WHITE PAPER

Emerging Battery Chemistries: Challenges and Opportunities

AUTHORS

Luke Kinsman

February 2026

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+44 (0) 203 176 0580
scott.mckellar@wellspring.com

1 Executive Summary

This white paper surveys emerging rechargeable battery chemistries that may supplement or partially displace incumbent lithium-ion (Li-ion) technology over time. It focuses on the innovation landscape, commercial momentum, and the practical barriers that determine whether promising laboratory results translate into bankable, scalable products.

Rapid electrification of transport and power systems is driving a step-change in battery demand and manufacturing scale. Global EV battery demand exceeded 950 GWh in 2024 (around 20% year-on-year growth), while grid-scale battery energy storage deployments increased in 2024 to >160 GWh. Battery manufacturing is now measured in terawatt-hours (around 1 TWh produced in 2024), with demand projected to reach ~4,700 GWh by 2030, intensifying pressure on materials supply chains and motivating diversification beyond incumbent lithium-ion solutions.

The battery ecosystem is highly geographically concentrated. China is the leading jurisdiction for battery patenting and is a dominant supplier across the entire battery value chain, including reported production shares of 85% of anodes, 82% of electrolytes, 74% of separators, and 70% of cathodes, alongside ~85% of global cell production capacity by value and 74% of battery pack/component exports in 2023. Western players by contrast remain heavily exposed to offshore supply chains and have struggled to build Li-ion manufacturing at scale: despite headline-grabbing, multi-billion-dollar commitments, both start-ups and established chemical companies have repeatedly failed to deliver major Li-ion projects.

Against this backdrop, technology activity is increasingly multi-track rather than converging on a single successor to Li-ion, with both literature and patent indicators showing growing focus on various non-Li-ion chemistries aligned to different value propositions (e.g., low-cost stationary storage, ultra-lightweight applications, enhanced safety/premium EV performance, and long-duration storage). This supports an outlook in which multiple chemistries coexist, with adoption driven by application-specific trade-offs in cost, performance, safety, and manufacturability. Key "next-generation" pathways highlighted include:

- **Sodium-ion (Na-ion):** Strong momentum since ~2021, with advantages in material abundance, safety/thermal stability, and cold-weather performance, targeting grid storage and cost-sensitive mobility; trade-offs include lower energy density and slightly lower efficiency. Commercial momentum includes announced Na-ion EV deployments and reported ~175 Wh/kg pack energy density claims, while business viability remains sensitive to lithium price fluctuations.
- **Lithium–sulfur (Li-S):** Positioned for ultra-high specific energy using abundant sulfur (theoretical up to ~2,500 Wh/kg; practical ~500–700 Wh/kg). The principal barrier remains cycle life, driven by polysulfide "shuttle" effects and cathode conductivity constraints. Early adoption is concentrated in aerospace/defence, drones and other weight-critical applications, supported by well-funded ventures and strategic OEM partnerships.
- **Solid-state batteries (SSBs):** Replacing liquid electrolytes with solid electrolytes is associated with improved safety and higher energy density potential. Multiple European spinouts and scale-up efforts are profiled, and commercialisation is framed around a roadmap extending towards the end of the decade, with manufacturability and interface durability as continuing challenges.

- **Metal–air:** Very high theoretical energy densities with strongest near-term fit in long-duration stationary storage (e.g., iron–air). Commercial progress is exemplified by multi-day storage systems (e.g., ~100-hour duration and ~$20/kWh system cost estimates cited), while rechargeable metal–air for EV-scale use remains speculative and outside mass production expectations for the 2020s.
- **Organic/flow batteries:** Carbon-based active materials (e.g., quinones/viologens) are positioned for safe, scalable stationary storage, with modular energy capacity via tanks, but with lower energy density than Li-ion and ongoing stability/cost challenges. Examples include pilot/prototype demonstrations, partnerships, and acquisitions by larger manufacturers.

Commercialisation outcomes are driven as much by industrial execution as by fundamental chemistry choice as battery manufacturing is capital-intensive and experience driven. European cell plants are estimated to cost ~€100 million per GWh – roughly 47% higher than equivalent capacity in China – with operating costs up to 70% higher. To meet projected European demand of ~1 TWh by 2030, capital requirements exceed €100 billion, rising to ~€175 billion if all announced projects proceed.

Battery packs typically represent 30–40% of EV cost, and when combined with elevated upstream material costs and limited access to critical supply chains, the resulting cost structure creates significant barriers for new entrants – particularly outside China. In parallel, manufacturing success increasingly depends on access to tacit know-how (e.g., process design, quality control, yield improvement) and early alignment with strategic partners.

Looking ahead, the battery sector is likely to remain pluralistic, with multiple chemistries coexisting and gaining traction across different segments. Investor expectations are also shifting, with some VCs advising portfolio companies to develop explicit approaches for partnering with, manufacturing in, or otherwise engaging China-dominated supply chains. Successful commercialisation will depend not only on electrochemical performance, but also on the ability to scale efficiently, manufacture reliably, secure upstream inputs, and navigate an increasingly competitive and geopolitically sensitive global ecosystem.

Contents

2 Introduction

The focus of this white paper is on emerging chemistries for rechargeable batteries (also known as secondary batteries) that may eventually replace or sit alongside the now well-established lithium-ion battery. It does not address primary (non-rechargeable) batteries or lead-acid rechargeable batteries. Additionally, an in-depth technical analysis of the operational mechanisms and comparative assessments of these battery chemistries falls outside the scope of this document and is covered extensively in other publications.[1] This white paper aims to highlight some of the current innovation challenges and opportunities in the emerging battery chemistries undergoing commercialisation, and an outline of the challenges that lie ahead.

2.1 Why (New) Batteries Matter

The climate crisis and the push to decarbonise energy systems mean that every sector – from cars and trucks to power grids and industrial processes – must electrify and run on low-carbon energy. Batteries reduce our reliance on fossil fuels and have become a cornerstone of the energy transition because they store electricity, buffer intermittent renewable generation and make electric vehicles (EVs) viable.

Global EV battery demand reached over 950 GWh in 2024, up 20% from 2023 and a more than fivefold increase from 2020, according to the International Energy Association.[2] A similar boom is occurring in stationary energy storage: deployments of grid-scale battery energy storage systems (BESS) jumped 68% in 2024, raising global installations to over 160 GWh.[3] As the share of wind and solar generation grows, flexible storage is critical for grid stability and to ride out daily intermittency issues. Models show that four hours of storage is enough today for most grids to ride out typical daily variations in supply and demand, but experts are increasingly pointing to longer-duration resources as variable renewable energy generation grows.[4]

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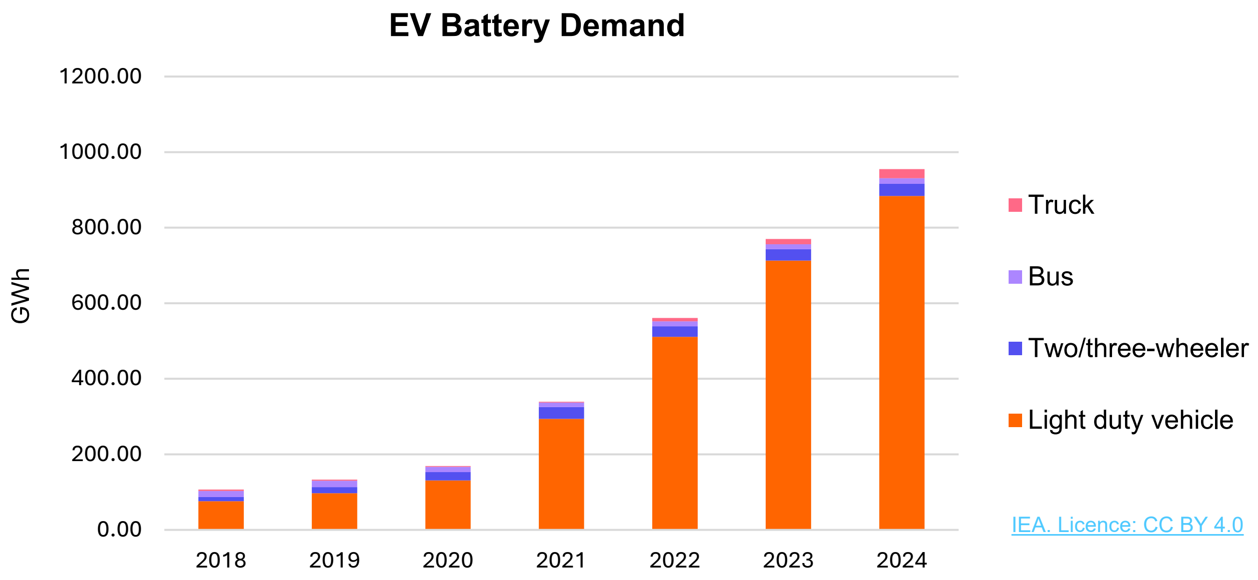
[1] Nat Rev Mater 6, 1020–1035 (2021). https://doi.org/10.1038/s41578-021-00324-w
[2] https://www.iea.org/reports/global-ev-outlook-2025/electric-vehicle-batteries
[3] https://www.irena.org/News/articles/2025/Aug/Battery-energy-storage-systems-key-to-renewable-power-supply-demand-gaps
[4] https://www.nrel.gov/grid/news/program/2023/from-minor-player-to-major-league-moving-beyond-4-hour-energy-storage



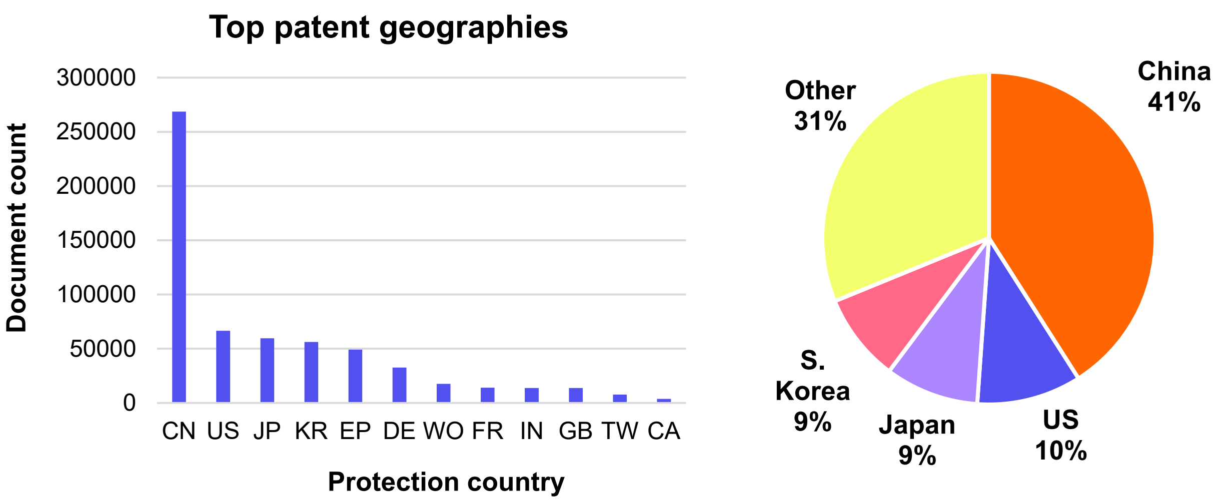
The International Energy Agency (IEA) estimated that 2024 saw around 1 terawatt-hour of batteries manufactured, up by a factor of 26 over the past decade – enough to meet global power needs for around half an hour. Demand is expected to rise to 4,700 GWh by 2030. The lithium-ion market now has a well-established industrial base with advanced supply chains and manufacturing excellence; however, scaling to multi-terawatt-hour demand not only depends on scaling manufacturing capacity but will also require new chemistries that use more abundant materials and reduce dependence on critical minerals.

