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Review

Powering the Future Smart Mobility: A European Perspective on Battery Storage

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Abstract: Batteries are central to the global energy system and fundamental elements for energy transition and future mobility. In particular, the growth in electric vehicle (EV) sales is pushing up demand for batteries. Most of the battery demand for EVs today can be met with domestic or regional production in China, while the share of imports remains relatively large in Europe and the United States. Boosting the industrial base for battery production is therefore a key task for the EU. To make its battery supply chains secure, resilient, and sustainable, the EU's approach consists of improving cooperation among stakeholders, providing the sector with funding, and establishing a comprehensive regulatory framework. In this paper, an accurate review of the state-of-the-art of automotive batteries is provided, including the performance, safety, sustainability, and costs of the different battery technologies. The significant challenges the EU battery sector must face, such as dependencies on third countries and high energy and labor costs, are discussed. An overview of the present European regulation and of future trends is provided.

Keywords: batteries; electric vehicles; automotive sector; European market; European regulation

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1. Introduction

Road transport is responsible for around a quarter of anthropogenic CO_2 emissions in Europe [1]. Vehicle electrification is a viable means to mitigate these emissions, and batteries play a key role in the success of this strategy. Electric mobility is transforming our daily travel experiences, driven by advancements in electric storage systems. Access to batteries is particularly important for ensuring the competitiveness of the automotive sector, as batteries are the most critical component of electric vehicles (EVs) and represent around 25–40% of the total cost of an electric vehicle. In fact, the growth in EV sales is pushing up demand for batteries. According to a Joint Research Center report [2], road transport accounts for 86% of all battery usage, primarily in personal cars, light-duty commercial vehicles, and buses. Automotive batteries need to provide high performance in power, energy storage capacity, and durability, while maintaining low weight, volume, and cost. Additionally, they must comply with automotive safety standards and be recyclable and environmentally sustainable. It is widely believed that an affordable and appropriately sized battery is crucial for the success of electric mobility, and EV manufacturers are actively working toward this goal [3].

In this context, it is not surprising that investments in batteries have been increasing in the last few years. In particular, global investments in EV batteries have increased eightfold since 2018, rising to USD 115 billion in 2023 [4]. Stationary storage accounts for USD 40 billion, for a global battery demand of 850 GWh. China accounts for more than half of this spending, followed by the EU and the USA, while the rest of the world invested only 10% of the global market.

Most venture capital investments focused on innovative battery chemistry and component manufacturers, highlighting a significant interest in alternatives to lithium technologies. An increasing share of investment has also been directed towards battery recycling and reuse, as is evident from Figure 1a. Early-stage investments in lithium technology dominate the market, although non-lithium technologies have been attracting increasing interest in recent times (Figure 1b). These non-lithium batteries include emerging technologies such as metal–hydrogen, solid-state, or sodium-ion, but also more mature solutions, such as redox flow batteries [4].

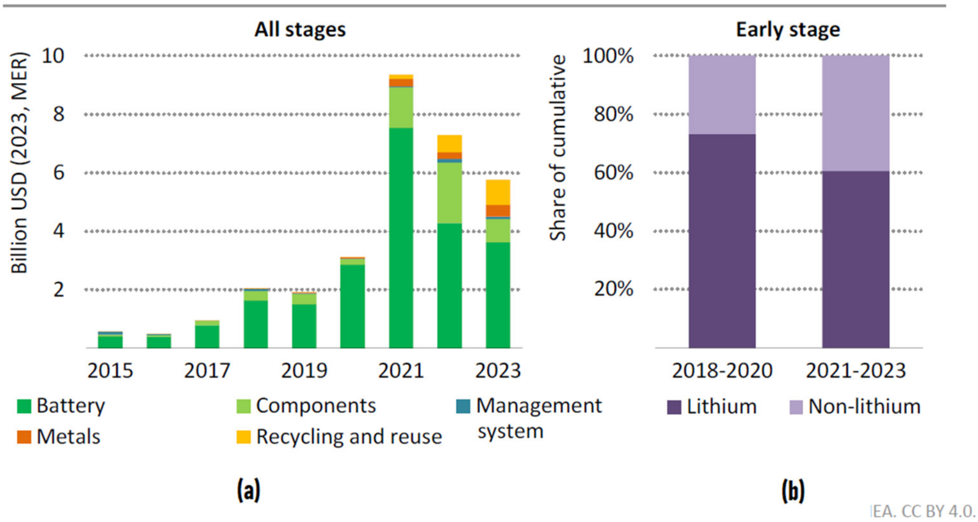

Figure 1. Distribution of venture capital investments per year in battery start-ups (**a**) by technologies; (**b**) by chemistry. Reproduced from [4] under CC BY 4.0 terms.

Under current policy settings, battery demand for electromobility is projected to increase 4.5 times by 2030 compared to 750 GWh of LIBs installed in vehicles worldwide in 2023 [5], and more than seven times by 2035, with EV batteries accounting for more than 4.3 TWh [6], as shown in Figure 2. If countries fully meet their announced climate and energy commitments, demand could rise fivefold by 2030 and ninefold by 2035. In a Net Zero Emissions (NZE) scenario by 2050, demand is expected to grow seven times by 2030 and twelve times by 2035 [7].

According to Bloomberg New Energy Finance (BloombergNEF) [8], LIB pack prices dropped 20% from 2023 to a record low of USD 115 per kWh in 2024, although prices may vary significantly across different countries and applications. Battery pack costs in the USA and Europe were 31% and 48% higher than in China, where prices already dipped below USD 100 per kWh in 2024, mainly due to higher manufacturing costs and lower volumes. LIB prices are projected to drop in the next five years, potentially reaching cost parity with internal combustion engine vehicles (ICEVs) in the mid-to-late 2020s [9]. Several factors are contributing to the decline in prices, including overcapacity in cell manufacturing, economies of scale, and reduced prices for metals and components [10]. However, the downward price trend may be halted due to the current very low profit margins of battery producers and possible shortages in the material supply chain. Figure 3 illustrates the price trends of battery packs and cells over the past few years, along with projected prices extending to 2030. These forecasts are averaged from estimates of reference [9], utilizing the average price ratio of packs to cells from the past five years.

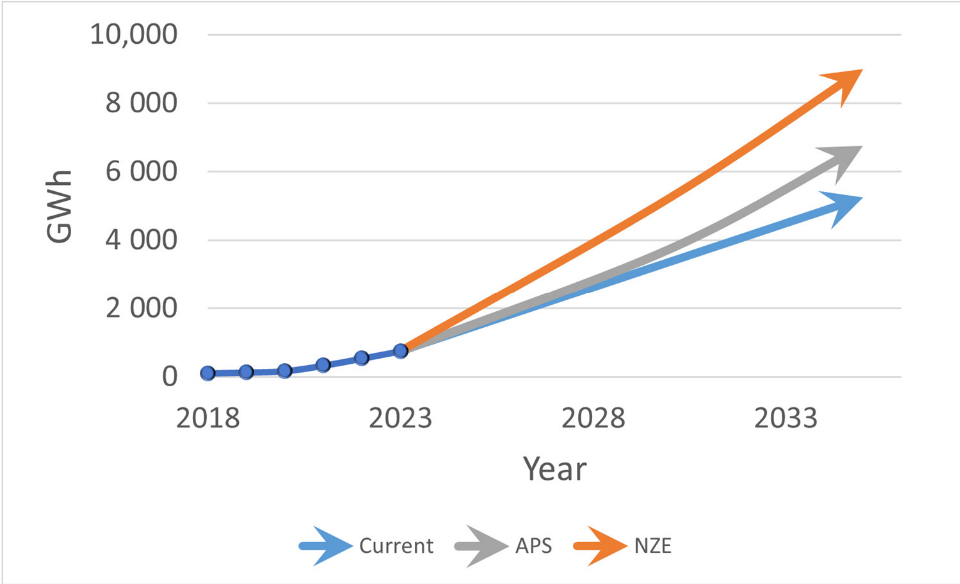

Figure 2. Battery demand growth under different decarbonization scenarios: Current, Announced Pledges Scenario (APS), and Net Zero Emission (NZE).

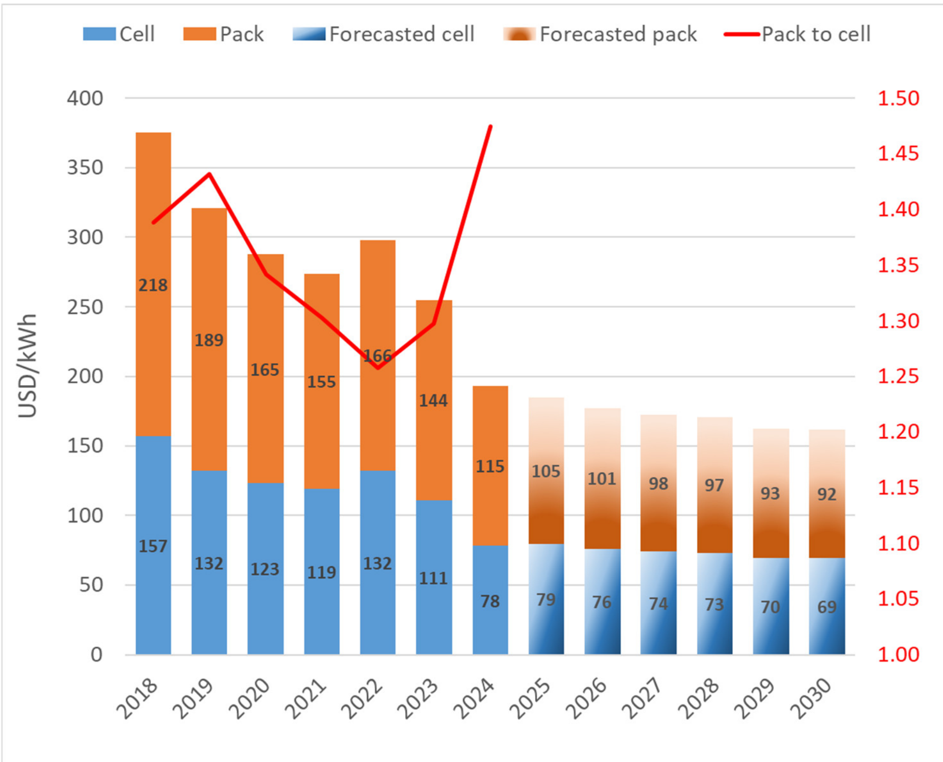

Figure 3. Pack and cell price trend from 2018 to 2024 [8]. The pack-to-cell price ratio is represented by the red line. Forecasted prices are reported for the 2025–2030 period.

