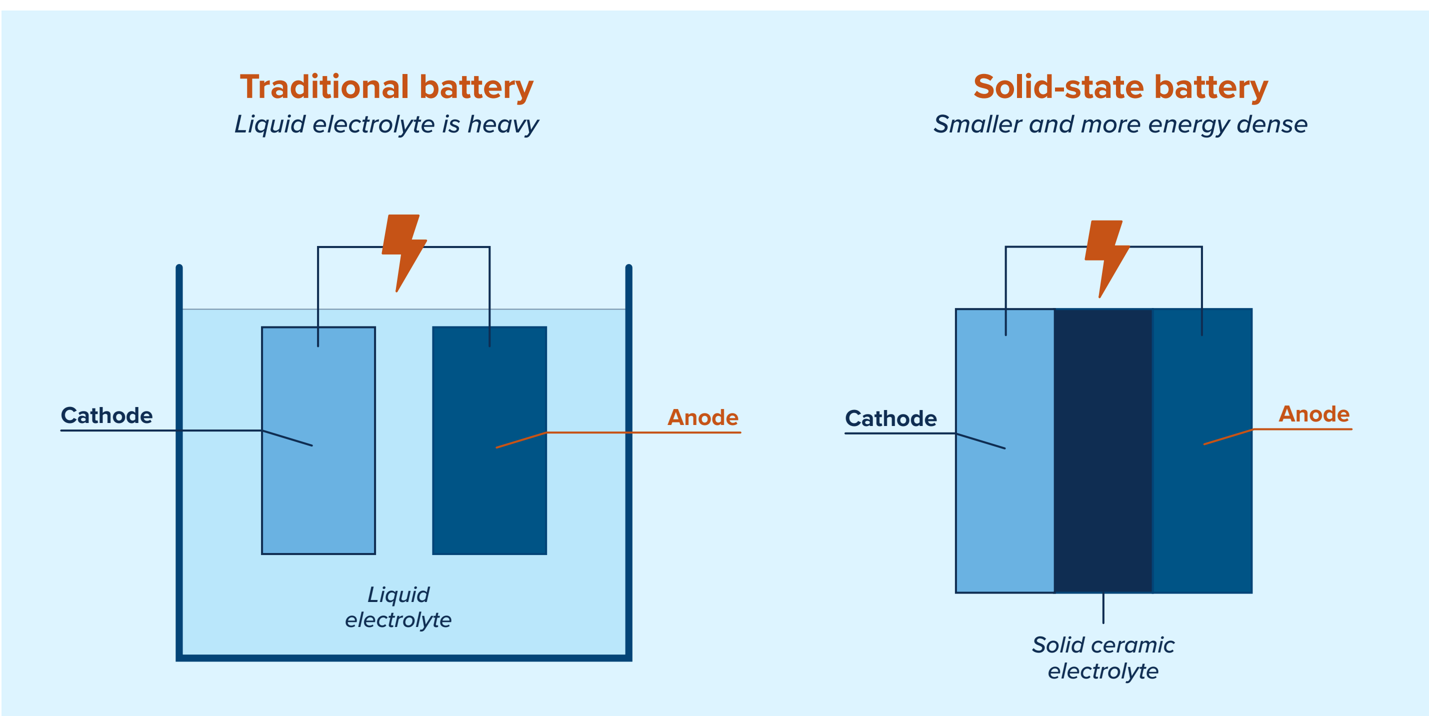
In late June, Toyota announced they will have EVs for sale, powered entirely by solid-state batteries by 2027. They claim their solid-state EVs will have a range of 1,200 kilometers and can be fast-charged in about 10 minutes. There is reason, however, to be skeptical of this delivery date. In 2017 and again in 2021, Toyota announced they would use solid-state in their hybrids by 2025. So, the delivery has already been pushed once. Toyota is not alone; several auto OEMs (original equipment manufacturers) and battery companies have solid-state batteries in development. Nissan has claimed a 2028 launch date. Last year, Dongfeng Motor Corporation of China put fifty solid-state powered cars on the road to great fanfare. But there was no disclosure on cost, nor have there been any news updates since.

Outside of cost, technical challenges have also plagued commercialization including micro-cracking in the ceramic separators, poor interfacial contacts between the electrodes and the electrolyte, and crystalline formations called dendrites that can destroy the cell, to name just a few. Rarely mentioned is that solid-state need as much as 35% more lithium than NMC and LFP.

Solid-state manufacturers have largely disappointed early investors. QuantumScape may be the best example. The company had early private backing from heavyweights like Bill Gates and Jeremy Grantham. It went public in November 2020 and the stock quickly rose to a $30 billion USD—today QuantumScape trades with a market capitalization of less than $4 billion. It is still years away from having a product to sell. Another listed solid-state company, Solid Power, despite partnerships with Ford and BMW has seen its share price decline about 60% in the past two years.

We suspect manufacturers will overcome most of the technical challenges, but manufacturing solid-state batteries at scale and remaining *economically* competitive is less certain to us.

FIGURE 4 – TRADITIONAL BATTERY VS SOLID-STATE BATTERY



Why manufacturing is an unlikely source of economic improvement

EV battery manufacturing looks nothing like traditional auto assembly. Imagine instead the dust-free highly automated environment of an advanced semiconductor fabrication plant, whirring robotics flipping thin sheets of metals, polymer films spooling at high speeds into cylindrical form factors, and so on. It's the type of scaled manufacturing we associate with lower costs and Asian countries are really good at it.