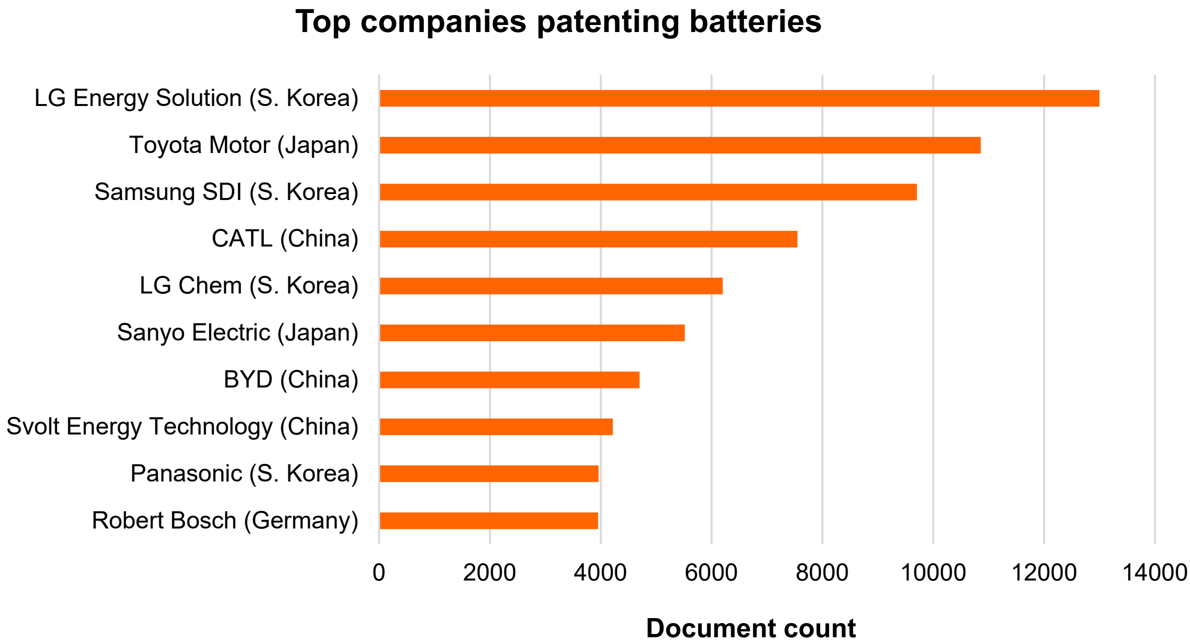
China dominates the battery innovation ecosystem and supply chain

Lithium-ion technology underpins today's battery boom, yet relying solely on Li-ion is becoming increasingly sub-optimal for Western countries. The world's top 10 battery cell producers are dominated by Asian giants, with five of the top ten from China. **CATL**, **LG Energy Solution**, **Panasonic**, **BYD**, **Samsung SDI**, **SK Innovation**, **Tianjin Lishen**, **Gotion High Tech**, **EVE Energy**, and **Amperex Technology** lead the industry in large-scale, highly automated cell production and rapid global expansion.[5]

The following charts illustrate the geographic distribution of patent filings in rechargeable battery technologies. **China is the dominant jurisdiction, accounting for 41% of all filings and nearly 300,000 documents, signalling its strategic focus on securing intellectual property in this sector**. The United States, Japan, and South Korea follow with shares of 10%, 9%, and 9%, respectively, reflecting their continued importance in innovation and manufacturing. European countries and other regions collectively represent **31%**, indicating broader but less concentrated activity. This pattern suggests that China is the primary market for IP protection and competitive positioning, while the US, Japan, and South Korea remain critical secondary markets for partnerships and technology transfer.

[5] https://tamarindo.global/insight/analysis/who-are-the-top-10-battery-cell-makers/





Source: Orbit Intelligence

In the decade since China's "Made in China 2025" industrial policy – identifying batteries as a strategic sector – China has dominated the global battery patent landscape and the commercial market, producing over three-quarters of batteries sold globally, at costs of 30% and 20% cheaper than European and North American companies.[6,7] This comparative lack of commercial traction and success by the west is also evident in patenting trends among leading companies filing patents over time.[8] Many of the key companies that are investing in battery research and development are headquartered in China, Japan, or South Korea.

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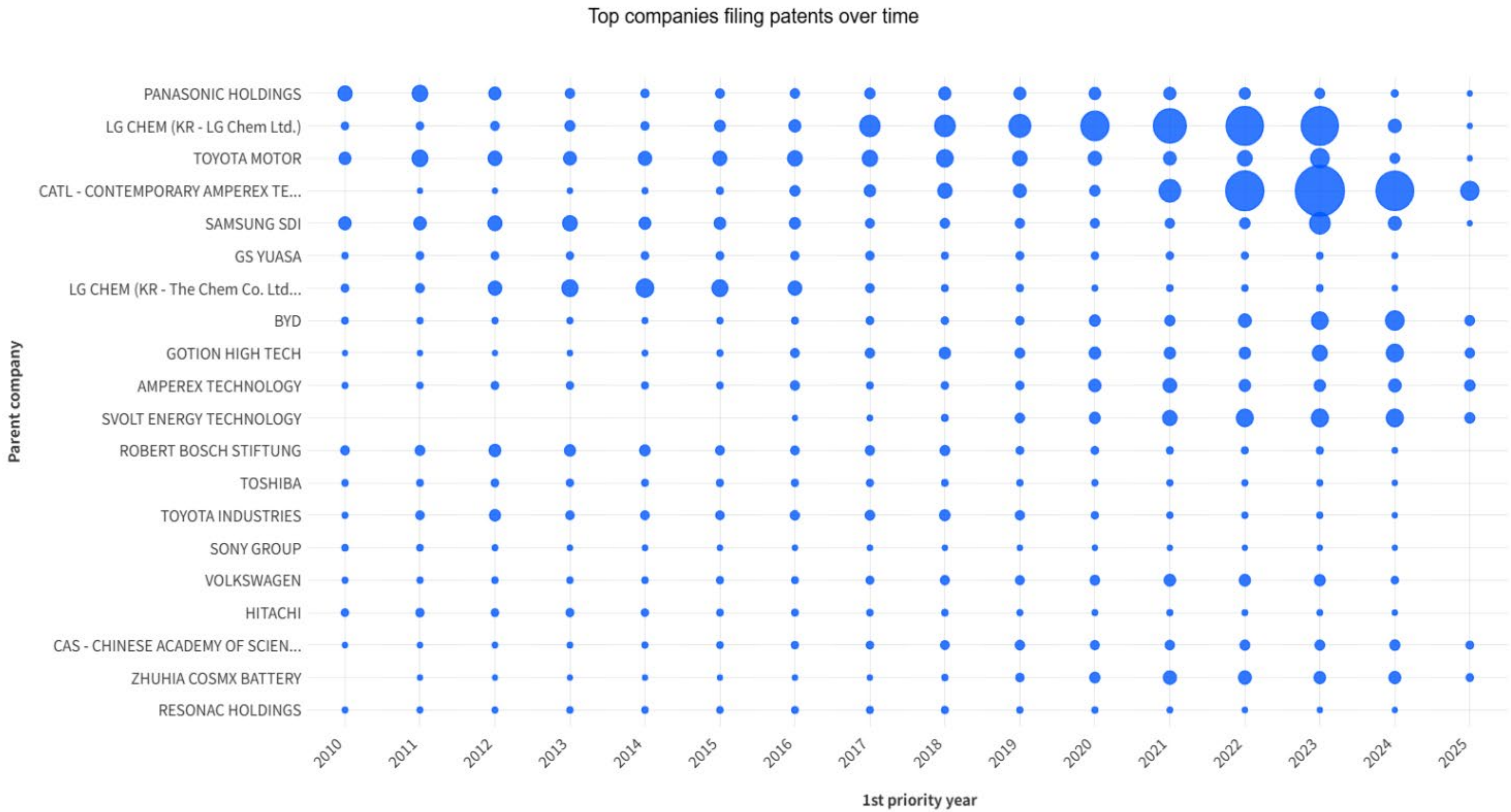
[6] https://www.weforum.org/stories/2025/06/how-china-is-reinventing-the-future-of-global-manufacturing/
[7] https://www.iea.org/commentaries/the-battery-industry-has-entered-a-new-phase
[8] Patent data based on an analysis of 563,444 patent families identified by Questel's Orbit Intelligence platform using the classification code H01M 10 (Rechargeable batteries)



Patent filing trends among leading battery technology companies. Bubble size represents the number of patents filed by each parent company each year.

Furthermore, China was responsible for producing 85% of anodes, 82% of electrolytes, 74% of separators, and 70% of cathodes globally. **By monetary value, China controlled nearly 85% of global battery cell production capacity and comprised 74% of battery pack and component exports in 2023**.[9]

China's dominance can be attributed to a combination of strategic resource acquisition, mineral processing capabilities, manufacturing scale, vertical integration, lower costs, and strategic initiatives:[10]

- **Lithium:** In 2023, China accounted for approximately 18% of global mined lithium production and controlled 25% of global lithium mining capacity. Chinese investments are notable in the "Lithium Triangle" (Argentina, Bolivia, Chile), which contains about half of the world's reserves.
- **Graphite:** China produced 79% of the world's natural graphite in 2024 and was responsible for processing over 90% of the global supply.
- **Cobalt:** Chinese entities control around 80% of cobalt production in the Democratic Republic of Congo, a country contributing over half of the world's cobalt supply.
- In 2023, China accounted for **46% of worldwide raw battery mineral imports**, with Australia directing most of its lithium exports to China.
- Chinese companies, including CATL and BYD, operate **across the battery supply chain** from raw materials to finished products.
- Government subsidies, research and development investments, and domestic demand **incentives** such as electric vehicle subsidies have contributed to industry growth.
- Early adoption of **Lithium Iron Phosphate (LFP)** chemistry provided cost and safety benefits for high-volume electric vehicles. Chinese firms maintain substantial expertise in manufacturing and supply-chain organisation as a result.

The 'global west' lacks a true battery champion to rival Chinese hegemony

Despite attracting billions in investment, the west risks being locked out of the battery market entirely, with automakers and energy storage companies alike becoming dependent on offshore supply chains, raising national security concerns. Although there have been headline-grabbing commitments to multi-billion-dollar projects, Western startups and established chemical companies alike have consistently failed to deliver Li-ion projects at scale. A few notable examples in recent years include:

- **Johnson Matthey**, a global chemical company whose catalytic converters are utilised in roughly one-third of internal combustion engine vehicles produced worldwide, sought to transition towards battery technologies in response to the growing market presence of electric vehicles and awareness of the threat to their catalyst technologies business. However, in 2021, the company discontinued these efforts after determining it was unable to effectively compete with established Chinese manufacturers.[11]

[9] https://www.eia.gov/todayinenergy/detail.php?id=65305
[10] https://cgsr.llnl.gov/sites/cgsr/files/2024-08/Mineral-Security.pdf
[11] https://matthey.com/may-26-announcement

- **Northvolt**, one of Europe's most promising battery startups, secured $15 billion in funding since 2016, but declared bankruptcy in late 2024, reflecting broader difficulties among smaller manufacturers attempting to increase production and efficiency in competition with established Asian companies.
- **FREYR,** a Norwegian battery startup focusing on Li-ion cell production, had planned a $2.6 billion, 700+ job battery factory in Georgia (USA) but abandoned it in February 2025, pivoted to solar PV production and energy storage, and rebranded to T1 Energy.[12] Its then-CEO blamed a surplus of cheap Chinese batteries making it harder to raise money to manufacture batteries.[13]

Performance ceilings and supply chain bottlenecks incentivise innovation

The theoretical energy density for Li-ion cells is around 400–500 Wh kg^{-1} – enough to power a typical EV for 560-700 miles – but due to material inefficiencies and thermal-management constraints, practical cells deliver only 100–270 Wh kg^{-1}, bringing actual EV ranges closer to 140-380 miles.[14] This has led to consumers citing 'range anxiety' as a primary reason for not buying an electric vehicle, and industry demanding higher-performance batteries with larger energy densities.

Pushing energy densities closer to the theoretical limit requires replacing graphite with silicon-carbon anodes or adopting solid-state electrolytes; however, these improvements still rely on lithium and face manufacturing complexities. For applications like heavy trucks, aviation and seasonal grid storage – where higher energy density, longer cycle life or tolerance to harsh conditions is critical – Li-ion will be insufficient, necessitating the development and commercialisation of alternative chemistries.

Furthermore, as EV adoption and renewable deployment continue to scale to terawatt-hour levels, bottlenecks in mineral supply and recycling at end-of-life also constrain Li-ion. Alternative chemistries such as sodium-ion, lithium–sulfur, flow batteries and metal-air batteries promise more abundant materials thus alleviating supply chain concerns, offer safer solid or aqueous electrolytes and may enable higher energy densities all while meeting a wide array of energy storage needs.

Innovating and diversifying battery chemistries away from Li-ion is therefore not optional but essential to ensure that the energy transition remains economically viable, socially equitable and resilient.

[12] https://apnews.com/article/georgia-freyr-electric-battery-plant-newnan-5b718f627462bb1d5cc3bf4d835ae879
[13] https://electrek.co/2025/02/19/freyr-rebrands-t1-energy/
[14] https://www.large-battery.com/blog/theoretical-energy-limits-lithium-batteries/

2.2 Li-ion Battery Basics

Lithium-ion batteries (Li-ion, or LIBs) are rechargeable batteries that exploit the reversible reduction of lithium ions to store energy The lithium ions are stored in active materials (electrodes) acting as stable host structures during charge and discharge. When the battery is charged, lithium ions flow from the cathode to the anode through an electrolyte. When the battery is discharged, the lithium ions flow back from the anode to the cathode, generating an electrical current (energy) that can be used to power devices.

The technical and design requirements of a battery in a mobile phone will differ to those found in an electric vehicle or a stationary energy storage unit. As such, there are a range of different Li-ion cell chemistries and designs on the market today, each with different properties depending on the specific chemicals and materials used to construct the cells. The performance of a lithium-ion battery is determined by the properties and interactions of its key components: the anode, cathode, electrolyte, and separator.