Among LIB technologies, lithium iron phosphate (LFP) batteries are expected to become more affordable sooner than nickel–cobalt-based batteries, reinforcing LFP's position in the market [11,12].

Historically, the decrease in prices for cathode materials and improvements in cell energy density have led to lower battery costs. However, in the future, the main driver of cost reductions is likely to shift toward optimizing the manufacturing process and minimizing waste [13]. Transitioning from small-scale battery materials research to large-scale production is crucial, particularly regarding material quality control, raw material procurement, electrode processing, and component design [14]. Advanced characterization tools and AI-based data analytics can significantly enhance quality control, process optimization, and cost reduction [14–20]. Reducing scrap rates will become a crucial factor in improving overall efficiency and affordability in the production of lithium-ion batteries [9]. Indeed, raw materials, such as lithium, cobalt, nickel, and graphite, represent the most relevant cost in batteries. Even though the actual share depends on cell chemistry, Argonne National Laboratories estimated that cell materials represent 63% of the 2024 NMC811-graphite battery pack cost, with cathode and anode materials accounting for 52% and 14% of all materials cost, respectively [21]. The supply and extraction of raw materials are concentrated in specific geographic areas, which poses significant risks to both supply and pricing. In response to this, there are ongoing efforts to decrease the demand for critical raw materials, leading to the development of new battery technologies. Additionally, recycling will be vital in the next decade for reclaiming materials from manufacturing scrap. By 2035, the number of discarded EV batteries will surge, making battery recycling important for reducing critical mineral demand [18,19,22–26]. Effective scaling of recycling could lower raw lithium and nickel demand by 25% and raw cobalt demand by 40% by 2050, while still meeting climate targets [7].

While expected to remain dominant, especially due to the growing BEV market, lithium-ion technology faces potential challenges, mainly due to concerns about lithium supply constraints and changing policy landscapes [6]. This situation highlights the need for research and investment in batteries that use more abundant raw materials. Sodium-ion technology, also known as sodium-ion battery (SIB), is a promising alternative. According to IdTechEx, at present, only pilot plants are operational, along with a few smaller factories that produce limited quantities of SIB batteries [27]. Nonetheless, several manufacturers have disclosed plans that indicate total capacities will surpass 100 GWh by 2030 [27,28]. Their cost and safety advantages make them suitable for specific applications, including two- and three-wheeled vehicles, smaller passenger cars, and certain stationary industrial applications, thus complementing lithium-ion technology. Early commercialization of SIB battery-powered EVs is happening in China [29,30].

In Europe, despite ongoing efforts, the battery industry faces significant challenges that need to be addressed to ensure its long-term success and competitiveness, such as dependencies on third countries, high energy and labor costs, strong competition from Asia, fluctuating demand for EVs, regulatory uncertainties, and difficulties in ramping up production.

Additionally, the battery industry is entangled in geopolitical tensions between China and the USA, which impacts investments in gigafactories [31]. Developing battery recycling or implementing more sustainable value chains could help address some of these challenges. Initiatives like BATTERY 2030+ are set up to promote the development of next-generation batteries. This program encompasses various projects focused on creating ultra-high-performance, durable, safe, sustainable, and affordable batteries for practical applications [32]. Emerging technologies, such as solid-state lithium batteries, promise extended vehicle ranges, shorter charging times, and reduced costs [33].

To make its battery supply chains secure, resilient, and sustainable, the EU adopted three approaches: improve cooperation among stakeholders, provide the sector with funding, and establish a comprehensive regulatory framework.

In this paper, an accurate review of the state-of-the-art of batteries for the automotive sector is provided, including performance, safety, sustainability, and costs, with a focus on the European context. The paper is organized as follows: in Section 2, an overview of the EU regulation framework is given; Section 3 illustrates the state-of-the-art and the future developments of battery technologies for the automotive sector; Section 4 is devoted to the sustainability issue. Promising innovations and regulation improvements are discussed in the Conclusions, in particular from the European perspective. Appendix A illustrates the methods and search results of the literature review.

2. The European Legislative Framework

The European Union has implemented policies to decarbonize industries and the energy system, significantly boosting battery demand. In particular, the global commitment to decarbonizing the transport sector has resulted in continuous growth in the EV battery market. The United States and Europe experienced the fastest growth among major EV markets, reaching more than 40% year-on-year, closely followed by China at about 35%. As a consequence, demand for EV batteries reached more than 750 GWh in 2023, up 40% relative to 2022 [34]. As aforementioned, one of the EU's approaches to support the EU battery sector is to establish a comprehensive legislative framework. Key initiatives include:

- RePowerEU: This initiative seeks to make Europe energy independent from fossil fuels by 2027, prioritizing clean technologies like battery energy storage.
- Fit for 55 Package: This package aims to reduce greenhouse gas emissions by 55% by 2030 and accelerate the electrification of various sectors, increasing battery demand.
- Net-Zero Industrial Act (NZIA): This act aims to increase clean-tech industrial capacity, including battery manufacturing.
- Critical Raw Materials Act (CRMA): This act enhances the collection and recycling of waste products to secure the supply of critical raw materials for batteries.
- EU Battery Regulation: This regulation promotes the circular economy, resource efficiency, and sustainability of batteries throughout their lifecycle. Key points in the Battery Regulation are the following:
    - Mandatory sustainability and safety requirements for the placing of batteries on the European market, including restrictions on certain substances, carbon footprint requirements, performance and durability requirements, etc.;
    - Recycled content requirements;
    - Traceability through labelling, marking, and information requirements, notably with the creation of the digital battery passport;
    - Mandatory implementation of due diligence policies;
    - Extended producer responsibility;
    - Targets for the collection of waste batteries, and provisions regarding the treatment, reuse, and recycling of batteries, notably materials recovery targets;
    - Green public procurement.

The new regulation aligns closely with the European Union's climate neutrality objectives. These policies collectively create a favorable environment for battery innovation, manufacturing, and deployment in Europe, contributing to the EU's goal of achieving climate neutrality.

The regulatory strategies for batteries vary significantly across the EU, China, and the US, reflecting different priorities regarding environmental protection, industrial policy, and consumer safety. The EU's approach emphasizes environmental sustainability, resource efficiency, and developing a circular economy for batteries. The EU aims to establish harmonized standards that apply across all member states. China's regulatory approach prioritizes the safety and reliability of batteries, especially given the rapid growth of the electric vehicle (EV) sector. In contrast, the regulatory landscape in the US is more fragmented. It focuses on transportation safety and on battery recycling through federal guidelines and state-level initiatives. Additionally, there is a growing emphasis on domestic battery production supported by economic incentives. However, the US currently lacks the comprehensive, life-cycle-based approach that is characteristic of the EU. Table 1 summarizes the main regulation aspects for different countries.

Table 1. Main regulatory framework in different countries.

Country	Main Regulations	Main Focus	Main Action	References
EU	Batteries Regulation (2023/1542)	Sustainability; safety; labeling, collection, and recycling of all battery types	Substance restrictions, carbon footprint declarations, recycled content requirements, and battery passports for traceability	[35]
China	EV battery safety standards (GB38031-2025)	Safety; promotion of technological standards	Prevention of fire and explosion after thermal runaway	[36]
US	Mercury-Containing and Rechargeable Battery Management Act; Inflation Reduction Act	Recycling; battery collection and labeling guidelines; safety; domestic battery production	Multi-faceted approach involving federal and state regulations, as well as voluntary standards	[37,38]

3. State-of-the-Art of EV Battery Technologies

The review focuses on battery technologies for automotive applications, from material to battery pack levels. Therefore, the main aspects considered are life duration, fast charge, energy density, cost and market aspects, safety, raw materials, and process sustainability. For this reason, we excluded documents with keywords referring to vehicle and charging technologies, or referring to recycling and post-use applications, or non-automotive purposes. We also excluded reviews focused on battery modeling approaches, as well as those on battery management systems (BMS) and thermal management systems (BMTS). Although these topics are crucial for battery performance and safety, they encompass a broad area of research beyond the scope of this paper and deserve a dedicated review.

Based on the literature review, the current battery technologies for EVs have been identified and are described in the following section, along with the battery requirements for EVs applications and the research developments.