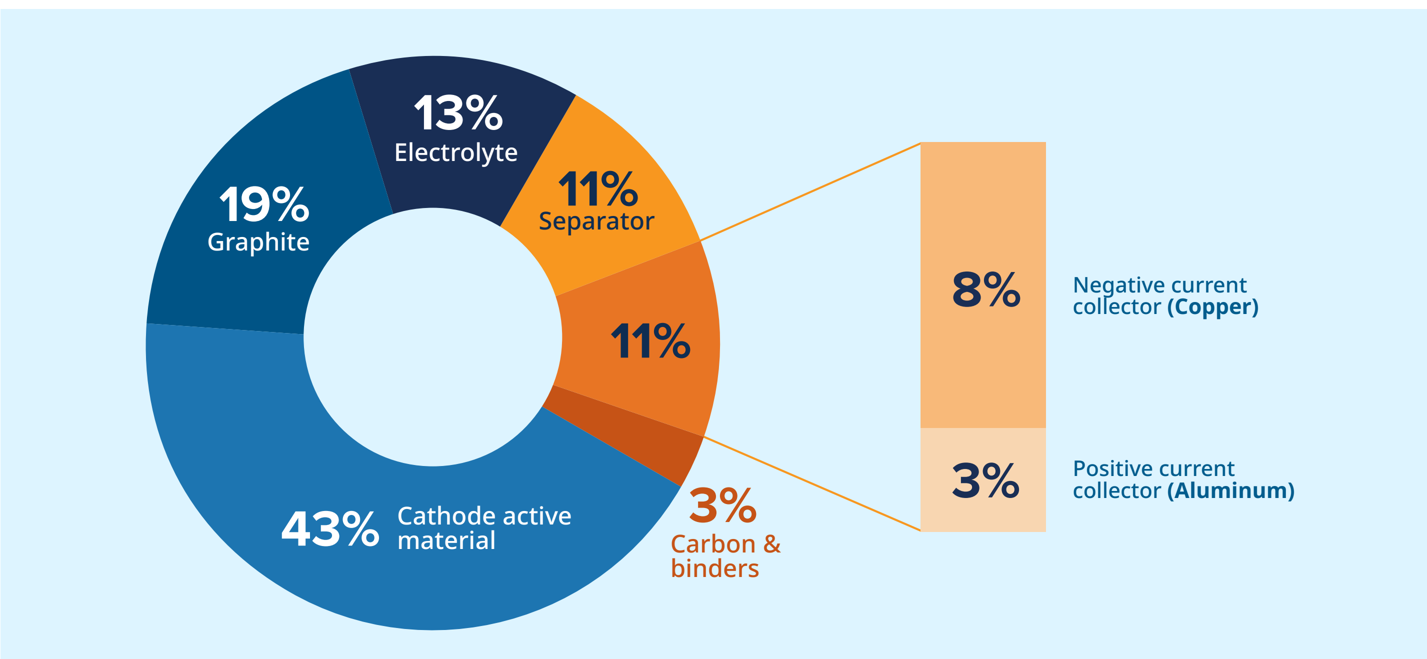
Despite the massive investment Western governments are making in battery manufacturing plants, the Asian manufacturing advantage seems unlikely to dissipate. Japan and Korea are major players, while China manufactures 66% of all batteries sold. The New York Times recently published figures of Chinese market share dominance: 77% of cathodes manufactured, 74% of separators, 82% of electrolytes, and 92% of anodes.

Perhaps more challenging for the West is that China alone controls between 60% and 95% of manganese, cobalt, graphite, lithium, and nickel - all key materials for battery production. Outside of thoughtful long-term industrial policy, there is a more obvious reason—China simply does it cheaper. In recent meetings with lithium miners Albemarle and Livent, management told us it is 3-6 times less expensive to process lithium concentrate to battery grade hydroxide or carbonate in China than North America!

Shifting more manufacturing to the West may create some geopolitical stability, but it likely moves us further away from the proverbial $100/kWh tipping point.

> **The US is building the equivalent of one gigafactory every four months, while China is building the equivalent of one every week.**
>
> ***Simon Moores,***
> *Managing Director*
> *Benchmark Mineral Intelligence*

FIGURE 5 – LITHIUM-ION BATTERY CELL COST BREAKDOWN BY COMPONENT



Source: The University of Warwick Automotive Lithium-ion Battery Recycling in the UK, September 2020

TABLE 2 – SELECTED PARTNERSHIPS BETWEEN BATTERY MAKERS AND AUTOMAKERS IN NORTH AMERICA

Battery maker	Automaker	Battery manufacturing capacity (GWh)
LG Energy Solution	GM	135
	Stellantis	45
	Honda	40
	Hyundai	30
Panasonic	Tesla	137
SK ON	Ford	129
	Hyundai	35
Samsung SDI	Stellantis	33
	GM	30
CATL	Ford	35

Source: BloombergNEF. Note: Capacity includes fully commissioned, under construction and announced battery plants

Why battery investment is so tricky

The world has been manufacturing high energy density batteries for 30 years and yet it is still far from clear which countries, companies, chemistries, form factors, manufacturing processes, supply chains, and so on will win the global battery race.

The trifecta in horse racing is a one wager bet on which of eight horses will finish first, second and third. The payouts are always compelling but with 336 possible outcomes, picking the right three horses, in the right order, is a colossal long shot.

It is a useful analogy for battery investing. The sheer scale of the global EV opportunity could produce lovely returns for those that pick the right horses. Yet this is not a race with just eight horses, there are hundreds of them, most of which are already trading at winning valuations. The odds are not good!

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