Anode

In general, the anodes of a LIB are made of graphite, a form of carbon which is relatively cheap and abundant, however a major anode innovation is the introduction of silicon additives to increase capacity – several companies now commercialise silicon-graphite composite anodes enabling ~10–20% higher cell energies. Tesla's 2021 introduction of partial silicon in Model 3/Y batteries and startups like Sila Nanotechnologies (whose Si-based anode is used in Mercedes EV cells) exemplify this trend. Silicon can store more lithium ions, boosting energy density, but it expands and contracts during charge-discharge cycling, a phenomenon far more pronounced than with graphite, posing cycle life challenges.

Electrolyte and Separator

Electrolytes typically consist of a lithium salt such as lithium hexafluorophosphate ($LiPF_6$) dissolved in an organic solvent resulting in a gel or liquid. The electrolyte facilitates ion transport and maintains electrochemical stability, whereas the separator, a porous membrane material provides a barrier between the cathode and the anode to prevent short-circuits.

There has been a drive to replace liquid electrolytes with solid alternatives such as sulfide, oxide, or polymer-based materials, on the grounds that they offer enhanced safety, higher energy density, and compatibility with lithium-metal anodes, positioning them as a key focus for next-generation energy storage. However, challenges remain around interfacial resistance, manufacturing complexity, and cost, which currently limit large-scale commercial adoption.

Cathode

Various types of lithium-ion cathode are found in commercialised batteries including:[15]

- Lithium Cobalt Oxide ($LiCoO_2$ – LCO)
- Lithium Aluminium Cobalt Nickel Oxide ($LiNi_{1-x}Co_{1-y}Al_{1-z}O_2$ – NCA)
- Lithium Nickel Manganese Cobalt Oxide ($LiNi_{1-x}Co_{1-y}Mn_{1-z}O_2$ – NMC aka NCM)
- Lithium Iron Phosphate ($LiFePO_4$ – LFP)

There is no ideal Li-ion battery suitable for every application as each chemistry type has advantages and disadvantages, as illustrated by the Volta Foundation's trade off maps.[16]

LCO batteries are a popular choice for portable electronics such as smartphones, laptops, and tablets due to its high discharge voltage, high gravimetric and volumetric energy densities, and good cycling performance.[17] However, their relatively short lifespan, fast capacity fade at high current rates, safety issues, and high cobalt content make them unsuitable for use in larger-scale applications such as in electric vehicles or grid storage. Instead, **NMC** or **NCA** are preferred for powertrains for e-scooters, e-bikes, and electric vehicles. **LFP** is a cheaper material than other Li-ion cathodes due to the absence of cobalt and nickel and they show excellent safety, long lifecycles and are quickly becoming the preferred material for use in lower-cost EVs and energy storage systems alike.[18,19]

[15] https://dx.doi.org/10.1021/acs.chemrev.9b00535 Chem. Rev. 2020, 120, 7020−7063
[16] "The Battery Report 2024." Volta Foundation, 25 January 2025.
[17] https://doi.org/10.1016/j.mattod.2014.10.040
[18] https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-vehicle-batteries
[19] https://www.energy-storage.news/lithium-ion-starting-to-dominate-ldes-pipeline/

3 The Battery Innovation Boom

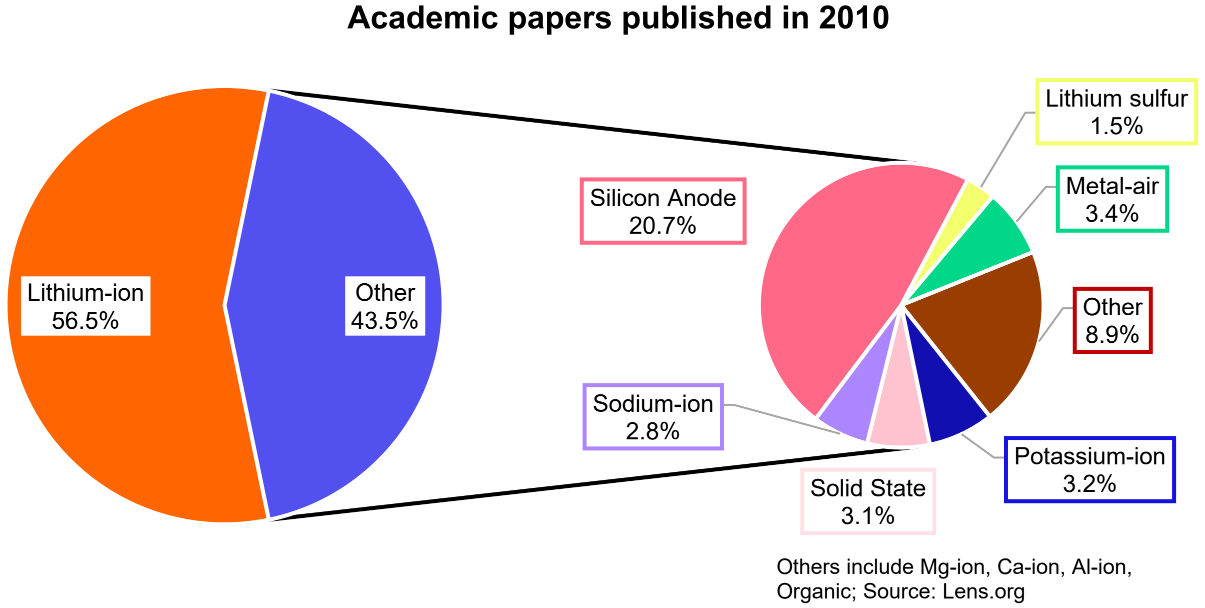
Battery R&D is at an all-time high

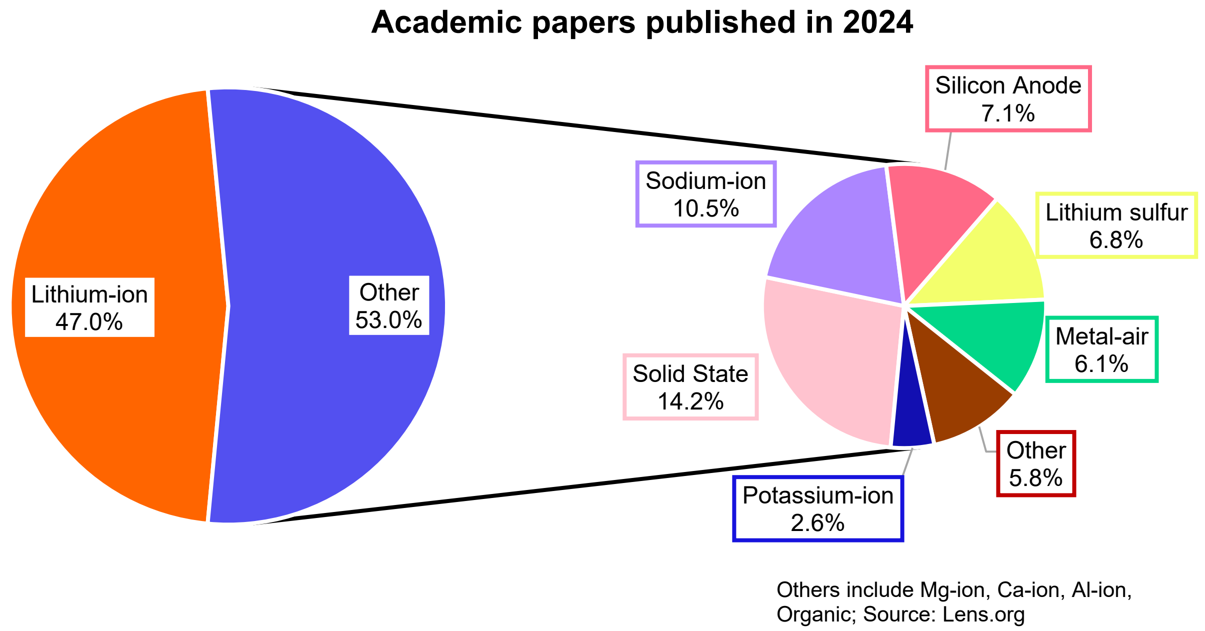
The research community is paying increasing attention to alternative, ‘non-Li-ion’ chemistries, as illustrated by the charts below.[20] Although Li-ion batteries currently maintain dominance in both academic publications and patent filings, there is a growing trend – among academia and industry – toward investigating solid-state electrolytes, lithium metal anodes, and alternative cathode chemistries such as Na-ion, metal-air, and lithium-sulfur systems. These alternatives are receiving heightened attention and are gradually accounting for a larger share of scholarly output relative to traditional Li-ion technologies, and in turn fuelling a rise in corresponding patent applications that reflects growing commercial interest and signals potential pathways to market adoption.[21]

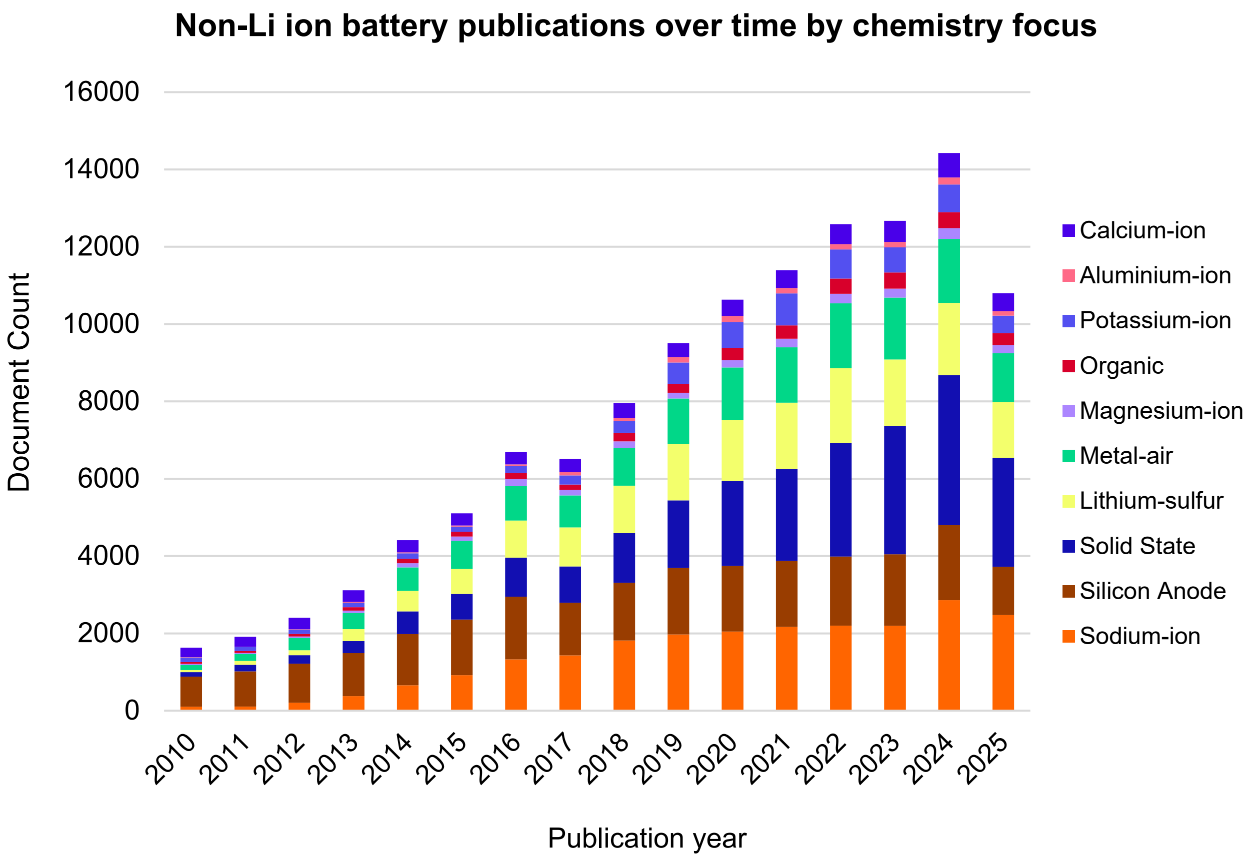
It is worth noting that this R&D push is not limited to entirely new chemistries; much of it is also directed to improving the incumbent Li-ion technology. For example, researchers have been exploring advanced anode materials like silicon-based materials to replace or supplement graphite, aiming to increase Li-ion cell capacity without altering the overall cathode chemistry.[22,23] Such silicon anodes can store more lithium ions, thereby boosting a battery’s energy density significantly. In the last five years especially, studies and startups developing silicon-rich anodes, new cathode coatings, electrolyte additives, and other incremental innovations have proliferated. This kind of research is leading to “next-generation” Li-ion batteries that charge faster or last longer even before completely new chemistries arrive.