3.1. Lead–Acid Batteries

Lead–acid batteries are a well-established technology that is commonly used in vehicles to power electrical systems. Lead–acid batteries can be configured in large systems without complex management. In automotive applications, six 2 V cells are connected in series to create a 12 V battery. These batteries are known for their low cost per kWh. Available designs include flooded (vented) and enhanced flooded batteries (EFBs), valve-regulated lead–acid (VRLA) batteries, and Absorbent Glass Mat (AGM) batteries [39]. Bipolar lead–acid batteries, a relatively recent development, feature a sandwich construction that reduces internal resistance and increases power density due to their lighter weight, allowing for possible applications in hybrid vehicles [40]. The bipolar electrodes concept has also been extended to other rechargeable battery technologies [41]. Lead–acid batteries excel in recycling, with 99% of active materials being recycled and over 90% efficiency [42]. This supports a circular economy and boosts Europe's reliance on domestic raw materials. Further research is needed to enhance secondary lead utilization and refine the recycling process to reduce impurities. Lead–acid technology is expected to maintain a stable market presence, primarily focused on 12 V starter batteries and industrial applications [43].

3.2. Nickel-Based Technologies

Nickel oxide electrodes serve as the positive plates in various types of rechargeable batteries, including nickel–iron (Ni–Fe), nickel–cadmium (Ni–Cd), nickel–hydrogen (Ni–H2), nickel–metal hydride (Ni–MH), and nickel–zinc (Ni–Zn) batteries. All nickel-based batteries are recognized for their long lifespan and their ability to operate effectively across a wide temperature range [44]. Notably, Ni-Cd batteries are celebrated for their durability; they do not suffer from "sudden death syndrome", and their gradual aging can be monitored effectively. However, they show that the so-called "memory effect", which occurs as soon as a battery is partially charged and discharged, causes their available capacity to degrade suddenly. Furthermore, the cadmium in this battery makes it unfriendly to the environment.

Ni-MH batteries, on the other hand, offer a higher energy density and are generally well-suited for applications with high current consumption [45]. However, this technology requires a BMS for optimal operation, which introduces some vulnerability. Ni-MH batteries are frequently employed as a backup energy source in hybrid EVs like the Toyota Prius [46].

The nominal voltage of Ni-Cd and Ni-MH is 1.2 V, which limits their employment in large battery packs.

3.3. Lithium Batteries

Electrified vehicles with traction motors require higher power and energy capacities than lead–acid batteries can provide. LIBs have proven to be the most suitable alternative for this application. Automotive LIBs demand increased by about 65% to 550 GWh in 2022, from about 330 GWh in 2021, primarily because of growth in electric passenger car sales, with new registrations increasing by 55% in 2022 relative to 2021 [47]. These batteries have a nominal voltage range from 2.3 to 3.85 volts (https://www.grepow.com/lihv-battery/lihv-battery-3-85-v.html accessed on 31 March 2025) and offer significantly high energy density, exceeding 150 Wh/kg [48], reaching 250 Wh/kg [49], surpassing those of lead–acid and Ni-MH batteries, which are 40–60 Wh/kg and 40–110 Wh/kg, respectively. Thanks to their higher energy and power densities, and consequently smaller and lighter cell designs, with respect to other existing battery technologies, LIBs are dominating the automotive battery market.

3.4. Sodium-Based Technologies

High-temperature sodium batteries use liquid sodium electrodes and a solid electrolyte, typically an ion-conducting ceramic. The most common types are sodium–nickel chloride (NaNiCl) and sodium–sulfur (NaS) batteries [50].

NaNiCl, or ZEBRA batteries, operate between 270 °C and 350 °C. This molten state allows high conductivity for sodium ions, providing a specific energy of about 120 and a nominal voltage of 2.3 V to 2.6 V. They are often used in small electric vehicle fleets and stationary energy storage [51,52].

NaS batteries operate in an optimal temperature range between 300 °C and 340 °C. During discharge, sodium oxidizes to Na+, allowing ions to enter the solid electrolyte and release electrons. The voltage during operation is around 2 V. NaS batteries have stable internal resistance, making them ideal for grid storage applications over 1 MWh [50].

NaS and NaNiCl batteries both exceed 4500 cycles and have efficiencies of 75% to 86%. However, they require heating to maintain temperature, which decreases their overall efficiency. NaNiCl batteries have high nickel demand and complex insulation, leading to greater energy and environmental impacts. In contrast, NaS batteries use recyclable materials like steel and aluminum, resulting in a lower environmental footprint [43].

In addition to high-temperature applications, advancements in NaS battery systems for intermediate (100–200 °C) and ambient (25–60 °C) temperatures are promising [53]. Room-temperature sodium-ion batteries (SIBs) are often compared to lithium-ion batteries because both operate on the "rocking chair" principle, where ions move between two host materials at the electrodes [54]. SIB technology is appealing since it is based on an abundant material, its specific energy is comparable to LFP [55], while power density, low temperature performance, and safety are superior [56,57], even though some issues regarding performance stability and safety remain [58,59]. Nevertheless, sodium-ion batteries have reached the market (technological readiness level (TRL) 9) [5]. The producer leader is China, which advances quickly, building the whole supply chain, scaling up production, and testing the first commercial products in real applications [28,29].

3.5. EV Batteries Requirements

Electromobility necessitates advancements in battery technology to compete with conventional vehicles [60]. The focus is on the advancement of LIBs and emerging chemistries. Battery technologies can be categorized into "generations" based on their chemical composition and performance. However, this classification is not officially defined and lacks a single source. In Table 2, we present a widely accepted classification of battery generations, along with their TRL, and typical technologies used for the cathode, anode, and electrolyte. We also add sodium-based technologies, as some batteries based on this chemistry are in TRL 9, and their performance evolution is of interest for automotive applications. However, we did not include them in the battery generation classification, which we use to refer only to LIB technologies.

Key areas for improvement include cell performance advancements and system-level enhancements like standardization, flexible manufacturing, battery swapping capabilities, and vehicle–grid integration for bidirectional charging [61].

At the system level, improving the thermal management of batteries is essential. This involves developing advanced cooling systems and utilizing digital twin models to enhance our understanding of battery performance, which can help to minimize capacity loss and performance degradation. In the short term, research should focus on developing advanced BMS with sensors for diagnostics and failure prediction, supporting remote upgrades while ensuring cybersecurity [62,63]. In the mid-term, the emphasis will be on battery reparability and refurbishment, exploring second-life applications, dismantling and recycling of battery components, and tracking data to meet Battery Regulation and Battery Passport requirements [64].

Table 2. Battery technology maturity. From [2,65,66].

Generation	TRL	Anode	Cathode	Electrolyte
1	9	Carbon/Graphite	LFP, NCA, LCO	Organic liquid
2a	9	Carbon/Graphite	NMC111	Organic liquid
2b	9	Carbon/Graphite	NMC532, NMC622	Organic liquid
3a	9	C/Si (5–10% Si)	NMC622, NMC811	Organic liquid
3b	5–9	Si/C (>10% Si)	HE-NMC	Organic liquid
3b	4	Si/C (>10% Si)	HV-LNMO	Organic liquid
3a	5–6 [1]	Si/C (>10%)	LCO, NMC, LMO, NCA	Solid state

Table 2. *Cont.*

Generation	TRL	Anode	Cathode	Electrolyte
4b	5–6 [2]	Li metal	LCO, NMC, LMO, NCA	Solid state
4	4	Li metal	Li2-S	Solid state
5	4	Li metal	O2	Different possibilities
-	9	Hard-carbon	PBA [3]	Organic liquid
-	4	Na-metal, Tin alloys	layered oxides, polyanion compounds	Different possibilities

[1] TRL 9 is achieved only in specific market segments (e.g., earbuds, wearables) or special operation conditions.
[2] TRL 9 is achieved for some niche applications (e.g., space, military). [3] Prussian blue analog.

High gravimetric energy densities are crucial for increased payload and cost-efficiency, especially for commercial and heavy-duty vehicles, alongside considerations of cycle life and total cost of ownership under diverse operating conditions [67]. Given that battery materials comprise a significant portion of cell cost, research and innovation in this area are essential to achieve cost-effective batteries with high energy density, long cycle life, and rapid charging [67].

Figure 4 reports the evolutionary roadmap for lithium-based chemistries from 2023 to 2030 with reference to both gravimetric and volumetric energy density. Actual values can vary depending on specific cell design, operating conditions, and manufacturing processes. Projected values can vary substantially depending on ongoing research and development.

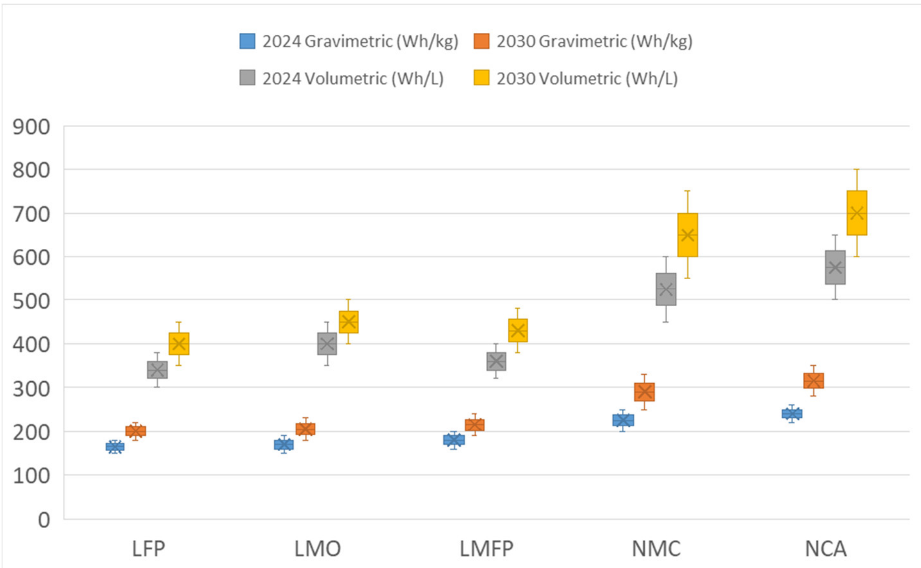

Figure 4. Evolutionary roadmap of lithium-based chemistries 2023–2030.

