

Title

A comprehensive overview of global start-ups and their innovations for lithium-ion batteries

Abstract

Research in the field of **lithium-ion batteries (LIB)** is currently being driven not only by academia, but also by many **start-ups**, most of which were founded directly as spin-offs from universities or research laboratories [1]. It is difficult to keep track of all these global activities in this area.

We provide a comprehensive, technology-oriented, and **manufacturer-independent** overview of new LIB technologies currently being developed by start-ups. We also examine cooperations with car manufacturers, which aim to gain early access to these LIB innovations.

With our background in the automotive industry, we share a more application-oriented view of the LIB research landscape. Therefore, our overview will not address basic research for LIBs being conducted worldwide in academia.

Nevertheless, we hope that this publication will help to better interconnect start-ups as LIB providers with LIB users such as automotive and eVTOL companies, thereby contributing to combating climate change.

1. Introduction

Unlike a few decades ago, suitable LIB technologies for electric vehicles (EVs) are nowadays available. In 2024, more than 17 million EVs (BEV + PHEV) were produced worldwide [2], indicating that LIB production has become an established industry.

Off course every LIB innovation must compete with the established technologies. Like in the **internal combustion engine (ICE)** world with its dominating Otto and Diesel engines, two LIB variants have prevailed in the EV world:

- With its high-energy density, **NMC** (Nickel-Manganese-Cobalt) batteries in a way play the role of the **Otto** engine being used in medium, premium, sports cars and small planes.
- Due to their robustness and lower price, **LFP** (Lithium Iron Phosphate) batteries are ideal for entry cars, trucks, buses, boats and stationary applications such as ESS (energy storage systems), comparable to the **Diesel** engine in the ICE world.

According to the International Energy Agency (IEA), the global market share of both cell types in the EV battery sector was 50% each in 2024, with LFP dominating in China and NMC in Europe and the US [3].

For a deeper dive into technologies and figures of both cell variants, we refer to a highly regarded RWTH Aachen publication [4].

A Tesla 4680 cell and a BYD Blade were analyzed as representatives for each cell type. In particular, key figures such as the **gravimetric energy density** have been measured which will

serve as reference values in this paper: The **NMC round cell** from Tesla had an energy density of **241 Wh/kg**, the **prismatic LFP cell** from BYD **160 Wh/kg**.

2. Research landscape shaped by LIB start-ups

The LIB research landscape shaped by start-ups can be classified and structured in various ways and dimensions. For our review, we use a rather simple two-dimensional approach, as depicted in Figure 1.

The **first, horizontal dimension** relates to the **research scope**, which can be mapped to the **upper** or **lower end** of the LIB performance scale:

- Research at the upper end addresses further increase of main LIB performance indices such as **energy density** and **fast-charging capability** or **safety**.
- Work at the **lower end** is mainly focused on **cost reduction**.

The **second, vertical dimension** relates to compatibility with established LIB **production technologies**.

We believe that this is a very important category as high-volume lithium-ion cell production is **extremely complex**. Like at a modern pentathlon at the Olympics, different types of production disciplines – slurry mixing, coating, automated montage, etc. – must be mastered to win the race to an effective and efficient cell production [5].

The development and operation of production lines for lithium-ion cells require lengthy trial-and-error phases and raise high costs. The bankruptcy of the Swedish start-up Northvolt dramatically illustrates how challenging it is to enter the EV LIB mass market as a newcomer.

LIB innovations that are **compatible** with established production technologies therefore have a big advantage; we call them **evolutionary approaches**. In general, these innovations aim for small improvements of the key cell performance parameters.

In contrast, **revolutionary approaches** strive for the “big leap,” which, however, require new production technologies.