[20] Please see the appendix for more details on search methodologies used to generate the charts.
[21] Note: Patent analysis is based on data available up to 2024 to enable a direct side-by-side comparison with academic publication data from the same year. Please note that 2024–2025 data shown in patent charts will not be complete due to the typical 12–18-month delay between priority application and publication, which may understate the most recent patenting activity.
[22] https://pubs.acs.org/doi/10.1021/acsmaterialslett.3c00253
[23] https://advanced.onlinelibrary.wiley.com/doi/10.1002/aenm.202301464

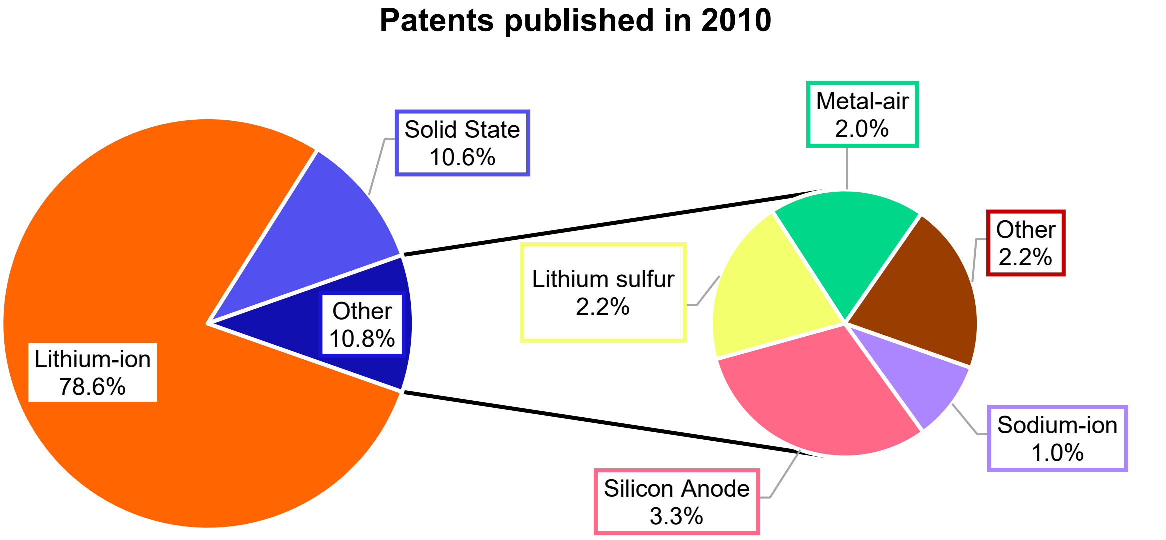
3.1 Academic Publishing Trends






Non-Li ion battery publications over time by chemistry focus
Document Count
16000
14000
12000
10000
8000
6000
4000
2000
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
Publication year
Calcium-ion
Aluminium-ion
Potassium-ion
Organic
Magnesium-ion
Metal-air
Lithium-sulfur
Solid State
Silicon Anode
Sodium-ion

3.2 Commercial R&D Trends (Patents)



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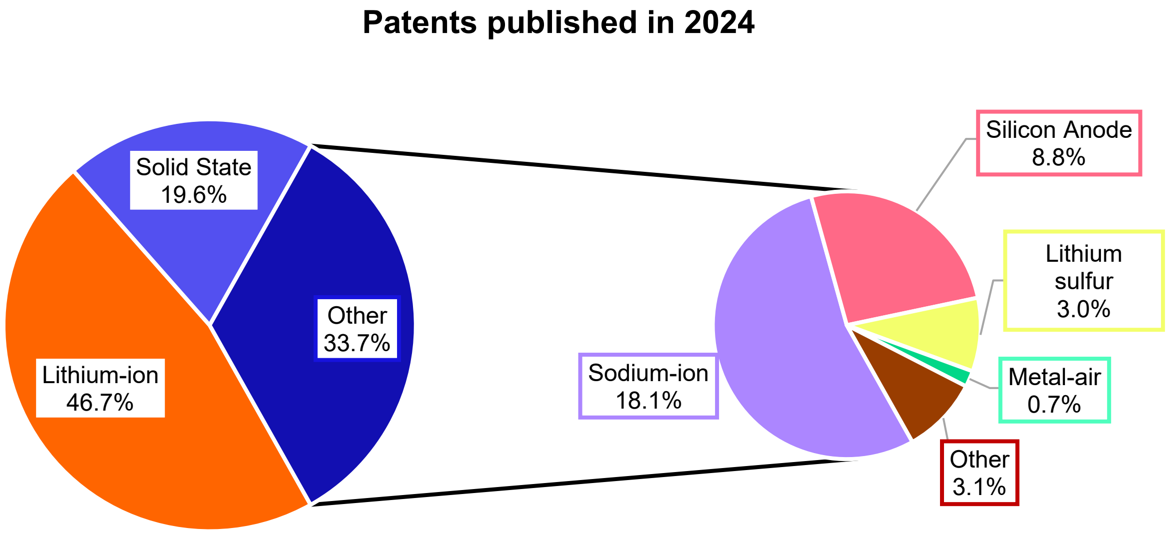
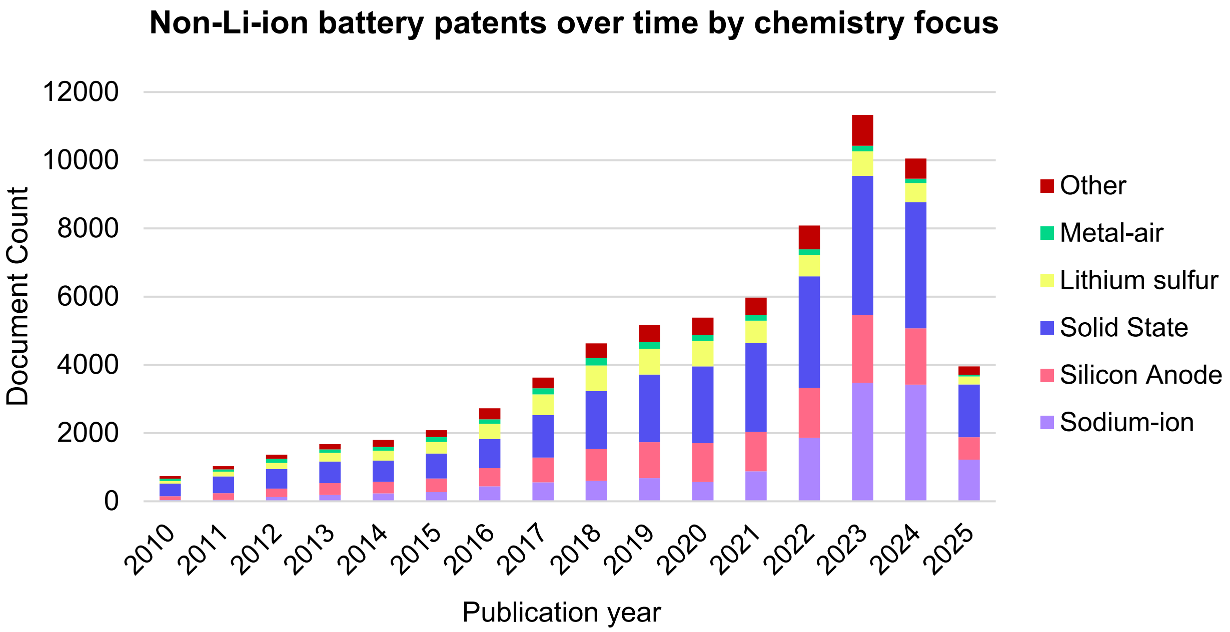


Others include K-ion Mg-ion, Ca-ion, Al-ion, Organic; Source: Orbit Intelligence



3.3 Emerging Technology Spotlights

While lithium-ion batteries continue to dominate today's market and are still improving, there remains an intense interest in commercialising a wave of new battery chemistries that could overcome Li-ion's limitations. Each of these emerging technologies – some nearing market-ready status, others more nascent – offer unique advantages for the future of energy storage. In the following sections, we profile leading examples of startups developing some of the most promising emerging technologies, highlighting not only their unique advantages and contributions to the future of energy storage, but also the challenges and setbacks encountered by some startups along the way. These spotlights highlight the innovation landscape and the commercial momentum behind next-generation energy storage solutions.

3.3.1 Sodium-ion Batteries (SIBs)

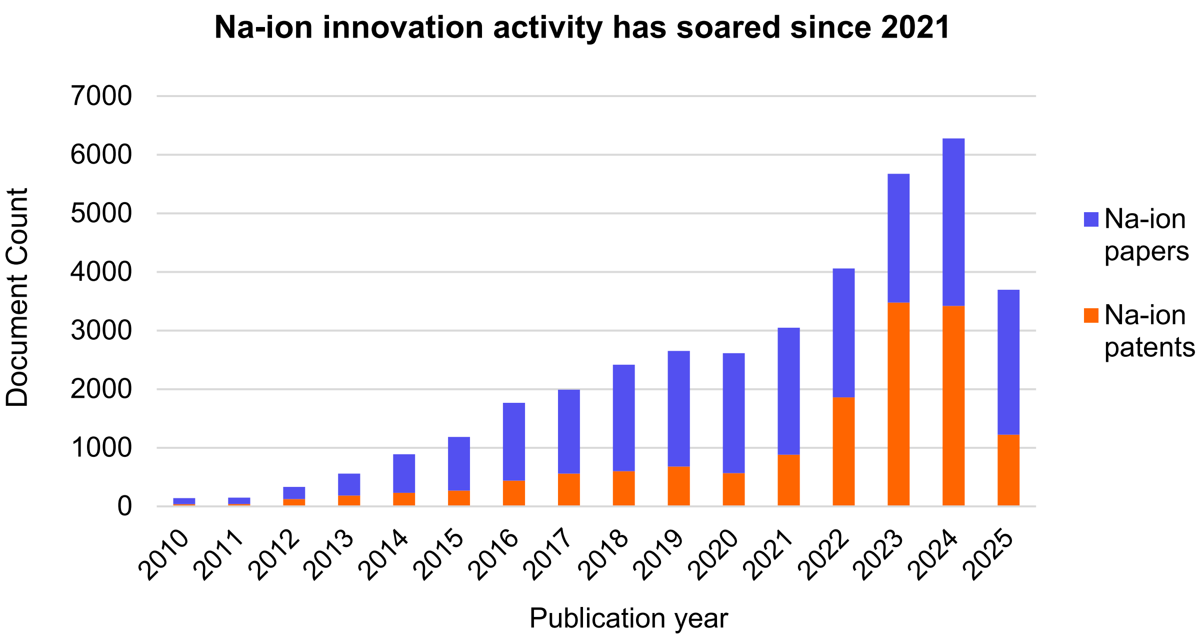
Sodium-ion batteries were being developed at around the same time as lithium-ion batteries, yet despite sodium's vast abundance (1,000+ times more common than lithium in the Earth's crust) and theoretically cheaper cost of materials, they failed to gain commercial traction in the 1990s due to lower energy densities than their lithium counterparts. The research and development of sodium-ion batteries has generally focused on three types of cathode: layered oxides (sodium transition metal oxides), Prussian blue analogues (PBAs), and polyanionic compounds.

The recent surge in demand for Li-ion batteries has intensified supply chain pressures for critical materials such as lithium, nickel, graphite, and cobalt, leading to a rise in the average Li-ion cell price index in 2022 for the first time.[24] Subsequent declines in mineral prices have alleviated costs, while

[24] https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/

simultaneously raising concerns about potential overreliance on Li-ion technology and associated risks, including production bottlenecks, supply chain disruptions, and geopolitical challenges. [25]

In response to these developments and given the compatibility of SIB materials with existing Li-ion infrastructure, both academic and commercial sectors have renewed their focus on SIB research and development in recent years with several sodium-ion projects being announced at record high lithium prices.[26]



This interest is particularly directed toward applications such as grid energy storage systems, uninterrupted power solutions, and low-speed electric vehicles including trucks, forklifts, and bicycles.[27] Indeed, the IEA's "Batteries and Secure Energy Transitions" report forecasts that sodium-ion (Na-ion) batteries will take a growing share of grid-scale energy storage by 2030.[28]

Safety is also inherently good – Na-ion cells are typically less prone to thermal runaway and perform better in cold temperatures (a big plus for northern climates or winter applications). The trade-offs are lower energy density and somewhat lower efficiency (slightly lower cell voltage). Research has shown that operating voltages and capacities of SIBs can be increased when adding more costly elements such as Co, Cr, Ni or V in these materials,[29,30] but commercial SIB manufacturers such as **Faradion** (UK) are looking to avoid or reduce using such elements as their use would mitigate some of the financial, safety and toxicity benefits of using sodium in the first place.[31]

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[25] https://www.bloomberg.com/news/articles/2023-11-26/battery-prices-are-falling-again-as-raw-material-costs-drop
[26] https://www.spglobal.com/automotive-insights/en/blogs/2025/06/sodium-ion-battery-technology
[27] https://www.nature.com/articles/s41560-024-01701-9
[28] https://www.iea.org/reports/batteries-and-secure-energy-transitions
[29] Energy Environ. Sci., 2011,4, 3680-3688 https://doi.org/10.1039/C1EE01782A
[30] Nat Rev Mater 1, 16013 (2016). https://doi.org/10.1038/natrevmats.2016.13
[31] J. Mater. Chem. A, 2021, 9, 8279 https://doi.org/10.1039/D1TA00376C