At the cell level, the objective in the short term is to enhance the energy density performance of cells while eliminating the use of critical materials like cobalt. This approach aims to reduce costs and concentrate on Generation 3b technology [68]. In the mid-term, solid-state Generation 4 LIBs are anticipated to become increasingly significant [65,69]. It is essential to ensure automotive-grade safety, including crash safety and the adoption of flame-retardant materials, as well as to focus on cyclability, lifespan, sustainability, and recyclability [64]. Addressing challenges related to safety, sustainability, and raw material criticality is also paramount for EU competitiveness [70]. This necessitates exploring sustainable materials, including bio-based and bio-mimetic options, and considering raw material abundance and cost in developing new battery chemistries [64]. Current research focuses on advanced materials for higher energy/power density, including high-nickel NMC cathodes, silicon-based anodes, and stabilized electrolytes. Efforts are also focused on reducing inactive materials. "Design-to-cost" approaches, like manganese-rich high lithium manganese (HLM) and improved LFP cathode, are also being pursued [71–73].

While LIBs have seen significant progress in energy/power density and cost reduction, further improvements are needed in material cost competitiveness, fast charging capabilities, ecological and social footprint reduction, high-energy anode and cathode synthesis, supply security, and cycle life enhancement to meet the demands of the automotive market. The industry has identified key battery targets for essential cell and pack characteristics to be achieved in a short-term period to meet mobility needs. In Table 3, we report some parameters' target values elaborated from the European Council for Automotive R&D (EUCAR) [74] and the United States Advanced Battery Consortium (USABC) [75] for cell performance expected goals. We also included the requirements identified in the Batteries Europe Roadmap [64], as well as from the literature [76]. These parameters depend on the application; thus, a range of values has been given instead, which includes high-power applications, such as plug-in hybrid EVs (PHEVs), and high-energy implementations, such as BEVs.

Table 3. Battery cell requirements for automotive applications. The value intervals are determined, including BEV and PHEV future needs and projections. Data from USABC have been estimated for the BOL assuming EOL condition is 80% of the initial capacity.

Parameters at Cell Level	Current 2020–2025	2030–2035	Source
Specific energy	160–290	275–450	[64,74–76]
Energy density Wh/l	450–730	750–1000	[55–57]
Continuous specific power—discharge W/kg	340–750	800–1750	[74,76]
Continuous power density—discharge W/L	1000–1500	2000–3850	[74,76]
Charging rate C (1/h)	2–3	6–3.5	[55–57]
Cost EUR/kWh	60–200	40–100	[74,76]
Hazard level	<=4	<=3	[74,76]

At the pack level, it is anticipated that the cell volume per battery pack will increase from 60% to 75%. Additionally, the cell weight per battery pack is expected to rise from 70% to 80%. The lifetime expectation should be comparable to that of a car, reaching up to 150,000 km. Furthermore, the cost of the battery pack should be approximately 15% to 20% higher than the cost of the individual cells. For PHEVs, the specific energy and density goals are somewhat less stringent than for BEVs, but peak power requests are generally higher. Key parameters are summarized in Table 4.

It should be noted that all USABC goals are written in terms of end-of-life (EOL), battery-pack-level values, whereas researchers and cell developers often highlight beginning-of-life (BOL), cell-level performance. A comparison of the USABC and EUCAR goals, reported on EOL values, on specific energy, calendar life, and cycle life, shows a good degree of alignment.

Table 4. Battery pack requirements for automotive applications. The value intervals are determined, including BEV and PHEV future needs and projections. Data from EUCAR have been estimated based on their actual and foreseen cell-to-pack integration.

Parameters at Pack Level	Current 2020–2025	2030–2035	Source
Specific energy Wh/kg	90–180	190–360	[74,76]
Energy density Wh/l	250–400	450–750	[74,76]
Continuous specific power—discharge W/kg	525	800–1400	[74]
Continuous power density—discharge W/L	900	1650–2600	[74]
Cost EUR/kWh	90–286	65–120	[74,76]

3.6. Life Duration

Battery durability is a critical requirement for EVs. Many vehicle original equipment manufacturers (OEMs) offer warranty periods that extend for many years and hundreds of thousands of miles. A study by P3 and Aviloo [77], analyzing data from over 7000 EVs, reveals promising insights into battery longevity. It shows that while battery capacity initially declines, it stabilizes over time. Specifically, capacity drops to about 95% after the first 30,000 km and around 90% at 100,000 km. Even after 300,000 km, most batteries retain about 87% of their original capacity. These findings exceed many original OEMs' predictions, which often anticipate a decline to 70–80% for the same distance range.

Efforts to improve battery life involve different levels of the storage system, from materials and cells to battery pack management. The cell's main components are the electrodes, where redox reactions occur during charge and discharge. The cathode—the electrode with the higher potential—is usually made of a lithium transition metal (TM) oxide material. The anode is typically an intercalation material like graphite or a graphite hybrid material, or sometimes lithium titanate oxide (LTO). Between the electrodes is a porous separator that prevents short-circuiting while allowing ion migration. The electrolyte plays a fundamental role in the battery, ensuring the transmission of ions and maintaining the reaction balance of the battery. During battery operation, or even during storage, the components may undergo physical and chemical changes that can alter the battery's performance [78]. These degradation mechanisms are not directly observable during normal battery operation, but they affect the battery performance, specifically with the reduction in the usable capacity of the cell (capacity fade) and the decrease in the cell's deliverable power (power fade) [79].

Degradation mechanisms can be categorized into distinct degradation modes, which reflect their impact on cell performance [80–82]. A commonly used classification identifies three main degradation modes:

1. Loss of Lithium Inventory (LLI): This mode includes mechanisms that reduce the amount of cyclable lithium available for transport between the electrodes.
2. Loss of Active Material (LAM): This encompasses mechanisms that lead to a decrease in the material available for electrochemical activity. LAM is often further divided into losses at the anode and losses at the cathode.
3. Conductivity Loss (CL): Also known as impedance change, this mode groups the mechanisms that affect the kinetics of the cell.

Figure 5 provides a simplified graphical representation of the relationships between battery components, degradation mechanisms, and degradation modes. The correlations between these phenomena are much more complex because all battery components are closely interconnected, and the details of specific degradation mechanisms depend on their composition and structure.

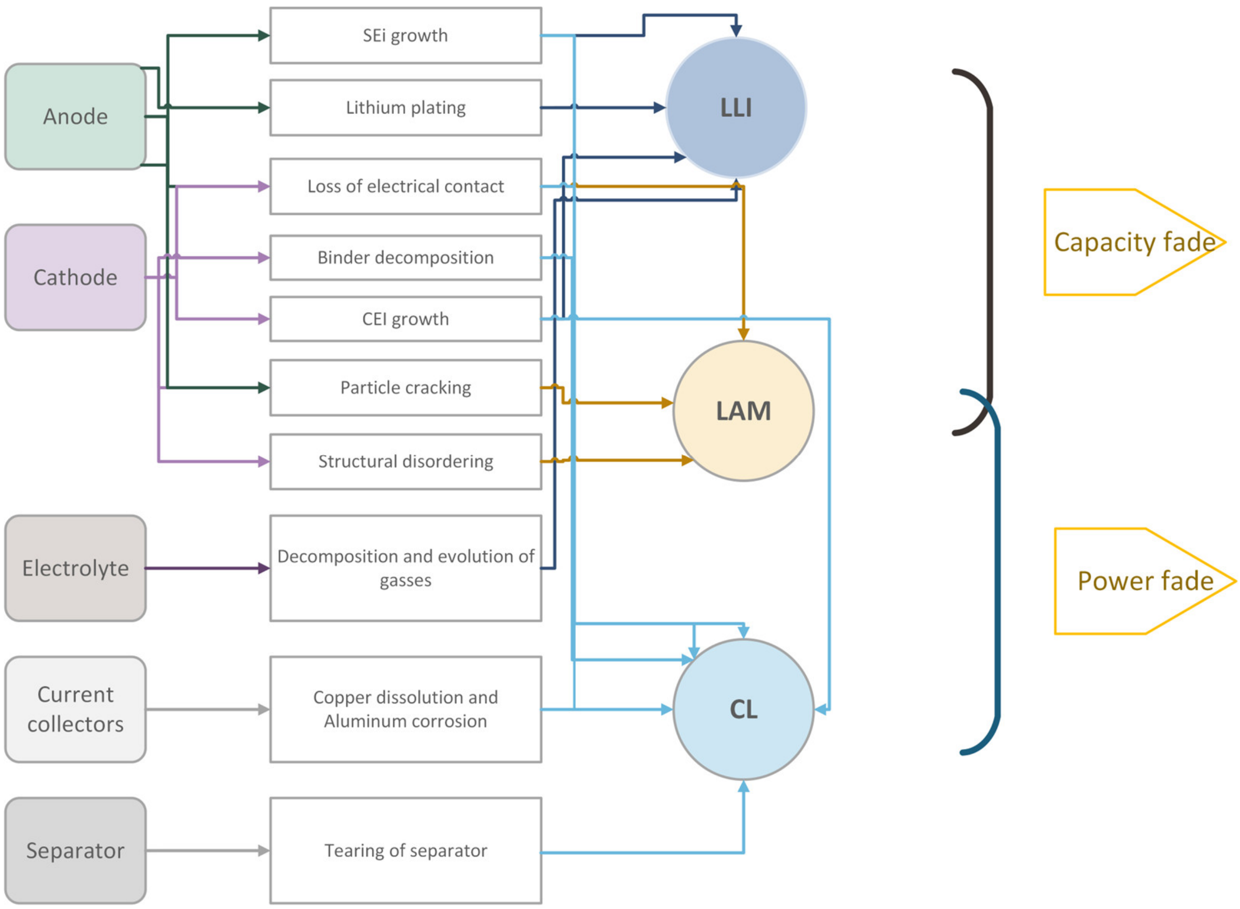

Figure 5. Schematic of degradation mechanisms and modes for different battery components.