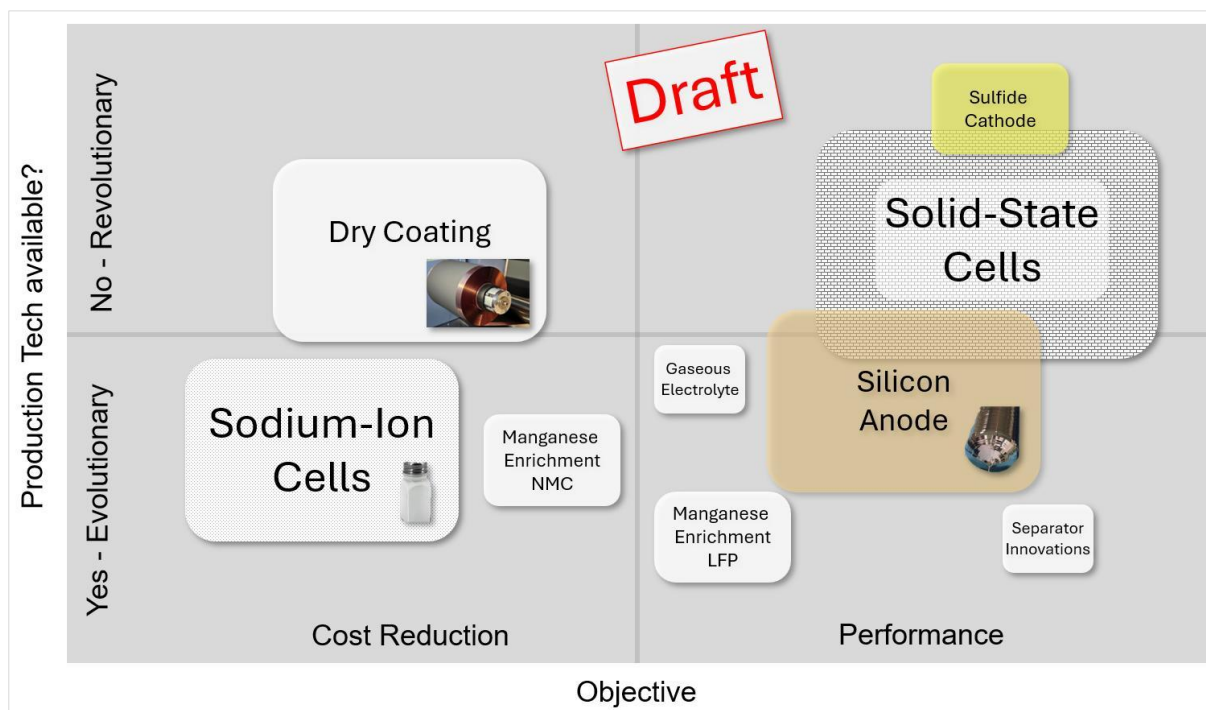


Fig. 1 – Research landscape lithium-ion batteries

Figure 1 shows the research landscape shaped by start-ups and established LIB manufacturers with the main technology fields mapped to our two-dimensional classification system. The font size reflects the relevance of the field, which, in our case, also corresponds to the number of start-ups active in this area.

To reduce the effort, we limit our review focus on the **two performance domains** - on the right-hand side in Figure 1 - with even more than 30 start-ups being active.

The most important technology field in the revolutionary performance domain is “Solid-State Cells,” in which more than a dozen start-ups are involved. In the evolutionary domain, it is the “Silicon Anode,” where we have identified eleven start-ups.

Main technology fields in the **cost reduction domains** are “Sodium-Ion Cells” and “Dry Coating”.

Some members of the LIB research community are extremely optimistic concerning the future of sodium-based batteries. For example, Markus Lienkamp from TU München assumes, that LFP batteries will be partly replaced by sodium batteries if the research can keep pace [6].

3. Evolutionary approaches

All components of the Li-ion cell, the electrodes, the separator, and the electrolyte, are subject to evolutionary innovations.

In the case of electrodes, the focus over the past years has been primarily on the **cathode**. The nickel content of the NMC cathode has been continuously increased to boost energy density and reduce the proportion of the critical raw material cobalt. Now that a certain saturation point

has been reached in terms of cathode innovations with the NMC mixing ratio of 811, the focus is shifting a bit more toward improving the **anode**.

3.1 Anode innovations

On the anode side, **silicon enrichment** of carbon compound is a prominent evolutionary approach to increase the ion capacity. Silicon can absorb 10 times the amount of lithium ions compared to graphite but swells up to 3 times its size when absorbing ions.

Severe swelling can lead to cracks in the anode and thus to the loss of active material, resulting in a reduction in cell capacity.

That's why so far only cells with moderately silicon-doped anodes have already found their way into series-production vehicles, for example into the electric Mercedes-Benz G model [7].

Asian suppliers dominate the market for silicon-doped anode material. Chinese companies **BTR** [8] and **Shanshan** [9], for example, supply LG Energy Solution and Samsung SDI, while South Korean company **Daejoo Electronics** [10] supplies material to CATL and SK On. Here, the silicon content is limited to 10% due to swelling issues.

Higher silicon doping fails due to excessive expansion of silicon anodes during charging. This is where many start-ups come into play.

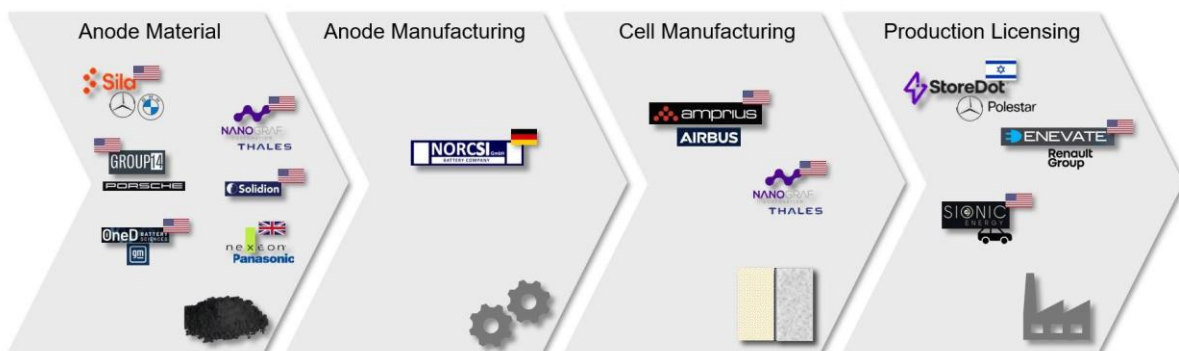


Fig. 2 – Start-ups for silicon anodes¹

Fig. 2 shows the main start-ups for silicon anodes and their position in the value chain. Business relations with car manufacturers or aerospace companies are also listed.

It is immediately obvious that

- most start-ups are active in materials production,
- only two start-ups are active in cell production, whereas
- three start-ups prefer to license their technology instead of setting up their own production lines.

¹ Start-ups developing solid-state cells with silicon anodes are listed in Fig. 3.

It is also notable that most start-ups have been founded in the US. Of course, silicon anodes could pave a way to reduce US's dependence on China for graphite anodes. However, under the Trump/Vance administration, it is less likely that for green technologies get federal support.

Amprius [11] supplies cells with anodes made of **100% silicon** to aerospace and defense companies. The anode consists of vertically aligned silicon nanowires that are directly grown onto a conductive substrate. According to Amprius, the cells have an energy density of up to **450 Wh/kg**.