Startups developing SIBs include:

- **Altris** (Sweden), developing Prussian White cathode Na-ion cells targeting stationary storage, commercial transport and low-cost mass market EVs. Altris successfully raised SEK 150 million ($15.7 million) in a Series B1 funding round in late 2024 with investors including **Clarios, Maersk, Volvo, InnoEnergy** and **Molindo**.[32]
- **Moonwatt** (Netherlands), developing Energy Storage Systems utilising advanced SIB technology. The company has raised €8 million in seed funding with plans for a pilot installation in Europe next year and commericial deployments by 2027.[33] The seed funding round was co-led by **daphni** and **LEA Partners**, **Founders Future**, **AFI Ventures** (by Ventech) and **Kima Ventures** also participated alongside strategic business angels and customers.[34]
- **TIAMAT** (France) plans to build a gigafactory to produce 5GWh of first-generation sodium ion cells. TIAMAT completed its third round of fundraising in June 2025, announcing a global partnership with Endeavor Inspired Infrastructure to deliver high-speed energy storage for AI data centers and power grids fed by TIAMAT technology.[35] TIAMAT was spun out of France's National Center for Scientific Research and is based at the Energy Hub in Amiens, at the scientific center of the University of Picardy Jules Verne. The company raised €30 million in early 2024 from investors including the carmaker **Stellantis**, french chemical company **Arkema**, arms manufacturer **MBDA**; as well as state-owned lender **Bpifrance**.[36]
- **Nanode** (Canada) has developed a low-cost tin foil anode technology for lithium-ion and sodium-ion batteries to increase volumetric energy density up to 50% while saving up to 60% on raw material costs and processing costs.[37]
- **LiNa Energy** (UK) spun out of the University of Lancaster in 2017, to commercialise solid state sodium-metal-chloride batteries for energy storage applications. In 2024, LiNa Energy secured £3.5 million funding – jointly provided through equity funding (£2.7million) and **Innovate UK** (£0.8 million) – to scale up to automatic manufacturing through the construction of the company's first pilot-scale production facility.[38]
- **Peak Energy** (US) – a startup founded in 2023, plans to produce SIBs for energy storage applications to support the growth of AI data centres. Peak closed a $55 million Series A funding round in July 2024 led by **Xora Innovation** and joined by existing backers **Eclipse**

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[32] https://www.altris.se/news/altris-welcomes-clarios-and-maersk-growth-as-new-investors-in-series-b1-funding-round
[33] https://www.ess-news.com/2025/03/12/dutch-start-up-develops-sodium-ion-battery-tech-for-solar-colocation/
[34] https://www.eu-startups.com/2025/03/moonwatt-raises-e8-million-to-transform-solar-power-with-novel-sodium-ion-batteries/
[35] https://www.tiamat-energy.com/accelerating-fundraising-for-industrialization-of-sodium-ion-batteries-in-france/
[36] https://www.ess-news.com/2025/04/25/consultation-over-5-gwh-french-sodium-ion-battery-factory/
[37] https://www.internationaltin.org/startup-nanode-demonstrates-low-cost-tin-foil-anodes-for-lithium-ion-batteries/
[38] https://www.lina.energy/2024/03/20/lina-energy-secures-3-5m-funding-to-take-significant-stride-in-scaling-journey/

Ventures and **TDK Ventures**. Peak plans to use the support in part to build a US factory that is expected to open in 2026.[39]

Lithium's recent price crashes have weakened the cost advantage of sodium-ion, highlighting the need for new technologies to not only succeed when the incumbent gets expensive, but also on its own technical merit.[40] Stanford University spinout **Bedrock Materials** announced in April 2025 that it is winding down operations and returning funds to investors after conceding that its Na-ion tech faced cost-competition challenges with Li-ion incumbents.[41] **Natron**, another US start developing Prussian Blue sodium-ion batteries for energy storage applications also announced it was ceasing operations in late August 2025, due to a lack of funding and cash flow. This lead to the permanent closure of its California headquarters and Michigan facility, as well as the cancellation of its planned $1.4 billion North Carolina gigafactory.[42]

In 2021, battery market leader **CATL** unveiled its first-generation Na-ion cell at ~160 Wh/kg and indicated plans for a supply chain by 2023.[43] True to that, in 2023 CATL announced that **Chery**, a Chinese automaker, will launch the first EV powered by CATL's sodium-ion batteries, integrating them into a small city car.[44] Earlier this year, CATL announced the mass-production of **Naxtra** sodium-ion packs capable of 500 km range EVs, with an energy density of 175 Wh/kg - the highest among sodium-ion batteries worldwide, and comparable to LFP batteries.[45]

With growing interest from battery giants, automakers and grid developers, sodium-ion batteries are poised to become a viable alternative for low-cost, safe, and scalable energy storage – particularly in regions seeking to reduce dependence on lithium supply chains.

3.3.2 Lithium-sulfur Batteries

Lithium-sulfur (Li-S) has long been touted as a "next big thing" in batteries due to its high theoretical energy density and low cost. Instead of metal oxide, the cathode is sulfur – a globally abundant byproduct with almost negligible cost, enabling localised supply chains. Sulfur's theoretical specific energy is extraordinarily high (up to ~2,500 Wh/kg) and its practical cell energy of **500–700 Wh/kg** has resulted in commentators describing Li-S as a "holy grail" which doubles the energy density of Li-ion at a fraction of the cost.[46,47]

Li-S batteries were originally invented back in the 1960s,[48] but commercialisation has been beset by poor cycle life: the chemistry involves a multi-step conversion, producing soluble lithium polysulfides

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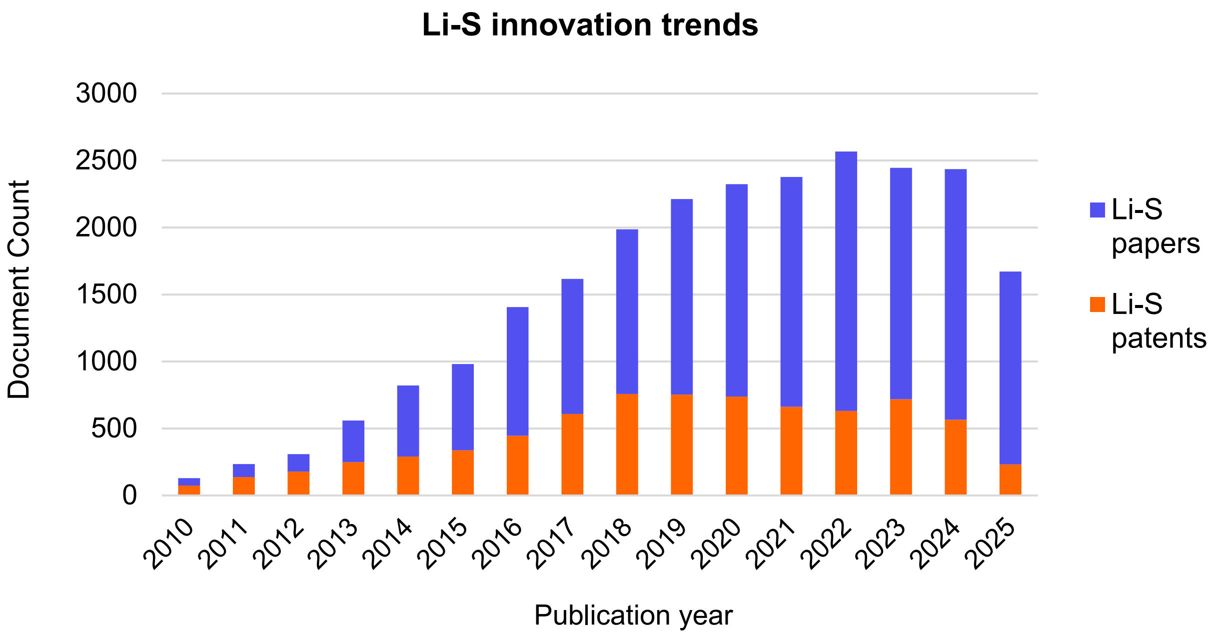
[39] https://www.peakenergy.com/news/close-series-a-2024
[40] https://www.goldmansachs.com/insights/articles/electric-vehicle-battery-prices-are-expected-to-fall-almost-50-percent-by-2025
[41] http://linkedin.com/pulse/sodium-stopped-making-sense-spencer-gore-uy9ac/
[42] https://www.manufacturingdive.com/news/sodium-ion-battery-natron-energy-shutters-halts-NC-factory-plans/759479/
[43] https://www.catl.com/en/news/665.html
[44] https://www.catl.com/en/news/6013.html
[45] https://www.catl.com/en/news/6401.html
[46] https://pubs.acs.org/doi/10.1021/acscentsci.0c00449
[47] https://pubs.acs.org/doi/10.1021/acsenergylett.4c02563
[48] US Patent: US3413154A – Organic electrolyte cells

that "shuttle" between electrodes, causing rapid capacity fade as active sulfur is lost from the cathode. Sulfur cathodes are also electrically insulating and require significant conductive additives leading to additional cost and manufacturing complexities.



Despite these issues, commercial and academic interest has grown steadily, with many start-ups targeting weight-critical applications that Li-ion currently struggles to adequately address such as satellites, drones and military vehicles. Electric aviation – including short-range flights or vertical take-off and landing aircraft – are also longer-term objectives.

Aerospace and defence are the likely first adopters of LiS due to its improved energy density characteristics. US start-up **Lyten** is one of the current Li-S frontrunners in terms of scale, capital and ambition. Lyten has developed nanostructured carbon scaffolds to trap polysulfides using a proprietary 3D graphene-sulfur cathode. It claims that its batteries weigh as much as 40% and 70% less than lithium-ion NMC and LFP batteries, respectively, and can be manufactured on the same equipment lines that fill gigafactories today. If the company's material and process claims hold up, it could dominate many of the high-energy, weight-critical markets (EVs, aerospace, drones). With over $625 million in capital raised from major investors including **Stellantis**, **FedEx**, **Honeywell** and the **U.S. Department of Energy**, Lyten recently acquired **Northvolt's** intellectual and physical assets including 16 GWh of existing battery manufacturing capacity in Sweden, and its Li-metal venture **Cuberg**.[49,50]

There are a number of other startups with significant amounts of financial backing and formal IP protection looking to commercialise novel battery chemistries. Investors also include EV manufacturers and incumbent automakers investing in these startups in order to gain a stake in the

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[49] https://lyten.com/2025/08/07/lyten-to-acquire-all-remaining-northvolt-assets-in-sweden-and-germany/
[50] https://lyten.com/northvolt-acquisition/

new technology and secure offtake agreements in an effort to enhance their competitive advantage. These are outlined below where information is publicly available:

- **Molyon** (UK) – a spinout from the University of Cambridge, developing a cathode technology based on metallic molybdenum disulfide (MoS_2) that allows sulfur to remain stable and provide high energy density over hundreds of cycles. Molyon have demonstrated pouch cell energy density of 500 Wh/kg and is targeting drones, robotics, EVs, and storage applications. Molyon raised $4.6M in its first round co-led by **IQ Capital** and **Plural** in November 2024.[51] The funding will support manufacturing activities at their pilot facility in Cambridge by increasing staff numbers, including battery engineers, material scientists, and operations personnel.
- **Theion** (Germany) – is developing crystalline sulfur cathode technology based on a Direct Crystal Imprinting (DCi) method (no slurry coating, no solvents, no water, no drying) directly from molten Sulfur in a few seconds. The company raised €15 million ($16.4 million) from investors to scale up its technology to pouch cell scale for further validation.[52] The Series A funding round was led by technology holding company **Team Global**, the **Geschwister Oetker Beteiligungen** group and German renewables firm **Enpal**.
- **Gelion** (Australia) is working on a sodium-sulfur and lithium-sulfur cell technology foundation following their acquisition of **OXLiD** and the IP acquired from **OXIS** and **Johnson Matthey**. Gelion previously announced the fabrication of a 395 Wh/kg lithium-sulfur 9.5 Ah pouch cell (commercial cell format).[53]
- **Zeta Energy** (US) use a proprietary **sulfurised-carbon cathode** with a lithium anode, aiming to solve the polysulfide shuttle and improve stability. **Stellantis** announced a partnership with Zeta for developing Li-S EV batteries in December 2024, with a view to power Stellantis electric vehicles by 2030.[54]

Though some companies have announced high-profile partnerships and funding, many have experienced setbacks and have had to pivot or close.