Despite the oversimplification, Figure 5 highlights some of the issues the researchers are focusing on to improve battery life performance. Reducing the solid electrolyte interface (SEI) modification or growth during cycling is of particular interest. The SEI is a layer that forms on the electrode–electrolyte interface during the first few cycles. This layer protects the electrolyte material from further depletion and prevents corrosion of the anode. However, during cycling, irreversible side reactions can lead to unwanted growth of the SEI layer on the anode, which significantly reduces the capacity and power rate [83]. This mechanism has a particular impact on intercalation anodes, such as graphite and silicon-based ones, which undergo large volume changes during lithiation and delithiation [84], but it also occurs with other anode materials and at the cathode, where it is usually referred to as cathode electrolyte interface (CEI). The addition of binders, coating, and doping at the electrode can help reduce this degradation mechanism [20]. However, the mechanisms behind SEI growth are still not well understood, and further research is needed to address the issue [85].

In Table 5, we summarize various degradation mechanisms and mitigation strategies for several cathode and anode materials that are currently attracting research interest.

External factors such as operating current, voltage conditions, state of charge, and temperature all play complex roles in influencing the battery degradation mechanisms [86–89].

Table 5. Degradation mechanisms and mitigation strategies for some advanced electrodes.

Type of Electrode	Degradation Mechanisms	Mitigation Strategies	Source
Ni-rich layered cathode	Microcracks, lithium–nickel hybridization and irreversible phase transitions, anisotropic lattice deformation, and surface degradation	Elemental doping, coating modification, electrolyte modification, construction of radial concentration gradients in polycrystalline secondary particles, fabrication of rod-shaped primary particles, single-crystal high-nickel cathodes.	[90–93]
Lithium-rich manganese oxide cathode	Irreversible oxygen loss, structural degradation of the material, particle fragmentation, and transition metal migration	Surface coating, ion doping, component regulation, single crystal structures.	[94,95]
Li-metal anode	Dendrite growth	Coating artificial protective films, surface morphology control, high electrolyte concentration, electrolyte additives.	[85]

The commercially available LIB temperature operating range is usually around −20 to 55 °C, even though the optimal range is generally 15–35 °C [96]. While using the batteries outside their operating range can lead to safety issues, operating outside the optimal range accelerates aging. Generally, low temperatures favor the deposition of metallic lithium on the anode, high temperatures enhance the rate of side reactions and the kinetics of the battery, accelerating the decomposition of SEI and electrolyte consumption [81,82].

Batteries have a specific operating voltage range that depends on the potential of the electrodes. The voltage of a battery is related to its state of charge (SOC); higher voltage indicates a higher SOC, while the low voltage cut-off marks a depleted capacity. It is important to note that the voltage operating windows remain stable throughout the aging process, whereas the SOC values can change, as the available capacity decreases over time relative to the nominal initial capacity.

When cells are overcharged, lithium deposition can occur. An increased cutoff voltage can lead to electrolyte decomposition and uneven degradation of the negative electrode [80–82], and the battery may experience significant volume expansion, as well as increases in temperature and internal resistance, which raises the risk of thermal runaway. Conversely, discharging at low voltages can result in the dissolution of the copper current collector, increasing charge transfer resistance, and leading to micro-short circuits [81,82,96]. Low voltages accelerate the growth of SEI and CEI films, causing changes in the microstructure of the cathode and resulting in faster capacity fade [80,90,96,97].

Table 6 presents an overview of the primary degradation mechanisms caused by various usage-related stresses. It is important to note that, in practical applications, these stress factors often occur simultaneously, amplifying their effects on the battery.

To accurately predict battery aging, it is essential to consider the intricate relationship between external factors related to working or storage conditions, chemical and material-level degradation modes, and aging mechanisms [98–100]. To effectively predict the degradation curve up to the EOL conditions, it is necessary to continue testing until the batteries reach EOL or rely on advanced diagnostic models able to extrapolate early-stage data into predictions for long-term degradation based on observed processes [99,101]. The results are used in BMS to maximize battery performance and duration through diagnostic and prognostic analysis [63,102–105]. Diagnostics assesses how much a battery's performance deviates from its optimal or reference state, a concept known as state of health (SOH). SOH is not linked to a single index, and its definition can vary depending on the perspective from which the battery's performance is evaluated [106–108]. Prognostics estimate how long the device can continue to operate based on its current SOH and usage patterns [99]. Their implementations can be broadly classified into model-based and data-based approaches. Model-based methods, such as physics-based, equivalent circuit, or empirical models, are effective when battery behavior is well understood and require extensive laboratory tests for the accurate identification of model parameters [96,108–110]. In contrast, data-driven approaches are increasingly popular, especially for applications where battery behavior is highly nonlinear and difficult to model precisely [86,96,111,112]. These methods can use real-world usage data to gain insights without relying on specific mathematical equations [87,113]. However, they demand high-quality training data that reflects a wide range of battery behaviors [99,114].

Table 6. Overview of the main degradation mechanisms induced by operating conditions.

External Stress	Induced Degradation Mechanism	Aging Effect
Low temperature	Lithium plating and dendrites formation	Conductivity loss/capacity fade/short circuit
High temperature	Electrolyte and binder decomposition SEI film growth and decomposition	Capacity/power fade
Low voltage/SOC	Corrosion of current collectors Transition metal dissolution Loss of electric contact Lithium plating and dendrites formation SEI and CEI growth	Conductivity loss/capacity fade/power fade
High voltage/SOC	Electrolyte and binder decomposition SEI film growth and decomposition Graphite exfoliation Lithium plating	Capacity/power fade
High current	SEI film growth and decomposition Graphite exfoliation Structural disordering and particle cracking Loss of electric contact	Conductivity loss/capacity fade/power fade

Digital twins and AI analytics can be effectively integrated into a BMS to enable advanced predictive maintenance, moving beyond traditional rule-based or statistical methods [115]. A digital twin is a dynamic virtual representation of a physical battery or battery pack. This model incorporates various elements, including the battery's design specifications, material properties, electrochemical characteristics, thermal behavior, and operational history [116]. The BMS continuously streams real-time data from various sensors embedded in the physical battery to the digital twin [117]. AI algorithms within the digital twin framework continuously process this real-time data to update the virtual model, accurately reflecting the current state and operational conditions of the physical battery [118,119]. AI algorithms, especially machine learning techniques like neural networks, clustering, and statistical process control, can analyze real-time data to identify deviations from typical operating patterns. These anomalies may serve as early indicators of potential faults or degradation. When an anomaly is detected, AI can analyze historical data, failure modes, and the current context within the digital twin to diagnose the potential underlying cause of the issue [120]. By learning from historical degradation patterns, usage profiles, and environmental conditions of similar batteries—both real and simulated within the digital twin—AI models can predict the RUL of individual cells and the entire battery pack. This capability allows for proactive maintenance planning. Furthermore, the digital twin, enhanced by AI, can simulate various future operating conditions (such as different charging profiles, temperature extremes, and load cycles) to predict their impact on battery health and performance. This enables the optimization of battery usage and the evaluation of different maintenance strategies. However, implementing AI and digital twins in BMS faces challenges such as poor data quality, integration issues, and high initial costs. AI struggles with data context and reliability, while digital twins require continuous updates and deal with model complexity and scalability. Both technologies also raise concerns about data security and organizational readiness [121–123]

To estimate the SOH of batteries, methods can be categorized as either direct or indirect [124]. Direct methods involve measuring indicators such as capacity and impedance, while indirect methods analyze data to gain insights into battery aging mechanisms [105,112,125,126]. Examples of direct methods include Coulomb counting, open circuit voltage (OCV) measurements, impedance assessments, and the acoustic emission technique [127–130]. Advanced sensors help to determine direct SOH measurements [131–133]. Indirect methods rely on voltage and current values, which are much easier to measure than battery capacity. They derive the degradation state from models based on the number of cycles performed or through numerical approaches [130,134–137].

Battery thermal models describe the generation and transfer of heat in a battery to predict its temperature. A crucial step in ensuring the efficiency and accuracy of these models is determining and extracting the model parameters [138]. Thermal models are particularly important for ensuring the safe and reliable use of batteries, as temperature levels outside of operating limits can shorten battery life, degrade performance, and increase safety risks [114,139–143]. These models are integrated into the BMS to predict and mitigate thermal risks. Battery thermal management system (BTMS) includes running additional components such as liquid cooling systems or phase-change materials that are employed to keep the temperature settings [142,144–148].

3.7. Fast Charge

Charging time is a significant concern for customers who frequently take long-distance trips and for those who do not have access to private charging. Direct current fast charging (DCFC) equipment can charge a BEV to 80% in just 20 min to 1 h. However, there is still a desire for charging speeds that can approach those of internal combustion engine vehicles (ICEVs).