They are manufactured using chemical vapor deposition (CVD), which allows precise control over the length, density, and uniformity of the nanowires. Of course, this process is more expensive and time-consuming than conventional foil coating, making it unsuitable for high volume low-cost automotive applications.

Other candidates producing cells with high silicon content include US start-ups **Enevate** [12] and **Sionic** [13] and Israeli company **StoreDot** [14]. It is perhaps worth mentioning that one of the three LIB Nobel Prize winners—John B. Goodenough—was a member of the Enevate advisory board.

The companies have in common that they are limiting themselves to the manufacturing of sample cells, with the aim of generating most of their revenue from **licensing** their technology. They all emphasize the fast-charging properties of their cells and are targeting the automotive industry with support from OEMs such as Renault and Mercedes-Benz.

They differ with respect to their technologies:

- Enevate approach is based on a porous, monolithic silicon film which is applied directly onto copper foil without the use of polymer binders or conventional silicon powders. A thin nanometer-scale coating (e.g., silicon carbide) protects the silicon surface from electrolyte reactions. They claim that their so-called Gen-4 XFC-Energy® cell reaches around **340 Wh/kg**.
- Sionic has developed a silicon anode cell platform based on Group 14 anode material (see below). According to the company, energy densities of up to **340 Wh/kg** are possible.
- StoreDots technology is based on one dimensional silicon nanoparticles or dots, which relates to the company's name. The company reports an energy density of **330 Wh/kg** for its current fast-charging cells.

Further start-ups betting on silicon nanoparticles is the US-based companies **Group14 Technology** [15], **Sila Nano** [16], **OneD Battery Science** [17], and the British **Nexion** [18]. These start-ups are located at earlier stages of the cell value chain as they produce anode materials, but no cells. They all have business relations with the automotive industry:

- Most prominent investors of Group14 are Microsoft and Porsche, the Swabian sports cars producer is also technology customer.
- Sila partners with Mercedes-Benz and BMW, Panasonic is a further user of Sila's anode material.
- GM venture is an investor of OneD.

- Nexion does not name its OEM partner; however, they signed a long-term supply agreement with Panasonic, starting around 2025 at Panasonic's Kansas plant.

The US start-up **Nanograf** [19] uses a hybrid business model. The company produces both silicon-based anode material and round cells in 18650 formats with the French defense company Thales as customer.

US start-up **Solidion** [20] emphasizes its sustainable approach for producing its cell materials, which includes silicon-enriched anode materials. Solidion has developed a process technology that allows for cost-effective production of anode-grade graphite from sustainable sources, such as biomass and recycled materials.

A very recent founding is the German **Norcsi** [21], which is holding patents on a very specific technology to produce silicon-based anodes.

The method is based on flash lamp annealing (FLA). Conventional copper carrier films are coated with a thin layer of pure silicon. A high-power flash lamp is then used to create a unique nanostructure that interconnects copper and silicon by dendrites and produces microscopic perforations and voids in the silicon layer.

According to German start-up, the surface of the anode remains planar and can therefore easily be sealed. All known problems of pure silicon anodes such as volume expansion, contact loss and solid-electrolyte interface phase are minimized according to Norcsi.

3.2 Cathode innovations

On the cathode side, evolutionary LIB innovations are mostly based on the adaptation of the cell chemistries standards NMC and LFP. A huge number of cathode chemistry variants for LIBs have been investigated during the last decades by academia. However, only a few could be industrialized so far.

Having a more industrial and application-oriented viewpoint, we will not cover the complete cell chemistry landscape here. Instead, we refer to already existing review papers, e.g. the "Mini Summary" from Canadian Energy, Mining and Environment Research Centre [22].

A very promising approach for cathode improvement is based on the element **manganese**. Interestingly, this approach works for both cell standards NMC und LFP.

In **NMC cathodes**, the **increase** of manganese would reduce the cost-intensive raw material nickel and even eliminate cobalt. Both materials are partly mined under harsh environmental and working conditions in countries with low social standards, so finding a substitute or reducing the use of these raw materials is in everyone's best interest.

The various chemical manganese variants are all grouped under the abbreviation LMR (Lithium- and Manganese-Rich). LMR compounds differ in terms of the ratio of nickel, cobalt, and manganese (Ni/Co/Mn), the use of dopants (e.g., Al, Ti, Fe), and structural modifications that affect capacity, stability, and oxygen release.

For **LFP cathodes**, the main purpose of adding manganese is to increase the energy density up to 20%. The energy density of current LFP cells is typically around **160 Wh/kg**, with manganese compounds expected to achieve up to **210 Wh/kg**.

Overall, manganese doping offers a path to bridge the gap between LFP's safety and NMC's performance, but it's not yet widely adopted at scale.

However, first suppliers for LMFP cathode materials appear on the market, e.g. HCM from Taiwan [23]. The first production line was launched in 2016 and a production line for mass production has been in operation since 2024. HCM is now looking for cell manufacturers who would like to get involved in LMPF cell production.

OEMs such as **GM** [24] and **VW** [25] are investing in manganese-rich chemistries as part of their battery platforms, seeking to minimize dependence on cobalt and improve supply chain resilience.

3.3 Electrolyte innovations

While the current trend in lithium-ion battery research is moving from liquid to solid electrolytes (see also 4.1 Solid-state batteries), US-based start-up **South8** [26] is pursuing a unique approach by developing a lithium-ion cell with a gaseous electrolyte. The start-up claims that its round cells have an extremely wide temperature range from -60 °C to +60 °C.

South8 produces cells with state-of-the-art cell chemistry for the anode (Graphite) and the cathode (NMC). They are also aiming for higher energy and higher power cells with up to **330 Wh/kg** on the base of a cobalt-free LNMO spinel cathodes.