- **Sion Power** (US) partnered with **Airbus Defence and Space** to test their Li-S technology in a prototype High Altitude Pseudo-Satellite (HAPS) aircraft powered by solar energy during the day and lithium sulfur batteries at night, in real life conditions during an 11-day flight.[55] Despite plans announced by the company intending to expand manufacturing volume in 2017,[56] the company appears to have shifted focus to a lithium-metal battery, having more recently announced plans to expand operations at its Arizona site.[57] Sion Power claims to have

[51] https://tech.eu/2024/11/26/cambridge-uni-spin-out-molyon-raises-46m-from-plural-to-manufacture-next-generation-batteries/
[52] https://www.reuters.com/technology/german-sulfur-battery-startup-theion-raises-164-mln-scale-up-2025-03-20/
[53] https://gelion.com/news/lithium-sulfur-cell-high-energy-density-milestone-achieved/
[54] https://www.stellantis.com/en/news/press-releases/2024/december/stellantis-and-zeta-energy-announce-agreement-to-develop-lithium-sulfur-ev-batteries
[55] https://sionpower.com/2014/sion-powers-lithium-sulfur-batteries-power-high-altitude-pseudo-satellite-flight/
[56] https://www.businesswire.com/news/home/20161003005315/en/Sion-Power-Delivers-Generation-Battery-Performance-Patented
[57] https://sionpower.com/2022/sion-power-announces-plans-to-expand-battery-manufacturing-operations/

developed a Li-metal battery capable of delivering up to 500 Wh kg^{-1}, more than double the capacity of existing Li-ion batteries in EVs today.

- **Sony** (Japan), the company that successfully commercialised the first Li-ion battery, reportedly had plans back in 2015 to introduce a Li-S battery into the consumer electronics market in 2020,[58] but no further announcements have been made since, suggesting that the company has scrapped such plans.
- **Oxis Energy** (UK) was a lithium-sulfur battery developer with notable investors including **Samsung**, **Sasol,** and **Umicore**. The company was also targeting aviation, working with US aircraft manufacturer **Bye Aerospace** to develop lightweight lithium-sulfur cells for battery packs with energy densities of 500 Wh kg^{-1}. However, the company failed to secure additional investment to continue with product development, forcing it to file for bankruptcy and sell off its assets, including some 200 patents.[59]

If technical hurdles around cycle life and stability can be overcome, lithium–sulfur batteries could unlock ultra-light, high-energy storage for aviation, defence, and long-range mobility – potentially redefining performance benchmarks in the industry.

3.3.3 Solid-state Batteries

Solid-state batteries (SSBs) replace the liquid electrolyte and separator with a solid electrolyte (ceramic, glassy or polymer) and often use a lithium metal anode. By enabling an ultra-high energy density lithium metal anode and eliminating flammable liquid electrolytes, SSBs promise higher energy density (theoretically 300–500 Wh/kg), improved safety, and faster charging than today's Li-ion incumbents.[60,61] SSBs have found commercial use in niche, small-scale applications such as in pacemakers and wearable electronic devices,[62,63] but mass adoption of the technology in large markets remains to be seen. A recent Bain report notes that solid-state batteries will likely stay in the single digits of market share by 2030,[64] as Li-ion continues to dominate in the near term. Challenges remain in scaling up manufacturing and ensuring longevity (e.g. preventing lithium dendrites forming through the solid electrolyte).[65]

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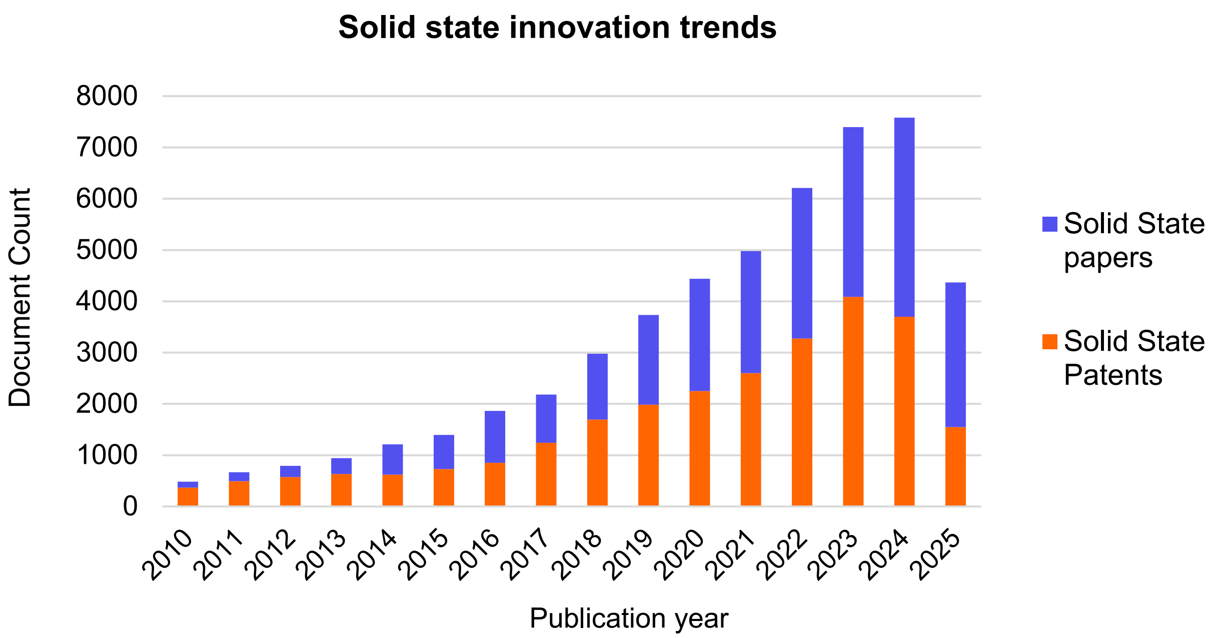
[58] https://asia.nikkei.com/Tech-Science/Tech/Sony-battery-to-offer-40-longer-phone-life
[59] https://www.electrive.com/2021/05/21/oxis-energy-is-facing-bankruptcy/
[60] https://www.sciencedirect.com/science/article/pii/S1385894722006842
[61] https://pubs.acs.org/doi/10.1021/acsenergylett.0c02584
[62] https://www.sciencedirect.com/science/article/pii/0167273881900977
[63] https://article.murata.com/en-eu/article/solid-state-battery-that-supports-wearables-2
[64] https://www.bain.com/insights/navigating-the-ev-battery-ecosystem/
[65] https://pubs.acs.org/doi/10.1021/acs.chemrev.0c00101



Major automakers and startups are racing to commercialise SSBs: **Toyota**, for instance, has touted an in-house program promising batteries that offer 20% further cruising range and 10-minute charging times and claimed mass-production will be achieved by 2027–28.[66] Japan's **Nissan** aims to launch solid-state batteries for EVs by early 2029,[67] while Germany's **Mercedes-Benz Group** and U.S. battery startup **Factorial** is working together on a solid-state battery that will be ready for production by the end of the decade.[68] Factorial also has joint development agreements with automakers including Stellantis, Hyundai and Kia.

A number of pure-play startups have attracted huge investments from major car manufacturers in recent years:

QuantumScape (US), in conjunction with **Volkswagen**'s battery division, **PowerCo**, demonstrated its solid-state lithium-metal batteries powering a Ducati electric motorcycle at IAA Mobility in September, boasting an energy density of 844 Wh/L (301 Wh/kg) and 10C continuous discharge.[69] QuantumScape and PowerCo have expanded their collaboration, with up to $131 million in new milestone payments over two years to scale manufacturing and increase prototype cell deliveries.

Solid Power (US) spun out of University of Colorado Boulder in 2011 with funding from **DARPA**, and now boasting significant collaborations with both **BMW** and **Ford** for the joint development of all-solid-state batteries. Prior to listing on the NASDAQ, more than $140 million in initial funding for Solid Power

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[66] https://www.toyota-europe.com/news/2023/battery-technology
[67] https://global.nissannews.com/en/releases/nissan-shows-in-construction-all-solid-state-battery-pilot-line-in-japan
[68] https://group.mercedes-benz.com/innovations/drive-systems/electric/solid-state-battery-test-car.html
[69] https://chargedevs.com/newswire/quantumscape-and-powerco-demonstrate-solid-state-ev-batteries-in-ducati-electric-motorcycle/

was provided by notable investors such as **Hyundai**, **Volta Energy Technologies**, **Umicore**, **Sanoh**, **A123 Systems**, and **Solvay**.

Ilika (UK), originally a materials discovery spin-out from the University of Southampton, is one of the UK's only listed pure-play solid-state battery companies, transitioning from micro-batteries (targeting medical devices, industrial sensors and wearables) to EV-scale solid-state cells with support from the UK's Faraday Battery Challenge.

ProLogium (Taiwan) is specialising in the development and manufacturing of next-generation lithium-ceramic batteries for electric vehicles, consumer markets, and industrial applications. It expects to begin construction of a €5.2 billion to a Dunkirk gigafactory with support from the French government.[70] **Mercedes-Benz** is a strategic partner,[71] making ProLogium one of the most credible non-Chinese, non-US SSB challengers operating in Europe.

OXLiD (UK) was focused on lithium-sulfur and solid electrolyte innovations licensed from the University of Oxford. Acquired by AIM-listed **Gelion** in 2023 for £4.2 million,[72,73] it developed a lightweight, ultra-thin and flexible electrolyte system targeting high-energy long-cycle batteries for aerospace and automotive applications.

BTRY (Dübendorf, Switzerland) is a spin-off from EMPA & ETH Zurich that raised CHF 900,000 ($1.1 million) in January 2024 and is currently raising seed funding.[74] It is developing all-solid-state battery technology with thin layers and no liquids either in the components or in the manufacturing process, and which relies on vacuum technology from the semiconductor industry.[75]

SOLiTHOR (Belgium) was founded in 2021 as a spin-off of **imec**, a world-leading nanoelectrics and digital technologies R&D organisation. Its nano-Solid Composite Electrolyte technology will target aviation, UAM (urban air mobility), aerospace applications initially. SoOLiTHOR raised €10 million in seed funding in 2022, led by **imec.xpand**, **LRM**, **Nuhma**, **FPIM**.[76]

Basquevolt (Spain) founded in 2021 based on research from **CIC energiGUNE** is developing solid-state battery electrolytes that claim to enable >50% more range and integrate into existing battery factories. Positioning itself as a leading European supplier, it has raised more than €50 million since launch (including public grants), most recently receiving €2.5 million in grant funding via European Commission EIC Accelerator; connected with possibility of an additional €10 million in equity investment.[77]

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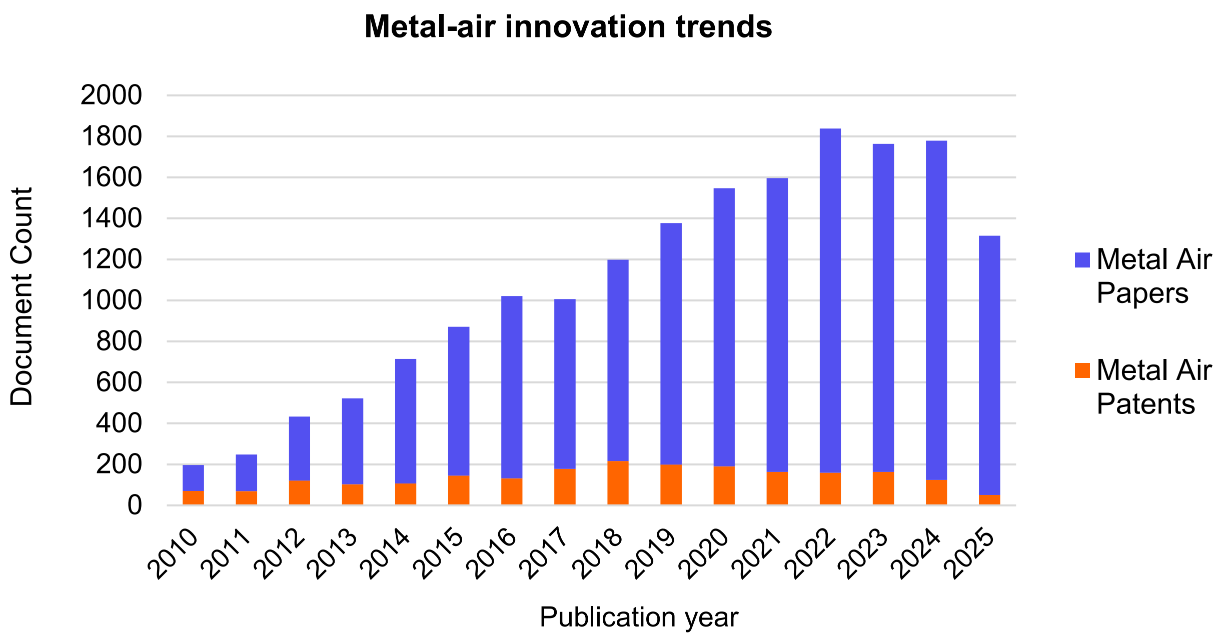
[70] https://prologium.com/giganews-the-construction-bulletin-prologiums-gigafactory-in-dunkirk/
[71] https://prologium.com/prologium-and-mercedes-benz-entered-into-a-technology-cooperation-agreement-to-develop-solid-state-battery-cells-for-electric-vehicles/
[72] https://www.faraday.ac.uk/success-stories/oxlid/
[73] https://gelion.com/oxlid/
[74] https://btry.ch/btry-raises-chf-900000/
[75] https://ethz.ch/en/news-and-events/eth-news/news/2024/04/eth-spin-offs-develop-high-performance-batteries.html
[76] https://www.solithor.com/en/media/111/press-releases/press-release
[77] https://basquevolt.com/en/news/news/basquevolt-selected-by-european-commissions-eic-accelerator-to-drive-solid-state-battery-electrolyte-technology-in-europe

While mass-market adoption remains several years away, solid-state batteries represent a transformative leap in safety and energy density, with strong backing from global automakers and a clear roadmap toward commercialisation by the end of the decade.