Key areas for improving fast charging include enhancing the diffusion rate of lithium ions (Li+) in the electrodes, optimizing transport in the electrolyte, and improving charge transfer kinetics at the electrode/electrolyte interface [149–153]. Research opportunities exist at both the cell and battery levels [150,154–156], focusing on the areas described in the following.

3.7.1. Electrode

Optimizing the design and structure of electrodes to enhance their conductivity and surface area significantly improves charge transfer rates. Reducing electrode thickness can improve ion diffusion but lower energy storage capacity. To balance capacity and fast charging with thicker electrodes, it is vital to optimize porosity and design, such as adding electrolyte channels or using a 3D grid porous electrode with vertically aligned pores for better ion transport [156].

Fast charging capability depends on the cathode's crystal structure. Layered oxides allow for high ionic mobility and quick charging due to minimal diffusion barriers. However, they can become structurally unstable during deep delithiation, but this can be contrasted with element doping or synthesizing layered Li transition-metal oxides with single-crystal (SC) [157,158]. As to polyanionic oxides, surface modification and coating improve their poor ionic conductivity [153,159,160]. Conversion-type cathode materials show poor performance upon cycling [161–163]. However, a composite cathode of FeF_2 nanoparticles embedded into a polymer-derived carbon (PDC) matrix showed a high capacity retention after 500 cycles at a high rate of 60C [164].

Carbon-based materials are the most widely used anode materials, but high current densities impact their performance. Graphite materials with porous structures, expanded interlayer spacing, or ordered alignment of graphite flakes perpendicular to the current collector are among the strategies proposed to enhance fast charging performance [153,165–167]. Transition-metal oxide anodes, like LTO, are better suited for fast charging but struggle with low intrinsic conductivity and slow Li+ diffusion kinetics. These challenges can be mitigated through surface modification, doping, and morphology control [149,168,169]. Silicon anodes face issues of large volume changes and low conductivity. To improve their rate and cycling performance while capitalizing on their high specific capacity, techniques such as particle size reduction, new microstructure design, and surface coatings are utilized [151,170–173].

3.7.2. Electrolytes

Important characteristics of electrolytes for fast charging include high conductivity, a high Li+ transference number, low desolvation activation energy, strong reductive and oxidative stability, good electrode compatibility, and a stable SEI layer [150,156,174]. Additives in electrolytes can contribute to the formation of a stable SEI layer, while the use of low-viscosity co-solvents can enhance ion mobility [175,176]. Flame-retardant additives can help reduce flammability and minimize side reactions [177–179]. In contrast, solid electrolytes are intrinsically non-flammable but tend to exhibit low ionic conductivity and high interfacial resistance. Recent advancements in garnet-type and sulfide-based solid electrolytes have demonstrated ionic conductivities that are comparable to those of liquid electrolytes [180,181].

3.7.3. Battery Engineering

The design of the battery cell is essential for ensuring mechanical stability and thermal safety. For instance, a high impedance ratio between the cathode and anode can help minimize lithium plating on the graphite anode and improve the distribution of current density on the collector, thus reducing the risks associated with fast charging [182,183]. At a broader system level, an effective thermal management system is vital for maintaining the performance, longevity, and safety of LIBs, especially in extreme conditions [184–186]. Additionally, implementing safer and more efficient charging strategies can significantly enhance battery performance, stability, and prolong battery lifespan [153,187–189].

3.8. Energy Density

There is an increasing market demand for batteries with higher energy density, driven by the need to extend the range of EVs and boost their adoption rates. Enhancements in battery energy density can be achieved at both the system level and the cell level [48,190,191], e.g., by improving the capacity of electrode materials and raising the operating voltage [192].

3.8.1. Anode

The dominant chemistry used nowadays in EV applications for the anode is graphite, thanks to its relatively low cost, abundance, high energy density, power density, and long cycle life [193]. Graphite consists of layers of single atomic hexagonal carbon atoms that provide enough interstitial sites to store lithium, with a 10% volume deformation during charge and discharge. However, limited capacity, degradation during cycle life, and low potential of graphite versus Li require the search for new anode materials [194]. For carbon anodes, many solutions have been investigated to meet the demand for stable and high-energy anodes. Anodes with different dimensionalities, such as nanotubes (1D), graphene nanosheets (2D), and various spherical structures (3D), have been developed to mitigate the effects of volume change during lithiation [194–196]. Fullerene derivatives (0D) have been investigated for their high charge capacity (861 mAh/g for carboxyl C60) and stable structure at a molecular level. Fullerene proved also useful to suppress dendrite formation on li-metal anodes [197].

Lithium titanate (LTO) is another alternative for the commercialized cells' anode. LTO-anode batteries show a lower nominal voltage (around 2.4 V) and lower specific energy compared to graphite anode batteries. On the other hand, LTO supports fast-charging and shows a remarkable lifespan [198,199]. However, degradation mechanisms are still under investigation, with gassing phenomena representing a potential hazard for safety [200,201]. Along with higher cost, these characteristics prevented the broad adoption of LTO lithium batteries in automotive applications, even though niche market applications are viable [198,202]. A series of titanium- and niobium-based intercalation materials have been developed as potential replacements for LTO, showing excellent electrochemical performance in terms of reversible capacity and electric conductivity [203]. However, most have high operating potentials above 1.5 V relative to Li/Li+. New titanium- and vanadium-based materials have emerged, capable of stable lithium storage below 1 V relative to Li/Li+ [204,205].

Both graphite and LTO work on the principle of intercalation: this process involves the storage of mobile ions in vacant sites or within interlayer spaces of a host lattice [206]. Among intercalation-type materials, MXenes—a new family of two-dimensional metal carbides or carbonitrides—have gained significant attention as anodes [207,208]. MXenes consist of graphene-like transition metal–carbon or nitrogen compounds. Their high conductivity and excellent surface chemistry make them particularly promising [209]. Unfortunately, the intercalation-type anode has a low rate capacity and a low specific capacity [206].

Alloy-based anodes are of great interest for their theoretically high specific capacity and increased energy density compared to graphite. Silicon anodes are particularly interesting alternatives to graphite anodes due to their high theoretical capacity of nearly 4200 mAh/g [210–212]. Silicon is appealing due to its abundance in the Earth's crust and the capacity of a single silicon atom to bond with four lithium ions. However, like all anode alloy materials, silicon anodes suffer from severe deformation during lithiation and de-lithiation, with a change of 300% of volume, which causes problems such as buffering, pulverization of the material, electrolyte consumption, and loss of contact [194,213]. The combined use of Si and graphite has become an appealing choice for high-energy anodes in LIBs [212,214,215]. This integration can also be achieved through the use of Si nanoparticles, Si suboxides, and Si-Graphite composites [216]. Silicon nanocrystals and nanotubes can reduce volume fluctuations during charging and discharging, improving the diffusion and conductivity of electrons and lithium ions [217]. However, cycling can cause agglomeration, increasing surface area and potentially leading to side reactions and reduced Coulombic efficiency [218]. Silicon suboxides (Si-Ox) materials have less volume expansion during lithium insertion compared to crystalline silicon. However, Si-Ox electrodes typically achieve a Coulombic efficiency of around 70% or lower, despite having a reversible capacity of about 1500 mAh/g [218]. The addition of specific binders and the use of tailored liquid electrolytes can help overcome those critical aspects [213,219].

Besides silicon, alloy metals such as tin (Sn), aluminum (Al), and antimony (Sb) have been intensively investigated. Sn-alloy anodes have a high onset voltage above Li/Li+, which can help prevent lithium deposition and dendrite formations while reducing interfacial resistance [211,220]. However, they usually suffer from high-volume deformation during cycling. Nanoscale synthesis of metals, such as nanoparticles and nanotubes, holds promise for addressing volume change during lithiation [194,221].

Transition metal oxides (TMOs) are of significant interest as anode materials for LIBs due to their favorable properties, including being non-toxic, having high power density, and being inexpensive [222–224]. They are based on the conversion reaction, which involves the formation and breaking of chemical bonds during lithiation and delithiation [206]. In LIBs, they can suppress the dendrite growth, increasing the battery's safety [194]. Notably, iron oxide (Fe_3O_4) has a theoretical capacity of about 926 mAh/g, making it a promising anode material. However, it suffers from rapid capacity loss and poor cycling stability due to the pulverization of active materials during operation, along with lower electrical conductivity compared to graphite [222–224].

Table 7 reports a comparison of some characteristics of these anode materials.

Other conversion-type transition metal compounds, such as transition metal chalcogenides, oxalates, carbides, nitrides, aluminum niobates, phosphides, and hydroxides, are also being explored as alternative anode materials in lithium-ion batteries [162].

Metal–organic frameworks (MOFs) are an emerging area of research and are considered promising materials for LIBs [225]. Their advantages include a high surface area, well-defined pore structures, and controllable chemical compositions. The unique porous structures of MOFs enhance electrolyte penetration and ion transport, support active materials, and selectively screen ions, making them ideal for use in battery separators, electrolytes, and electrodes [226]. Additionally, MOFs have several beneficial properties for battery applications, such as significant hygroscopic adsorption capabilities, high thermal stability, excellent electrochemical stability, and substantial mechanical robustness [227].

Table 7. Comparison of some electrochemical characteristics for some anode materials.