Target markets are defense, aerospace, and automotive.

3.4 Separator innovations

The safety of lithium-ion batteries is heavily influenced by the separator, a thin, porous layer that keeps the anode and cathode apart while allowing lithium ions to flow. While conventional separators are often made of porous polyolefin films, a few start-ups are working on innovative materials and designs to improve cell safety.

The US-based start-up **24M** [27], a MIT spin-off, is best known for its SemiSolid™ electrode technology.

In addition to this, the company has developed a new separator which aims to improve the battery's thermal stability and safety from within. The separator contains a conductive layer sandwiched between two insulating layers, which acts as an embedded sensor. This allows it to continuously monitor the electrical properties within the cell.

When it detects an impending issue, such as the initial growth of metallic dendrites, it sends an electrical data signal to the Battery Management System (BMS). The BMS can then safely discharge or shut down the individual cell, actively preventing a short circuit and a potential thermal runaway. This allows for a proactive safety measure, addressing problems before they escalate.

However, the increased safety requires additional wiring in the HV battery and adjustments to the BMS software. According to 24M, its separator technology can be used in conventional Li-ion cells and lithium metal cells.

The US company **Soteria** [28] is not a classical startup, but rather an advanced technology development and licensing company that operates as a global consortium of over 100 companies.

Their innovation consists of a combination of two key technologies: a thermally stable separator and a new type of current collector. Soteria's separator is a non-woven material reinforced with heat-resistant fibers, such as aramid. This prevents the separator from shrinking during an internal short circuit, which would allow the cathode and anode to come into direct contact. The corresponding current collector, which replaces conventional copper and aluminum foils, is a polymer-coated foil with an extremely thin metal layer. In the event of a short circuit, this thin metal layer melts like a fuse, interrupting the current flow at the point of failure and preventing further energy from feeding the short and causing a fire.

While the technology is being evaluated by major partners like Mercedes-Benz for future use, it has already begun to find practical applications. Soteria has actively pursued commercialization by acquiring **Voltaplex**, a company that designs and manufactures custom battery packs. This has allowed Soteria to bring its patented technologies to market directly, with a current focus on e-bike batteries and other small devices.

4. Revolutionary approaches

Revolutionary approaches strive for the “big leap,” in LIB technology. Unfortunately, they still struggle with non-existing high volume and highly efficient production technologies.

Many revolutionary approaches seek for the “holy grail” of battery research, the **solid-state batteries (SSB)**. Here, the fluid electrolyte is replaced by a solid material substituting the liquid as an ion conductor.

A few start-ups are sticking with liquid electrolytes but reinventing the electrodes of Li-ion cells, e.g., by using a sulfur-based cathode.

4.1 Solid-state batteries

SSB can be considered as a quantum leap in LIB technology. Like standard Li-ion batteries, they consist of three main components anode, cathode, and electrolyte that enables lithium-ion transport. However, unlike traditional Li-ion cells, which use a liquid electrolyte, solid-state batteries employ a **solid electrolyte**.

In conventional Li-ion cells, the liquid electrolyte and the porous separator are two separate components, whereas in solid-state batteries, these two functions are combined into one material: the **solid electrolyte**. It simultaneously conducts lithium ions and physically separates the electrodes.

By merging separator and electrolyte into a single component, SSBs promise a **higher gravimetric energy density** (400–500 Wh/kg) with an **increased safety** as no flammable liquids exists at a **lower price** (<100\$ per kWh), at least in the long run.

Due to its strategic importance, China has launched a highly regarded national SSB research initiative which is also integrated into China's 14th Five-Year Plan. Key participants include state-owned research institutes, universities, and leading battery manufacturers such as CATL, BYD,

and CALB, which are actively building pilot production lines. These efforts are aiming to commercialize solid-state batteries in electric vehicles (EVs) by the late 2020s.

One of the biggest challenges with SSBs is maintaining **good contact** between the cell layers: the anode, the electrolyte/separator, and the cathode. Even the smallest gap between the cell components can significantly reduce the ion conductivity.

High pressure is one solution to reach for a good contact and ion conductivity at the cell-internal interfaces. Alternative approaches use **semi-solid** or **gel-like** electrolytes.

A wide variety of SSB cell variants have been investigated in academic research, a nice overview is given by Sen and Richter [29].

The authors use a triangle to structure the SSB landscape, where each corner stands for a dedicated electrolyte type. The upper corner represents cells with **inorganic solid electrolytes**, the lower right corner cells with **organic solid electrolytes** and the lower left corner for state-of-the-art cells with **liquid electrolytes**.

What we like about this graphical representation is that hybrid approaches like semi-solid cells can easily be depicted in areas in-between two corners.

What we don't like about the electrolyte triangle is that it does not help to structure the SSB start-ups according to further criteria such as maturity or cathode type.