3.3.4 Metal-air Batteries

Metal-air batteries are another class with huge theoretical energy densities.[78] They use a metal (such as iron, zinc, aluminium, or lithium) as the anode and oxygen from air as the "active" cathode material (drawn in during discharge) resulting in an extremely weight-efficient and low-cost battery. Many metal-air chemistries today are primary (non-rechargeable) or only slowly rechargeable, but new designs are emerging for rechargeable metal-air systems**.** While this category remains very much in the academic domain, as reflected by the chart below, a handful of start-ups are actively pursuing commercialisation pathways.



A standout example is iron-air batteries for stationary storage. Iron-air cells (which combine iron and oxygen to form rust when discharging and reverse the reaction when charging) can potentially store energy at very low cost using abundant materials. Massachusetts startup **Form Energy** has made headlines with its iron-air battery aimed at multi-day grid storage. Form's battery can store energy for 100 hours (4+ days) at system costs estimated around $20/kWh – far cheaper than Li-ion for long-duration applications.[79] While these systems are not ideal for high-power applications or rapid charge and discharge cycles (because charging and discharging require several hours), they increasingly address the critical need to mitigate renewable energy curtailment, provide backup during extended periods of low wind and solar generation, and enhance overall grid resiliency. Form Energy has raised a total of $1.2 billion since its inception in 2017, backed by cleantech financiers **GE Vernova**, **Bill**

[78] https://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_M-Air.pdf
[79] https://www.utilitydive.com/news/form-energys-20kwh-100-hour-iron-air-battery-could-be-a-substantial-br/603877/

Gates' Breakthrough Energy, **ArcelorMittal** and others, and is constructing its first full-scale factory in West Virginia with the goal of field deployment at a 1 MW/100 MWh scale in 2025.[80]

Zinc-air batteries have been used for decades as primary cells in hearing aids. Rechargeable versions are difficult due to dendrite formation and air electrode degradation,[81] so much of the R&D continues to be in the academic domain,[82,83] however, there are some companies trying to tackle the problem. **ABOUND Energy** (Formerly Zinc8 Energy, Canada) developed a flow-style zinc-air system: zinc particles are generated in a charge tank and recombined with oxygen in a discharge tank, physically separating power and energy components. Another Canadian startup **e-zinc** is also developing zinc-air batteries that can supply power long-term at a low cost and are backed by Mitsubishi Heavy Industries and Toyota Ventures.[84]

Lithium-air (Li-O_2) is the ultimate in energy density – theoretical specific energy over 2,000 Wh/kg (comparable to gasoline). It uses a lithium metal anode and oxygen from air to form lithium oxides during discharge. However, it is extremely challenging to scale the technology: the reactions form insulating precipitates; round-trip efficiency is low; and oxygen components can destroy electrolytes. In 2023, Researchers at the Illinois Institute of Technology (IIT) and U.S. Department of Energy's (DOE) Argonne National Laboratory announced a lab-scale Li-air cell that could operate in a closed pure oxygen environment with high capacity and claimed to have overcome some cathode clogging issues by using a mixed catalyst.[85] Following this, the Argonne Scientists established **Air Energy** focus on developing prototypes for small-scale applications like wearable technology and unmanned aerial systems. Over the next five years, the company plans to scale its technology to power electric vehicles, personal electronics, and heavy-duty transportation.[86]

Aluminium-air is another variant – it is already used in specialty applications as a primary battery for stationary backup power generators for data centres with companies such as **Phinergy** targeting the replacement of diesel generators. However, traditional Al-air batteries cannot (yet) be electrically recharged – the aluminium oxide byproduct clogs the electrodes, and the cell must be mechanically refuelled (i.e., replace the aluminium, refresh electrolyte). R&D has aimed to make "rechargeable" Al-air by clearing or regenerating the aluminium,[87] but as of 2025, most aluminium-air systems are effectively single-use; fully rechargeable commercial Al-air batteries (or indeed Al-ion) are not yet

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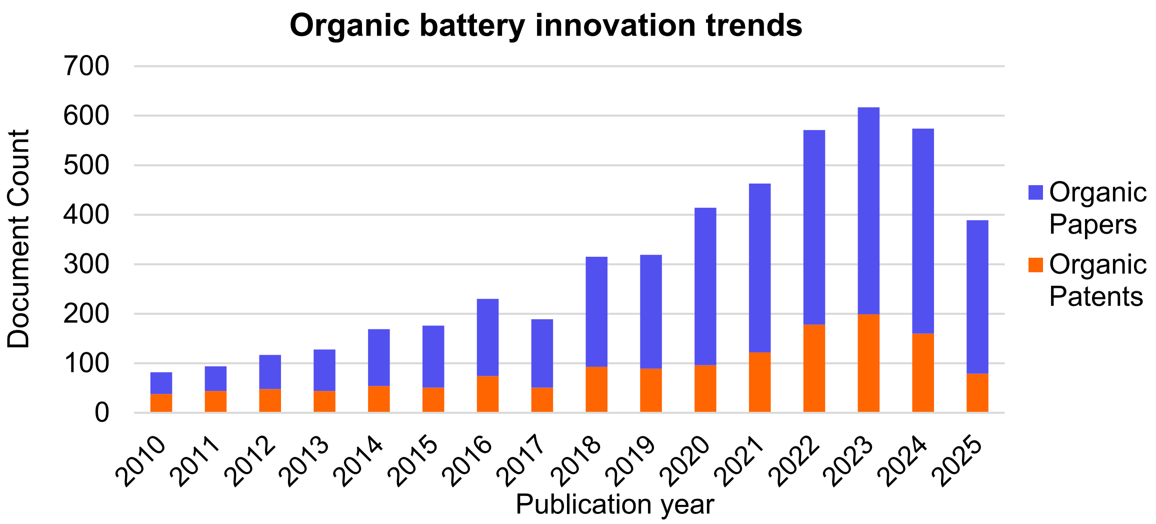
[80] https://formenergy.com/form-energy-secures-405m-in-series-f-financing-to-expand-iron-air-battery-business-and-operations/
[81] https://pubs.rsc.org/en/content/articlelanding/2014/cs/c4cs00015c
[82] https://hiperzab.eu/en
[83] https://onlinelibrary.wiley.com/doi/10.1002/inc2.12014
[84] https://www.mhi.com/news/24062702.html
[85] https://www.anl.gov/article/new-design-for-lithiumair-battery-could-offer-much-longer-driving-range-compared-with-the-lithiumion
[86] https://www.ess-news.com/2024/11/29/air-energy-launches-to-bring-solid-state-lithium-air-batteries-closer-to-commercialization/
[87] https://pubs.rsc.org/en/content/articlelanding/2014/ra/c3ra44659j

available. Similarly, magnesium-air and calcium-air are being researched but are far from practical, with no credible startups aiming to launch a commercial product yet.[88,89]

In summary, metal-air batteries hold promise especially for grid storage (enabling seasonal storage at low cost) and potentially for ultra-long-range mobility (if rechargeable versions succeed). Companies like Form Energy are turning promise into reality for stationary needs now. For EVs, a practical metal-air (rechargeable many times) would be a paradigm shift – allowing perhaps a small "breathing" battery to give car ranges of thousands of kilometres – but significant scientific breakthroughs are still needed, and commercial candidates must be cost competitive with incumbent technologies. Thus, metal-air batteries in EVs remains speculative and, in any case, outside the 2020s timeframe for mass production.

3.3.5 Organic Batteries

"Organic batteries" refer to a broad class of energy storage devices that use carbon-based compounds (such as quinones or viologens) as the active materials, instead of the inorganic metals or metal oxides found in conventional batteries.[90] The primary advantage cited is scalability; increasing energy capacity can be achieved by utilising larger tanks. Organic batteries cannot deliver high energy density and power output and thus are not aiming to replace lithium-ion in EVs but are carving niches in stationary grid storage, safe residential backup, and sustainable industrial storage solutions. Their competitive edge lies in safety, sustainability, and tunability, though challenges remain around scalability, stability, and cost.



Several startups and research groups have attempted to commercialise this. In the US, **Quino Energy** (a Harvard spin-off) is developing quinone-based flow batteries for commercial and grid applications. Following significant US Department of Energy backing and a $4.55 million seed funding round in 2023, Quino announced a collaboration with the established vanadium-flow company

[88] https://pubs.rsc.org/en/content/articlelanding/2023/ta/d2ta07774d
[89] https://www.nature.com/articles/s41586-023-06949-x
[90] https://www.nature.com/articles/s44359-025-00079-5

Terraflow Energy, targeting deployment of organic long duration uninterrupted power supply solutions for AI data centres, industrial operations, and remote infrastructure.[91]

French startup **Kemiwatt** is developing non-corrosive alkaline organic redox flow batteries and built a 10 kW prototype and a 20 kW industrial demonstrator for smart grid and microgrid electricity storage applications. In late 2023, Kemiwatt announced a strategic partnership with the filtration company **MANN+HUMMEL** to co-develop a new generation of their flow batteries.[92] While this suggests progress toward commercial product, further publicly available progress updates have not been forthcoming. In 2023, German startup **JenaBatteries** showcased a 10 kW/100 kWh industrial prototype but, after financial challenges, was acquired by **Suqian Time Energy Storage**, a major Chinese manufacturer of metal-free flow batteries. [93]

As the demand for sustainable, safe, and scalable energy storage grows, organic batteries offer a compelling pathway – leveraging abundant materials and modular designs to support long-duration grid applications and decentralised power systems, with the potential to reshape how we think about battery sustainability. While their energy density and long-term stability still lag behind more mature technologies, targeted R&D and niche deployments could pave the way for practical adoption in low-impact, stationary environments.

[91] https://quinoenergy.com/terraflow-energy-and-quino-energy-sign-agreement-to-advance-organic-flow-battery-chemistry/
[92] https://kemiwatt.com/
[93] https://www.jenaflowbatteries.de/en-de/ueber-uns

4 Commercialisation Challenges

Following a visit to Chinese battery factories in July 2025, several venture capital firms – including **2150**, **Energy Impact Partners**, **Extantia Capital**, **Kompas VC**, and **Planet A Ventures** – have elected to either pause investments in certain sectors or explore collaborative opportunities between Chinese companies across the supply chain with their portfolio companies. They are now advising portfolio companies to develop a "China strategy" that could involve European cleantech firms setting up manufacturing in China, forming partnerships with technology leaders, or inviting Chinese companies to help build and operate plants in Europe.[94] Western startups face several headwinds that have led these VCs to conclude that China's advances have made it difficult or impossible for them to compete.

High capital expenditures and investor alignment

Scaling a new battery technology from lab prototype to gigafactory is capital-intensive. The European non-governmental organisation **Transport & Environment** estimates that:[95]

- A European battery cell factory costs about €100 million per GWh, which is 47% more expensive than building the same capacity in China.
- Operating costs (energy, labour, materials) in Europe can be up to 70% higher.
- Meeting Europe's projected demand of 1 TWh of batteries by 2030 will require around €100 billion of investment. If all of the announced 1.8 TWh of capacity were to be built, the required investment would rise to €175 billion.

High capital expenditure makes financing gigafactories difficult, as equity investors may hesitate due to the large investments required and the long payback periods. Financing may also rely on offtake agreements with creditworthy customers, which can be challenging for emerging, unproven technologies. Additionally, hardware scale-up timelines often exceed venture capital expectations for liquidity, creating funding gaps that may require government grants, corporate partnerships, or non-dilutive funding sources.

The high capital intensity of a gigafactory has knock-on effects on the supply chain – recent analyses state that battery packs account for 30–40% of an EV's total cost.[96] If European manufacturers source cells from these higher-cost plants, their vehicles will be structurally more expensive than Chinese competitors. This is underscored by **Ford**'s recent admission that it cannot match **BYD**'s battery cost structure.[97] Chinese automakers like BYD benefit from vertical integration controlling raw materials supply, cell production, vehicle assembly and even distribution, enabling them to price aggressively.