Composition	Gravimetric Capacity (mAh/g)	V vs. Li/Li+	Volume Change	Reference
C (graphite)	372	0.3 V	10%	[194,228]
$Li_4Ti_5O_{12}$	175	0.87 V	1%	[194,199]
$Li_{22}Si_5$ ($Li_{4.4}Si$)	4200	0.1 V	310%	[210,211]
$Li_{15}Si_4$	3570	50–60 mV	280%	[179]
Porous carbon–iron oxide (PC–Fe_3O_4)	926	0.8V	200%	[222–224,229]

Other emerging candidates for anodes are metal hydrides, like MgH_2 and TiH_2, which are made from abundant elements and offer low voltage hysteresis and high specific capacity. However, their capacity degrades after around 1000 to 2000 cycles, and they exhibit poor Coulomb efficiency. Metal phosphides are promising anode materials for lithium-ion and sodium-ion batteries due to their high specific capacity, safe operating potential, and excellent thermal stability. Improving long-term cycling performance is essential for hydrides to become viable for battery applications [206].

Finally, lithium metal is a promising anode material due to its high theoretical specific capacity (3860 mAh/g), low electrochemical potential (−3.04 V vs. SHE), and low density (0.59 g cm^{-3}). However, it faces challenges like lithium dendrite formation and continuous solid electrolyte interface (SEI) development, which can cause safety hazards, low Coulombic efficiency (CE), and reduced cycle life. Another challenge is the price of lithium metal itself and the expenses associated with refining the preparation process [222].

3.8.2. Cathode

Lithium battery cathodes use various technologies, each with specific advantages and disadvantages related to cost, safety, and performance. Lithium cobalt oxide (LCO) is the main cathode chemistry used in consumer electronics. In the past, lithium nickel oxide (LNO) was the second most common choice due to its lower cost and higher capacity, but its thermal instability limits its applications.

Recently, the automotive sector has moved to alternative cathode chemistries like lithium nickel cobalt aluminum oxide (NCA), lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium manganese oxide spinel (LMO) due to their better performance and safety compared to LCO [193]. According to the IEA [47], in 2022, NMC market share was 60%, followed by LFP (about 30%), and NCA with a share of about 8%. Cobalt-based technologies (NCA and NMC) are among the favorites for automotive applications due to their higher energy density, reaching 260 Wh/kg, and specific energy compared to LMO and LFP batteries. However, they suffer from thermal instability, which leads to a shorter cycle life than NMC [10]. NMC was originally formulated in the 1:1:1 ratio, which resulted in high energy density, power density, durability, and safety. However, NMC111 cost and value chain sustainability become critical, due to the growing demand for cobalt and its poor ecological and political sustainability [230]. NMC532 and NMC622 have recently become the dominant battery in EV applications, with NMC811 gaining market share [2], and higher-nickel content chemistry such as NMC955 emerging. However, increasing nickel content requires more complex production processes [4]. Moreover, cobalt guarantees the stability of the cathode.

On the other hand, LFP technology is expected to gain traction in automotive applications due to its stable and safe performance. LFP batteries have life cycles exceeding 2000 cycles, a wide operating temperature range, and costs that are over 20% lower than NMC batteries [4,13,231]. However, LFP batteries typically have an energy density that is 20–30% lower than that of high-nickel chemistries. A growing number of EV manufacturers are adopting LFP technology, including Tesla, Ford, Opel, and Citroën [232,233]. This trend is bolstered by researchers' successes in increasing the energy and power density of LFP batteries. In 2024, Zeekr announced an upgrade to its electric vehicle LFP battery, which can support ultra-fast charging at a rate of 5.5 C [234]. Meanwhile, SAIC-GM revealed the production of a 6 C charging LFP battery in collaboration with CATL [235]. Additionally, Geely introduced its latest generation of the self-developed Aegis LFP blade battery, which boasts an energy density of 192 Wh/kg [236].

Researchers have also developed a new iron and manganese form of LFP, termed LMFP, which was commercialized in 2024 [12] According to producer Gotion, the LMFP can reach an energy density of 240 Wh/Kg, has a volumetric energy density of 525 Wh/L, and a lifespan of 4000 cycles at room temperature and 1800 cycles at high temperatures [237]. A volumetric cell to pack (CPT) ratio of 76% allows for an LMFP battery pack energy density of 190 Wh/kg, surpassing the commercial NMC performance. The Chinese OEM BYD reached a 40% increase in cell-to-pack integration efficiency, reaching an energy density pack of 140 Wh/kg, using elongated LFP battery cells (blade cells), which are as long (600–2500 mm) as the pack [238].

In Table 8, we compare different lithium-ion technologies in terms of some electrical parameters and performance parameters.

Table 8. Comparison among some lithium-ion battery technologies for automotive applications. Data were processed from [100,194,199,203,238–244].

Cathode	Anode	Operating Voltage (V)	Energy Density (Wh/kg)	Power Density (W/kg)	Fast-Charging	Lifespan (Cycles)
LFP	C or Si-C	2.5–3.6	90–190	247	3 C	2000–4000
NMC	C or Si-C	3–4.2	130–280	300–800	0.7–1 C	1000–2000
NMC	LTO	1.5–2.8	70–90	2200	10 C	3000–10,000
LMO	C or Si-C	3–4.2	100–185	925	0.7–1 C	300–1000
LMO	LTO	1.5–2.8	70–90	3600	5 C	3000–7000
NCA	C or Si-C	3–4.2	175–300	670	0.7–2 C	500–1000

3.9. Safety

Battery safety encompasses a broad range of investigations aimed at understanding and mitigating the hazards associated with lithium-based batteries. It is of paramount importance, since the ageing process, abusive use, or battery defects can compromise performance and lead to dangerous consequences like fires or explosions [245–247].

Among the objectives of fault diagnosis, there is understanding the failure mechanisms by investigating the root causes of battery failures, including thermal runaway, internal short circuits, over-charging, over-discharging, and mechanical damage, and analyzing the chemical and physical processes that lead to these failures [248]. The risk assessment comprises determining the likelihood and severity of potential hazards, such as fires, explosions, and the release of toxic gases, and quantifying the risks associated with different battery chemistries, designs, and operating conditions. Reliability assessment employs experiments (accelerated aging, in situ diagnostics, failure analysis), computational models, and model or data-driven methods [109]. Experimental techniques include accelerated aging to simulate long-term degradation and in situ diagnostics for real-time monitoring [249]. Understanding thermal runaway is critical, especially in relation to operating conditions such as extreme temperatures, overcharging/discharging, and fast charging [250]. Thermal runaway is a critical failure mode where internal battery temperature rapidly increases due to exothermic reactions, leading to potential fires or explosions [248,251–254]. External factors like mechanical stress [249,255–257] and environmental conditions [84,258] can damage batteries, necessitating robust designs for diverse real-world use.

Risk management and safety assessment must take a comprehensive approach that considers both material and cell risks to evaluate the safety of battery systems effectively [247]. Indeed, the material choices for cathode, anode, electrolyte, and separator directly impact thermal stability and safety, with stable SEI layer formation and separator integrity being crucial [85,259–261]. Ongoing research is devoted to improving the intrinsic safety of battery components. Fire retardants, tailored solvents, and solid or quasi-solid state electrolytes are possible solutions to enhance battery safety [177,178,262,263]. Element doping, surface engineering, nanostructure, single-crystal design, and concentration gradient structure are strategies proposed to stabilize high-nickel cathodes [264–268].

Safety concerns are particularly critical for batteries used in automotive applications. As power and energy levels rise, the risk of vehicle fires and potential harm to people and property increases. For instance, in NCM-type batteries, a higher nickel (Ni) content results in increased specific capacity but reduced thermal stability.

The thermal runaway process is a complex chain reaction that consists of multiple steps, with its outcome influenced by various factors. The different components of the cells—such as electrolytes, electrodes, binders, and separators—affect both the sensitivity to thermal runaway and the severity of its consequences. LIB electrolytes typically consist of organic solvents and participate in several exothermic reactions during thermal runaway.

One critical reaction is the breakdown of the SEI, which is exothermic and starts at temperatures between 51 °C and 69 °C, depending on the electrolyte, particularly in the presence of carbonaceous anodes like graphite. Research has demonstrated that LTO anodes exhibit better safety performance due to their higher thermal stability [269].

The decomposition of the cathode, aside from being influenced by its chemistry, also depends on the electrolyte employed. For example, in an ethylene carbonate/diethyl carbonate (EC/DEC) solvent, the onset temperatures for the decomposition of LCO, NCM, and LFP are approximately 150 °C, 220 °C, and 310 °C, respectively.

Another crucial factor in assessing the safety of the cathode is the heat released during its decomposition and the rate of that heat release. Generally, the thermal reactivity of the cathodes can be ranked as follows: LCO > NCA > NMC > LMO > LFP. For more detailed information on the safety performance of various lithium-ion batteries (LIBs), readers are encouraged to refer to the analyses presented in specific research papers [270–272].

The unique nonlinear characteristics of lithium-ion batteries can render traditional reliability models ineffective [273]. Early fault diagnosis is vital for preventing component breakdown and improving overall EV reliability and safety [274]. Designing and evaluating safety features, such as thermal management systems, protection circuits, and flame-retardant materials, is fundamental to ensure safety [246]. Finally, manufacturing quality must be consistent to prevent defects like contamination and misalignment, requiring rigorous testing [249]. Utilizing data from real-world applications can be extremely beneficial. Recognizing this, many large companies have developed cloud-based platforms for monitoring and analyzing EV batteries in real-world settings [109,111,275].

Policies are essential for improving battery safety throughout their lifecycle, from manufacturing to disposal [276]. Regulations can enforce quality control measures, such as mandatory testing for defects and thermal stability, and require the use of safer materials. They also establish guidelines for the safe transport and storage of batteries, particularly lithium-ion ones, which present fire risks, and mandate safety features in battery-powered devices, like thermal management and overcharge protection. Effective recycling and disposal systems are crucial to prevent environmental contamination and fire hazards from damaged batteries, with regulations promoting responsible practices and traceability in production to identify defects and their origins.