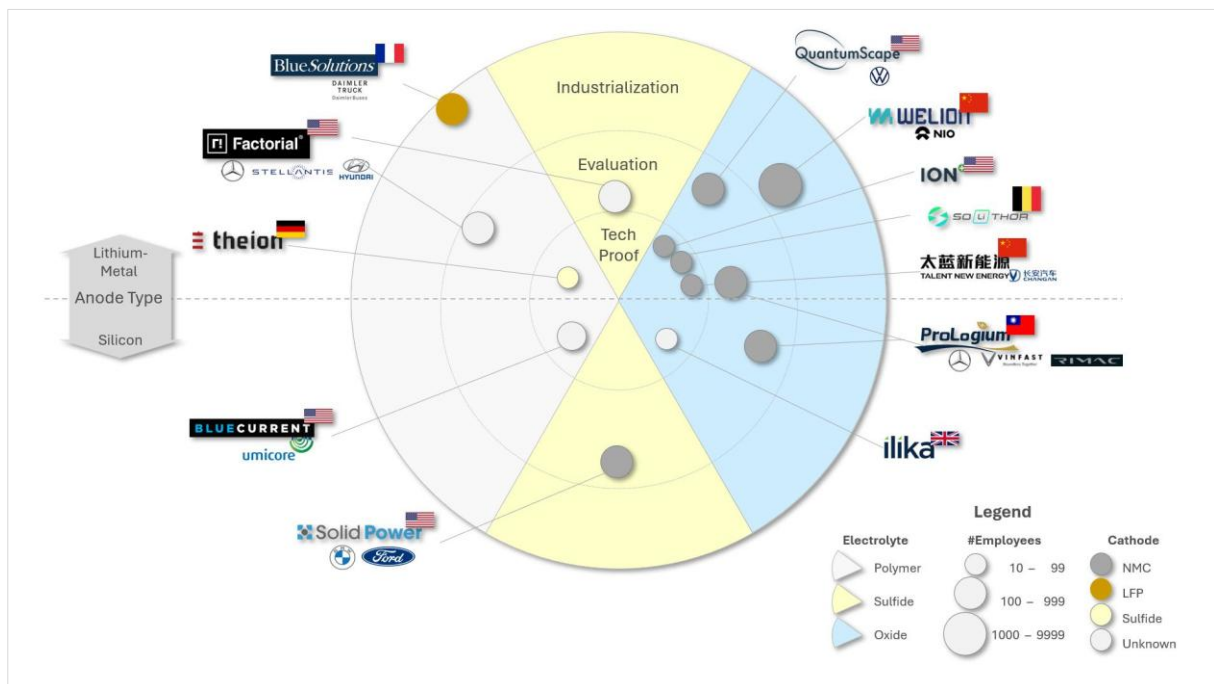


Fig. 3 – Start-ups for Solid-State Batteries

Figure 3 shows our approach to illustrate the SSB landscape. Our “SSB cosmos” does not only the electrolyte variant but also the electrode types, company size, and maturity of the technology in a single graphical representation.

Many facts about the start-ups landscape are immediately apparent from Figure 3:

- Even though SSBs are in general associated with lithium metal anodes, some companies still prefer a silicon anode.
- Most start-ups use a standard NMC cathode.
- Only two companies have already reached the industrialization phase.
- Many newly founded SSB start-ups are based in the US, which could be a disadvantage in terms of national financing opportunities given the current political situation.

4.1.1 Organic solid-state electrolytes

The only organic solid-state electrolytes that have been used industrially to date are polymer-based electrolytes.

4.1.1.1 SSB start-ups with polymer-based electrolytes

Polymer-based SSBs in general require a higher temperature than room temperature to achieve good ion conductivity, they are the first SSB type already industrialized on a large scale.

The French company **Blue Solution** [30] was one of the earliest manufacturers which successfully commercialized SSBs in large scale. The company produces cells in pouch format as well as its own modules with integrated cells.

The anode consists of a lithium metal foil, the cathode uses LFP chemistry. A solid lithium polymer compound is used as the electrolyte, which must be heated to a temperature of 50-80 degrees for a good ion conductivity.

So far Blue Solutions only markets its **cell modules** with a corresponding heating device, i.e. not individual cells. The volumetric energy density at module level was 255 Wh/l in 2022 and is to be increased to 290 Wh/l by 2025.

Unfortunately, the French company does not publish gravimetric energy-density data for its existing solid-state cells and modules. However, for their next-generation GEN4 SSBs, they target over **450 Wh/kg** for cells with NMC cathodes and over **350 Wh/kg** for those with LMFP/LFP cathodes.

Industrial production of GEN4 is scheduled for around 2030.

Daimler Buses GmbH was one of the first customers in the automotive sector but changed suppliers and stepped back into an NMC-based LIB with liquid electrolyte. According to unconfirmed sources, Blue Solutions is also in contact with **VW**.

Further companies betting on polymer-based SSBs are **Factorial Energy** [31], **BlueCurent** [32] and **Theion** [33].

Among these three candidates, the US start-up Factorial is most advanced in terms of automotive applications, as it is supported by **Mercedes-Benz**, **Stellantis**, and **Hyundai**.

The automotive-sized solid-state pouch cells for Stellantis have been validated at **375 Wh/kg**, with over 600 cycles.

The Swabian manufacturer Mercedes-Benz recently unveiled a research vehicle based on the EQS model, equipped with an SSB based B-sample cells in pouch format. The prototype cells use a quasi-solid electrolyte and a lithium metal anode, and probably a standard NMC cathode, which, however, has not been disclosed by the start-up.

The research vehicle is equipped with a **pneumatic pressure system** for the SSB packs, so the cells operate under higher outside pressure. This is required for maintaining the surface contact inside the cell and the avoidance of dendrites growing in the anode. According to Mercedes the cell breathing – the expanding during charging – could be reduced to 10-15%, of course also with the help of the pressure system [34].

During the International Motor Show in Munich (IAA), Mercedes announced that the EQS had been driven from Stuttgart to Malmö without recharging. After covering 1,205 km, the battery still had enough capacity left for another 137 km.

The US start-up **BlueCurrent** uses a polymer-ceramic composite as a solid electrolyte and a silicon anode. The exact composition of Blue Current's ceramic component has not been disclosed; however, available patent information suggests that it may be based on sulfide-type conductors such as argyrodites, although this cannot be confirmed.