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[94] https://www.bloomberg.com/news/articles/2025-09-21/china-road-trip-exposes-list-of-uninvestable-assets-in-the-west

[95] https://www.transportenvironment.org/uploads/files/An-industrial-blueprint-for-batteries-in-Europe-How-Europe-can-successfully-build-a-sustainable-battery-value-chain.pdf

[96] https://assets.kpmg.com/content/dam/kpmg/cz/pdf/2024/Charging%20ahead.pdf

[97] https://fordauthority.com/2025/10/ford-ceo-jim-farley-says-company-cant-match-byd-ev-battery-cost/

Supply-chain challenges

The IEA's Global Critical Minerals Outlook 2025 notes that the top three producing countries (Argentina, Chile and China) account for nearly 96% of global lithium carbonate supply.[98] Similar patterns exist for cobalt, nickel and graphite. In addition, mineral prices are volatile: after a dramatic run-up in 2021–22, **lithium spot prices fell 75% in 2023**, while **nickel, cobalt and graphite prices dropped 30–45%** while demand for these minerals continued to grow. Such volatility can undermined business plans and deter investors.

This concentration exposes new entrants to supply disruptions, geopolitical risk, and the risk of accessing precursor materials on favourable terms. Regulatory initiatives such as the EU Critical Raw Materials Act seek to diversify supply and incentivise recycling initiatives, but achieving resilience and building up end-of-life battery capacity will take years.

Manufacturing know-how and competence

Battery manufacturing involves hundreds of interdependent process steps—coating, drying, calendering, formation and more. Efficient production requires tacit knowledge gained through trial and error that cannot be gleaned from published research alone. Many innovators focus on chemistry but neglect process development until it is too late, leading to poor yields and costly delays. Incumbents like **CATL** and **LG** benefit from decades of experience and vertically integrated supply chains, allowing them to scale efficiently and protect margins. Start-ups must therefore either build manufacturing teams early or partner with experienced contract manufacturers, assuming they have the expertise in scaling novel chemistries.

It is clear that overcoming these commercialisation barriers will require more than technical breakthroughs observed in the lab – success demands strategic alignment across capital allocation, manufacturing capability, and policy support from the outset. Without that coordination, even the most promising battery innovations risk stalling before they scale. The startups that break through will be the ones that move quickly, iterate in production, and lock in the right partners early.

[98] https://www.iea.org/reports/global-critical-minerals-outlook-2025

5 Conclusions

This white paper has explored the technical, commercial, and strategic landscape surrounding emerging battery chemistries. The findings point to a clear inflection point in energy storage innovation: while lithium-ion remains dominant in the market today, its limitations in energy density, material availability, and geopolitical exposure are driving a surge in alternative technologies.

The data shows that academic and industrial R&D is increasingly shifting toward non-Li-ion chemistries, with patent filings and publications on sodium-ion, lithium–sulfur, solid-state, and metal-air batteries growing rapidly. These technologies offer distinct advantages — in cost, safety, scalability, and/or performance — but each faces specific commercialisation hurdles. Sodium-ion batteries are gaining traction for stationary storage and low-cost mobility, while lithium–sulfur and solid-state batteries are targeting high-performance applications like aviation and premium EVs. Metal–air and organic systems are emerging as candidates for long-duration and sustainable grid storage.

Against this backdrop of technical diversification, the global market dynamics reveal a widening gap between East and West. China's dominance in battery manufacturing, mineral processing, and IP generation has created an entrenched position that Western startups have struggled to match in recent years. Despite significant investment, Western ventures have repeatedly failed to scale, highlighting the importance of manufacturing competence, supply chain access, and strategic partnerships – factors that will ultimately determine who leads the next wave of battery innovation.

These findings suggest that the future of battery innovation will be pluralistic: no single chemistry will replace Li-ion, but a portfolio of technologies will emerge to serve different segments. Success will depend not only on technical merit but on the ability to navigate scale-up, secure materials, and align with industrial ecosystems. The next decade and beyond will be defined by how effectively innovators can translate promising lab results into reliable, cost-effective products at scale.

Appendix: Literature Search Methodologies

To assess research and intellectual property trends in alternative battery chemistries, the following approach was adopted:

Patent literature search strings

Comprehensive patent searches were conducted using Questel's Orbit Intelligence platform. Boolean search strings were applied to capture as many relevant results as possible while minimising irrelevant hits. Searches targeted keywords and technology classes associated with solid-state electrolytes, lithium metal anodes, sodium-ion, metal-air, and lithium-sulfur systems. To ensure relevance to rechargeable batteries, searches included the classification code H01M-010, which covers secondary (rechargeable) battery technologies.

Chemistry	Search String
Lithium-ion	((LITHIUM_ION OR LI_ION OR (SECONDARY 1D LITHIUM 1D (BATTERY OR BATTERIES)) OR LIB OR (LI_ION 1D (BATTERY OR BATTERIES)) OR LCO OR LICOO2 OR LFP OR LIFEPO4 OR NMC OR NCA OR LMO OR LIMN2O4)/TI/AB/CLMS AND (H01M-010/+)/IPC/CPC)
Sodium-ion	((SODIUM_ION OR NA_ION OR (SECONDARY 1D SODIUM 1D (BATTERY OR BATTERIES)) OR (NA_ION 1D (BATTERY OR BATTERIES)))/TI/AB/CLMS AND (H01M-010)/IPC/CPC)
Potassium-ion	((POTASSIUM_ION OR K_ION OR (SECONDARY 1D POTASSIUM 1D (BATTERY OR BATTERIES)) OR (K_ION 1D (BATTERY OR BATTERIES)))/TI/AB/CLMS AND (H01M-010)/IPC/CPC)
Magnesium-ion	((MAGNESIUM_ION OR MG_ION OR (SECONDARY 1D MAGNESIUM 1D (BATTERY OR BATTERIES)) OR (MG_ION 1D (BATTERY OR BATTERIES)))/TI/AB/CLMS AND (H01M-010)/IPC/CPC)
Aluminium-ion	(((ALUMINIUM_ION OR ALUMINUM_ION) OR AL_ION OR (SECONDARY 1D (ALUMINIUM OR ALUMINUM) 1D (BATTERY OR BATTERIES)) OR (AL_ION 1D (BATTERY OR BATTERIES)))/TI/AB/CLMS AND (H01M-010)/IPC/CPC)
Lithium sulfur	((LITHIUM_SUL?UR OR LI_S OR (SECONDARY 1D LITHIUM_SUL?UR 1D (BATTERY OR BATTERIES)) OR (LI_S 1D (BATTERY OR BATTERIES)) OR (SUL?UR 1D (BATTERY OR BATTERIES)))/TI/AB/CLMS AND (H01M-010)/IPC/CPC)
Metal-air	((METAL_AIR OR METAL_OXYGEN OR LITHIUM_AIR OR LI_AIR OR LITHIUM_OXYGEN OR LI_O2 OR SODIUM_AIR OR NA_AIR OR SODIUM_OXYGEN OR NA-O2 OR ZINC_AIR OR ZN_AIR OR IRON_AIR OR FE_AIR OR ALUMINIUM_AIR OR ALUMINUM_AIR OR AL_AIR)/TI/AB/CLMS AND (H01M-010)/IPC/CPC)
Silicon Anode	((SILICON_ANODE OR SILICON NEGATIVE ELECTRODE OR SILICON-RICH ANODE OR SILICON-DOPED ANODE OR SI_ANODE OR SILICON_BASED ANODE OR SI_BASED ANODE OR SILICON_CARBON COMPOSITE OR SI-C COMPOSITE OR SI_GRAPHITE OR SILICON NANO+ OR SI NANO+ OR SILICON ALLOY ANODE OR SI ALLOY ANODE OR (SILICON 1D BATTER+) OR (LITHIUM 4D SILICON))/TI/AB/CLMS AND (H01M-010)/IPC/CPC)
Solid State	((SOLID_STATE BATTER+ OR ALL_SOLID_STATE BATTERY OR SOLID POLYMER ELECTROLYTE OR SOLID ELECTROLYTE OR GLASS ELECTROLYTE OR CERAMIC ELECTROLYTE OR SULFIDE ELECTROLYTE OR OXIDE ELECTROLYTE)/TI/AB/CLMS AND (H01M-010)/IPC/CPC)
Calcium ion	((CALCIUM_ION OR CA_ION OR (SECONDARY 1D CALCIUM 1D (BATTERY OR BATTERIES)) OR (CA_ION 1D (BATTERY OR BATTERIES)))/TI/AB/CLMS AND (H01M-010)/IPC/CPC)
Organic	(((ORGANIC 1D BATTER+) OR (ORGANIC 1D (ELECTRODE OR CATHODE OR ANODE)) OR CONDUCTING POLYMER BATTERY OR (POLYMER-BASED BATTERY) OR (REDOX ACTIVE POLYMER+))/TI/AB/CLMS AND (H01M-010)/IPC/CPC)

Academic literature search strings

Academic publication data was gathered through **Lens.org**, using equivalent Boolean search strings to ensure consistency between patent and literature datasets. **Filters applied include:**

- **Document type:** Journal article
- **Fields searched:** Title, Abstract, Keyword, or Field of Study
- **Date range:** Articles published from 2010 onwards

A full-text search was deliberately avoided to reduce noise from papers mentioning adjacent chemistries in passing rather than as the main subject.

Chemistry	Search String
Lithium-ion	("lithium-ion" OR "lithium ion" OR "Li-ion" OR "Li ion" OR "secondary lithium battery" OR LIB OR "Li-ion battery" OR "Li ion battery" OR LCO OR "LiCoO2" OR LFP OR "LiFePO4" OR NMC OR NCA OR LMO OR "LiMn2O4") AND (battery OR batteries) NOT ("fuel cell" OR SOFC OR "solar cell" OR photovoltaic OR perovskite OR supercapacitor OR supercapacitors)
Sodium-ion	("sodium-ion" OR "sodium ion" OR "Na-ion" OR "Na ion" OR "Na-ion battery" OR "Na ion battery") AND (battery OR batteries OR cell OR cells) NOT ("fuel cell" OR SOFC OR supercapacitor OR supercapacitors)
Potassium-ion	("potassium-ion" OR "potassium ion" OR "K-ion" OR "K ion") AND (battery OR batteries OR cell OR cells) NOT ("fuel cell" OR SOFC OR supercapacitor OR supercapacitors)
Magnesium-ion	("magnesium-ion" OR "magnesium ion" OR "Mg-ion" OR "Mg ion") AND (battery OR batteries OR cell OR cells) NOT ("fuel cell" OR SOFC OR supercapacitor OR supercapacitors)
Aluminium-ion	("aluminium-ion" OR "aluminum-ion" OR "aluminium ion" OR "aluminum ion" OR "Al-ion" OR "Al ion") AND (battery OR batteries OR cell OR cells)
Lithium sulfur	("lithium-sulfur" OR "lithium sulphur" OR "Li-S" OR "Li S" OR "Li sulfur" OR "Li sulphur") AND (battery OR batteries OR cell OR cells) NOT ("fuel cell" OR SOFC OR supercapacitor OR supercapacitors)
Metal-air	("metal-air" OR "metal air" OR "metal-oxygen" OR "metal oxygen" OR "lithium-air" OR "Li-air" OR "lithium oxygen" OR "Li-O2" OR "sodium-air" OR "Na-air" OR "sodium oxygen" OR "Na-O2" OR "zinc-air" OR "Zn-air" OR "iron-air" OR "Fe-air" OR "aluminium-air" OR "Al-air") AND (battery OR batteries OR cell OR cells) NOT ("fuel cell" OR SOFC OR supercapacitor OR supercapacitors)
Silicon Anode	(“silicon” OR "silicon anode" OR "Si anode" OR "silicon-based anode" OR "Si-based anode" OR "silicon-carbon composite" OR "Si-C composite" OR "silicon graphite" OR "Si-graphite" OR "silicon nanowire" OR "silicon nanoparticle" OR "Si nanoparticle" OR "Si nanowire" OR "silicon alloy anode" OR "Si alloy anode") AND (battery OR batteries OR cell OR cells) NOT ("fuel cell" OR SOFC OR "solar cell" OR photovoltaic OR perovskite OR supercapacitor OR supercapacitors)
Solid State	("solid-state battery" OR "solid state battery" OR "all-solid-state battery" OR "solid polymer electrolyte" OR "solid electrolyte" OR "ceramic electrolyte" OR "sulfide electrolyte" OR "oxide electrolyte") AND (battery OR batteries) NOT ("fuel cell" OR SOFC OR "solar cell" OR photovoltaic OR perovskite)
Calcium ion	("calcium-ion" OR "calcium ion" OR "Ca-ion" OR "Ca ion") AND (battery OR batteries OR cell OR cells) NOT ("fuel cell" OR SOFC OR supercapacitor OR supercapacitors)
Organic	(“Organic” OR "organic battery" OR "organic batteries" OR "organic electrode" OR "organic cathode" OR "organic anode" OR "polymer battery" OR "polymer cathode" OR "polymer anode" OR "redox-active polymer" OR "conducting polymer battery") AND (battery OR batteries OR cell OR cells) NOT ("fuel cell" OR SOFC OR "solar cell" OR photovoltaic OR perovskite OR supercapacitor)

Data processing

For each search, the number of patents and papers for each year retrieved was exported as CSV files. These datasets were then processed and visualised by creating comparative charts in Microsoft Excel, enabling side-by-side analysis of publication and patenting activity by year and technology category.