The polymers also limit the swelling of the anode, allowing the silicon particles to circulate at low pressure without expanding dramatically. The US start-up claims to achieve an energy density of up to **450 Wh/kg**.

Blue Current is backed by **Umicore**, a leading global supplier of battery materials, through both investment and a joint development agreement. So far, we are not aware of any collaborations in the automotive sector, although the US start-up plans to tap into this market.

The German start-up **Theion** focuses on a solid-state battery with a polymer-based solid electrolyte and a sulfur cathode. The company targets an energy density of up to **500 Wh/kg** for its GEN2 cells.

This approach, however, requires entirely new production technologies and significant investment for mass production. The start-up has developed a patented process called direct crystal imprinting (DCi). This method forgoes traditional, energy-intensive techniques like slurry coating and instead uses molten sulfur to create a pure sulfur wafer structure in seconds.

According to Theion, this technology is not only faster and more cost-effective but also enables the production of cathodes in any desired geometric shape. By precisely controlling the sulfur crystal structure, the battery's cycle life is also improved, which has been a critical issue with sulfur cathodes.

4.1.2 SSB start-ups with inorganic electrolytes

SSBs with inorganic electrolytes are in general based on **sulfate-** or **oxide** compounds.

China's solid-state battery initiative mentioned above strongly emphasizes **sulfide-based electrolytes** as the main route toward industrialization, due to their high ionic conductivity and scalability. However, the program does not exclude other approaches.

4.1.2.1 SSB start-ups with sulfide-based electrolytes

The two leading start-ups developing SSBs based on sulfide-based electrolytes are the US companies **Factorial Energy** and **Solid Power** [35].

Factorial uses a dual electrolyte strategy, as it also employs polymer-based electrolytes (see also 4.1.2).

The start-up claims that its sulfide-based SSB achieves an energy density of **450 Wh/kg**, which is more than the **375 Wh/kg** of polymer-based SSBs. However, Factorial's sulfide-based SSBs lag behind polymer-based ones in terms of maturity, the latter having already been tested in research vehicles such as the Mercedes EQS.

Solid Power is supported by **BMW**, **Ford**, and **Stellantis**. The start-up uses a silicon-based anode and a standard NMC cathode in its SSB cell, which has an energy density of up to **390 Wh/kg**.

BMW has already licensed the production technology and is setting up a prototype production line at its Cell Manufacturing Competence Center (CMCC) in Parsdorf, Germany.

In May 2025, BMW began testing Solid Power SSB cells in a BMW i7 test vehicle. Like in the Mercedes EQS, new approaches for managing cell behavior, including expansion control and pressure regulation are investigated.

A further US start-up betting on sulfide-based electrolytes is **Adden Energy** [36]. Compared to Factorial and Solid Power, this company is younger and smaller; we are also not aware of any collaboration in the automotive sector to date.

Adden Energy's core technology was developed at Harvard University. Lithium metal is used for the anode; the critical problem of dendrite growth is controlled by a porous 3D scaffold anode and a special layer design.

The cathode is based on standard high-nickel NMC chemistry.

A solid electrolyte with a patented **self-healing separator** based on the phenomenon of "dynamic stability" is used to ensure the stability of the interfaces. The company has not yet officially confirmed the exact composition, but some sources describe the electrolyte as sulfide-based ceramic.

The company reports achieving energy densities above **500 Wh/kg** at the cell level, according to recent press materials. These figures are based on prototype or early-development data rather than validated large-scale production results.

They also claim extremely fast charging times and a long lifespan of up to 10,000 cycles.

4.1.2.2 SSB start-ups with Oxide-based electrolytes

The leading start-ups focusing on oxide-based electrolytes are **QuantumScape** [37], **ProLogium** [38] and **WeLion** [39]. All three companies are backed by car manufacturers and have already succeeded in setting up production lines for small series of cells.

QuantumScape is supported by Volkswagen, cell samples have already been delivered to the German OEM.

The US start-up uses an **oxide ceramic separator** made of lithium-filled garnet materials (LLZO garnet oxides) and a lithium metal anode. For its current SSB generation QSE-5, QuantumScape reports an energy density of about **301 Wh/kg**.

This ceramic separator is combined with an **organic liquid catholyte** and an NMC cathode to ensure optimal ion flow between the cathode and the solid separator. In other words, QuantumScape is using a **semi-solid SSB architecture**.

The company holds several patents covering the **production**, surface treatment, and rapid thermal processing of these thin ceramic films, including engineered surface finishes for garnet-type electrolytes.

At the International Motor Show Germany 2025 in Munich (IAA), Volkswagen subsidiary Ducati and QuantumScape unveiled a modified electric race bike, marking the first live demonstration of a vehicle powered entirely by QSE-5 cells. Of course this motorcycle is still a **test bed** for SSB technology, not a preview of a production model.

The Taiwanese company ProLogium is backed by automakers such as **Mercedes-Benz** and **VinFast**. Its electrolyte technology is based on a patented oxide-based ceramic compound with extremely good ionic conductivity. The company claims that its fourth-generation electrolyte achieves an ionic conductivity of **57 mS/cm**, which is even higher than that of liquid electrolytes.

Regarding the anode technology, ProLogium follows a two-pronged approach based on a **silicon composite anode** and a **Lithium-Metal anode**. Target values for the energy density are **355 Wh/kg** for silicon-anode variants and up to **470 Wh/kg** for the lithium-metal anode type.

ProLogium has developed a production process which avoids the need for high-pressure sintering, a principal bottleneck for ceramic-based materials. The manufacturing technology is a scalable, roll-to-roll approach which relies on continuous wet coating.

Mass production is already underway at a Gigafactory, Taiwan, which began production in late 2023 with a planned capacity of 2 GWh per year. SSBs with silicon-based anodes are produced firstly.

For global expansion, ProLogium is constructing an overseas gigafactory in Dunkirk, France, where construction is expected to start in 2025 and mass production, with a total planned capacity of 48 GWh per year, is slated to begin in 2027.

At the IAA Mobility Show 2025, ProLogium and the Croatian **Rimac Technology** announced their cooperation to co-develop a next-generation battery platform. Unlike the research vehicles from Mercedes and BMW, a system for generating external cell pressure is not required.

The Chinese start-up **We-Lion** develops cells with a hybrid electrolyte system, based on a lithium polyethylene oxide polymer (PEO) combined with a small amount of liquid electrolyte.

The anode features an ultra-thin metallic lithium foil and often uses pre-lithiation to boost initial capacity. The cathode is based on a standard high nickel NCM chemistry; WeLion reports an energy density of **360 Wh/kg** for its cells.

The production technique involves coating solid electrolytes onto electrode materials, adding liquid electrolytes, and then polymerizing it within the assembled cell to create a solid and uniform structure. WeLion calls this manufacturing process in-situ solidification.

WeLion gained recognition through its cooperation with the Chinese automaker **NIO**. The 106Ah cell is used in NIO's 150 kWh battery pack, which enables an impressive range of over 1,000 kilometers in models like the ET7.

The battery was integrated into NIO's battery swapping network around mid-2024. These packs, which achieved over 1,000 km in range tests, are primarily offered as a swappable option for compatible NIO vehicles, rather than a single sold-with-the-car unit.

Between January and May 2024, approximately **1.62 GWh** of WeLion's semi-solid-state batteries were installed in NIO vehicles — equivalent to roughly **10,800 battery packs** (assuming 150 kWh each). Industry estimates suggest that each 150 kWh WeLion pack costs around US \$40,000–45,000, making it one of the most expensive EV batteries currently in limited production. These figures are based on industry reports and calculations, not official numbers released by NIO or WeLion.

However, the WeLion-NIO-cooperation illustrates the main advantage of a battery replacement concept: electric vehicles that have already been built and delivered to customers can benefit from advances in battery technology that are made after the vehicle has been manufactured.

There are four additional start-ups focusing on oxide-based SSB types, but they are still in the early stages of development. Interestingly, two of them have been founded in Europe.

Ilika [40] is a UK-based start-up for SSBs with **oxide solid electrolyte**, a silicon-based anode and an NMC cathode. Its large-format cell has achieved an energy density of **250 Wh/kg**. The company's roadmap for its first commercial product is targeting a significantly higher energy density of **350 Wh/kg**.

Piloting production is scheduled for mid-2025, **BMW** and **Jaguar Land Rover** are members of the steering committees for development programs which focus on developing and industrializing 50Ah A-sample prototype cells. This licensing-focused business model prepares the technology for eventual GWh-scale production by manufacturing partners.

Solithor [41] is a Belgian spin-off from imec, one of the world-leading research and innovation hubs in nanoelectronics and digital technologies. The start-up develops SSB cells with an electrolyte based on stable backbone of a nanoporous **silicon dioxide** matrix.

This solid material is filled with an organic lithium salt through a liquid-to-solid process. A liquid precursor solution, which contains the components including the organic lithium salt and ionic liquid, is first impregnated into the porous electrodes. This liquid solution then solidifies in-situ to form the final solid composite electrolyte

The start-up reports a measured energy density of **384 Wh/kg** and targets over 400 Wh/kg for the next samples. First applications are expected in Aviation and Maritime sectors, Solitor has a partnership with **Sonaca**, a leading Belgian aerospace company specialized in components for the civil, military, and space markets.

Ionstorage [42] is a US-based start-up founded as a spin-off from the University of California. Its solid electrolyte is based on a doped lithium garnet oxide (LLZO) matrix, optimized for high ionic conductivity and stability at room temperature. The start-up combines this electrolyte with a lithium-metal anode and a high-nickel NMC cathode.

The company reports an achieved energy density of **410 Wh/kg** at cell level, targeting more than 450 Wh/kg for next-generation samples. Its technology roadmap includes a modular production concept that can be integrated into existing LIB manufacturing lines with minor adjustments — a potential cost advantage over sulfide-based SSBs.

Pilot production of A-sample cells is planned for 2026, with a focus on electric vehicle and aerospace applications.

Talent New Energy [43] is a Chinese start-up developing oxide-based solid-state lithium battery cells with a focus on ultra-thin composite oxide electrolyte layers and lithium-metal or lithium-rich alloy anodes. The company claims to have demonstrated a prototype cell with 120 Ah capacity and an energy density of **720 Wh/kg** in April 2024 — setting a new reported industry record for single-cell gravimetric performance.

However, the claimed energy density should be viewed with caution, as no independent validation or third-party measurement has been published so far. Such high values are generally achievable only in laboratory conditions or for cells with exceptionally high gravimetric energy due to minimal packaging and inactive material content. It therefore remains uncertain whether similar figures can be maintained in large-format automotive cells with complete safety and thermal management systems.

Its architecture reportedly incorporates a dense oxide electrolyte, likely based on a garnet-type LLZO composite, combined with flexible interfacial layers to reduce contact impedance and suppress lithium dendrite formation. The cathode is described as a lithium-rich manganese-based compound, while the anode consists of a composite lithium-metal structure designed for high areal capacity and stable cycling.

The company's manufacturing concept relies on roll-to-roll thin-film deposition and co-sintering processes, which, if proven scalable, could significantly simplify oxide-based SSB production.

Talent New Energy has announced strategic collaborations with Chinese automotive OEMs such as Changan and battery producer Narada, aiming to move from pilot-scale production toward industrialization by 2027. If the company succeeds in transferring its laboratory results into stable, high-volume production, it could become one of the most disruptive players in the oxide-based SSB segment.

4.1.2.3 SSB start-ups with glass-based electrolytes

The US-Start-up **Polyplus Battery** [44] develops li-io cells with a glass-based solid electrolyte. The company originated from research at the Lawrence Berkeley National Laboratory and holds more than 100 patents.

Polyplus' electrolyte is a lithium-conducting glass similar in composition to lithium phosphorus oxynitride (LiPON) or related lithium borate–phosphate glasses. The amorphous materials exhibit ionic pathways created by a disordered network of lithium, oxygen, phosphorus, and nitrogen (or boron) atoms.

The lithium ions migrate through interstitial sites within the glass matrix, while the rigid network prevents dendrite growth and blocks electron flow — effectively combining ionic conductivity with electronic insulation.

This glass electrolyte forms a chemically stable and hermetic barrier around the lithium metal, allowing direct contact with reactive environments such as water or oxygen without corrosion.

The company reports energy densities exceeding **500 Wh/kg** for lithium–sulfur prototypes and even higher theoretical values (> 1,000 Wh/kg) for lithium–air systems.

4.2 Start-ups with other revolutionary technologies

There are a few start-ups working on revolutionary Li-Io technologies that do not originate from solid-state technology.

Interestingly, the US start-up **SES AI** [45], an MIT spin-off, originally began researching solid-state cells but then decided to abandon this path and return to developing cells with liquid electrolytes.

SES AI now relies on a proprietary, highly concentrated liquid "Solvent-in-Salt" electrolyte in combination with a Lithium-Metal anode. For the cathode, standard NMC chemistry is used. The company has set a target energy density of up to **400 Wh/kg** and has already manufactured 100 Ah Li-Metal cells that have successfully passed Chinese safety standards.

SES AI has Joint Development Agreements (JDA) for the development of B-samples with GM, Hyundai, and Honda.

The US start-ups **Lyten** [46] and **Zeta Energy** [47] both bet on a **sulfide-based cathode** in combination with a liquid electrolyte.

Lyten became known to a wider public through the acquisition of Northvolt's assets. Its approach combines a sulfur cathode with a lithium metal anode. To manage one of the key challenges in Li-S chemistry, the "polysulfide shuttle effect", its own 3D graphene material is used to form the highly conductive and porous framework for the **sulfur cathode**.

The start-up is backed by the auto maker **Stellantis**. A-samples that exceed **300 Wh/kg** have been already shipped to Stellantis, the roadmap targets reaching **400 Wh/kg** by 2026.

The Lyten plans to take over almost all sites of the Northvolt came as a surprise, as both companies had previously been targeting completely different markets with different technologies. While Northvolt wanted to serve the high-volume automotive market with its NMC cells, the US start-up has so far only addressed niche markets such as aviation with its particularly lightweight and innovative graphene-sulfur cells.

Zeta Energy's strategy parallels Lyten in its use of a lithium metal anode matched to a sulfurized carbon cathode, but it emphasizes a fully integrated redesign across both electrodes to suppress common Li-S failure modes.

Its cathode leverages a sulfurized carbon host structure to enhance electrical conductivity and stabilize sulfur species, helping to contain the polysulfide shuttle. On the anode side, Zeta grows vertically aligned carbon nanotube arrays which are lithiated to form a stable, dendrite-free lithium structure.

The company claims cell energy densities up to **450 Wh/kg**, along with high charge rates (up to 10 C) and robust cycle performance. In 2024, Zeta entered into a joint development agreement with **Stellantis**.

5. Summary and Outlook

The current landscape of lithium-ion battery (LIB) innovation is defined by an ongoing competition between established technologies and emerging concepts. Mature chemistries such as NMC and LFP dominate global production and continue to evolve through incremental improvements such as higher nickel ratios, silicon-enriched anodes, and manganese-doped cathodes. These evolutionary developments build upon existing production infrastructures and supply chains, ensuring predictable scalability and reliability.

In contrast, a growing number of start-ups pursue revolutionary concepts that promise to redefine the limits of energy density, safety, and sustainability. Solid-state batteries, lithium-sulfur systems, and other next-generation cell architectures aim for disruptive performance gains — yet often face critical challenges in manufacturability and cost efficiency. The transition from laboratory-scale prototypes to stable, high-yield mass production remains a formidable barrier.

This tension between the proven and the new increasingly defines the strategic direction of the global battery industry. Established players focus on optimizing known technologies within mature production ecosystems, while newcomers attempt to break these boundaries entirely. The recent bankruptcy of Northvolt dramatically illustrates that technological ambition alone cannot overcome the challenges of industrialization.

Geopolitical and policy developments will further influence this technological race. Under the Trump/Vance administration, U.S.-based start-ups are expected to face reduced federal support for green technologies and early-stage clean-tech ventures. This shift may slow domestic innovation momentum and investment in advanced cell chemistries, particularly compared to Asia and Europe, where government-backed programs continue to strengthen the integration of emerging battery technologies into industrial ecosystems.

Whereas the invention of the lithium-ion battery was the result of an international collaboration across three continents - a fact also reflected in the nationalities of its three Nobel Prize laureates - it is impossible to predict where the next breakthrough in LIB research will take place.

However, we would not be surprised if this time it came from a country that demonstrated its expertise in materials science and chemistry already more than a thousand years ago with the invention of china and gunpowder.

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