The EU Battery Regulation [35], which includes the battery passport, aims to enhance sustainability and safety in battery use. The battery passport provides transparency and traceability by recording essential information about each battery's composition, performance, and lifecycle. This system allows for better tracking of batteries throughout their lifespan, making it easier to identify and recall defective batteries. Additionally, the battery passport offers detailed information about a battery's condition and history, which can help prevent misuse and promote safe handling practices.

Table 9 reports a résumé of the main performance characteristics reported for LIB technologies with respect to automotive applications.

Table 9. Summary of the main performance index for LIB batteries.

Battery Chemistry	Cost	Energy Density	Specific Power	Lifespan	Safety	Thermal Stability	Overall Suitability for EVs
LFP	Low to Med	Moderate	Good	Excellent	Excellent	Very Good	Good for mass-market EVs, especially where cost and longevity are prioritized.
LMFP	Medium	Moderate to High	Good to Very Good	Very Good to Excellent	Good	Good to Very Good	Promising for mid-range EVs, potentially bridging the gap between LFP and NMC.
LMO	Low to Med	Low to Moderate	High	Moderate	Good	Good	Niche applications (e.g., some hybrids, power-focused EVs if lifespan is acceptable).
LMNO	High	High	Good to Very Good	Potentially Good	Moderate	Moderate	Potential for future high-performance EVs if safety and cost challenges are overcome.
LCO	High	High	Moderate	Moderate	Poor to Med	Poor to Moderate	Limited suitability for EVs due to cost, safety concerns, and lifespan.
NCA	Medium to High	Very High	High	Good	Moderate	Moderate	Well-suited for premium, long-range EVs where performance is a key factor.

3.10. Current Trends and Future Developments in EV Batteries Research

Lithium-ion batteries (LIBs) alone cannot meet the increasing demand for batteries in the coming years, creating opportunities for more affordable and sustainable alternatives. Continuous advancements in Li-ion technology raise the performance standards for new technologies. However, improvements in one area, like energy density, can sometimes compromise safety or drive up costs. Therefore, emerging technologies must balance enhancements in range, safety, charging time, and sustainability to offer transformative solutions for EVs. Below, we highlight several promising battery technologies at various TRLs.

Research is focused on many other technologies, such as aqueous batteries [277–279] and dual-ion batteries [278,280]. Even though these technologies show promising performances, it is not yet proven that these batteries can be competitive in transportation applications, as they are still in the early stages of development.

3.10.1. Solid State LIBs

Lithium-ion solid-state batteries (SSBs) are among the most promising technologies for the near future. They are composed of the same cathode and anode of today's LIBs, but instead of a separator soaked with liquid electrolytes, they use a solid-state electrolyte (SSE). Since liquid electrolytes constitute one of the main safety concerns of LIBs due to the high flammability of the organic solvents they are made of, solid-state LIBs may reduce the risk of venting and fire [20]. In addition to improved safety, SSEs broaden the electrochemical window up to 6 V compared to lithium metal, allowing the use of high-voltage cathode materials [281]. Furthermore, SSEs could facilitate the adoption of lithium metal as anode resulting in an increased energy density thanks to its high theoretical specific capacity (3860 mA h/g), its low electrochemical potential (-3.04 V vs. the standard hydrogen electrode, SHE) and its low density (0.53 g cm^{-3} at room temperature) [282,283].

In comparison with traditional organic liquid electrolytes (OLEs), SPEs are lighter, non-flammable, and have lower cost, superior mechanical and processing properties, good flexibility, and uniform lithium deposition. Despite the considerable advantages offered by solid-state batteries, several challenges and limitations currently hinder their widespread adoption in the automotive industry. One of the primary hurdles is the increased electrical resistance of many solid electrolytes compared to liquid electrolytes [284]. This higher resistance can lead to difficulties in achieving the fast charging speeds that are highly desired for EVs. It can also contribute to a gradual degradation of the battery's performance over extended periods of use [285]. To be of interest, solid electrolytes must meet the following requirements [286]:

(1) Room temperature conductivity $\geq 10^{-4}$ S cm^{-1};
(2) Electronic insulation $<10^{-10}$ S cm^{-1} (Li+ migration number is approximately 1);
(3) Wide electrochemical window (>5.5 V vs. Li/Li+);
(4) Good compatibility with the selected electrode material;
(5) Good thermal stability and mechanical properties, wet environment resistance;
(6) Low cost and low environmental impact raw materials;
(7) A simple synthesis method.

SSEs have excellent elasticity and flexibility that result in good interface contact properties [287]. Especially in the presence of electrodes with high volume expansion and contraction during charging and discharging, they can maintain good contact, reducing the interface impedance and assuring the stability of the SSB [288].

The SSEs investigated in the last few decades are generally grouped in three categories: solid polymer electrolytes (SPEs), inorganic solid electrolytes (ISEs), and organic–inorganic composite solid electrolytes (CSEs) [289,290]. Common polymer matrix materials used for SPEs include poly-ethylene oxide (PEO), polyacrylonitrile (PAN), poly-vinylidene fluoride (PVDF), and poly-methyl methacrylate (PMMA) [286,291], while the following lithium salts are generally used: lithium hexafluorophosphate ($LiPF_6$), lithium bis(fluorosulfonyl)imide (LiFSI), [292] and Lithium Bis(Trifluoromethanesulfonyl)Imide (LiTFSI) [293]. Generally, the ionic conductivity for SPEs varies from 10^{-4} and 10^{-5} S cm^{-1}. Sun et al. [294] developed a polymer bi-phase SSE with an excellent ionic conductivity of 1.9 mS cm^{-1} at room-temperature, a high oxidation potential of 4.9 V (vs Li/Li^+) and a lithium transference number (t_{Li+}) of 0.56, by using in situ thermal cross-linking of 2-ethyl cyanoacrylate (CA), polyethylene glycol methyl ether acrylate (PEGMEA), succinonitrile (SN), and fluoroethylene carbonate (FEC) additives. They coupled an 11 μm bi-phase SPE with an NCM811 cathode and a 30 μm lithium metal anode, obtaining a discharge capacity of 208 mAh/g with a cut-off voltage of 4.5 V, resulting in an energy density of 400 Wh/kg.

ISEs, on the other hand, show the highest ionic conductivity, reaching 10^{-2} S cm^{-1}, which is comparable to that of liquid electrolytes at the operating temperature [295]. The ISEs can be grouped into three types: oxide, sulfide, and halide electrolytes.

Solid oxide electrolytes have a high electrochemical oxidation voltage and chemical and mechanical stability, while the disadvantages are mainly the high resistance at the electrode–electrolyte interface and the high synthesis temperature [284]. Among them, the garnet-type SSEs have the highest ionic conductivity (10^{-4}–10^{-3} S cm^{-1}), a good oxidation stability (6 V vs. Li/Li+), and a high stability allowing compatibility with lithium metal anodes. The most promising garnet-type SSE is the $Li_7La_3Zr_2O_{12}$ (LLZO) with a Li+ conductivity of 1 mS cm^{-1} [296].

Sulfide ISEs have the highest ionic conductivity, comparable to that of organic liquid electrolytes [297]. Most sulfide ISEs have a conductivity that exceeds 1 mS cm^{-1}, and some can reach 20 mS cm^{-1}. They also have good flexibility that allows good contact with the electrodes. On the other hand, sulfide ISEs have low oxidation stability, and they are sensitive to air and decompose in the presence of toxic gases in the air, constituting a safety problem [298].

The third type of ISEs, halide solid electrolytes, are not inherently stable with lithium metal anodes, but they can be stabilized through various methods [299]. They offer high mechanical strength and good cycling performance in high voltage windows, but they suffer from low ionic conductivity, which in a few cases can reach 10^{-3} S cm^{-1}, and poor air stability [300,301].

To overcome the low ionic conductivity of SPEs and the high interfacial resistance of ISEs, organic–inorganic composite solid electrolytes (CSEs) were developed. They are composed of both a polymeric matrix with lithium salt and an inorganic filler. The polymeric matrix reduces the interface resistance with the electrode materials, bringing toughness and elasticity, while the inorganic filler improves the ionic conductivity by reducing the crystallinity of the polymer matrix while bringing mechanical strength [302]. Several types of polymeric matrix and lithium salt described before are used in CSEs, as well as several types of ISEs described before are used too. The resulting ionic conductivity for the different CSEs lies between 10^{-4} and 10^{-3} S cm^{-1} [303,304].

Maintaining a stable and effective interface between the solid electrolyte and the solid electrodes (anode and cathode) is crucial for efficient ion transport. However, achieving good and consistent contact at these solid-to-solid interfaces, while also ensuring electronic insulation to prevent short circuits, has been a persistent technical difficulty, due to high interfacial resistance, poor interface contacts, interface instability, and side reactions between solid-state electrolytes and electrodes. To address these challenges, surface coating is often used [305,306]. Another way to improve the electrode–electrolyte interface is the adoption of bilayer heterostructure composite electrolytes where poly-vinylidene fluoride-hexafluoropropylene (PVDF-HFP) and oxidation-resistant PAN were used for the contact with the cathode ($LiFePO_4$), and PVDF-HFP and reduction-resistant PEO were used for the contact with the anode (metal lithium) [305,307]. Another strategy is the adoption of laser-ablated geometrical structures [308].

Some types of solid electrolytes, particularly ceramics, can exhibit sensitivity to temperature and pressure. Their performance might degrade at low temperatures, and some designs require the application of high pressure to maintain adequate contact with the electrodes [309]. Additionally, ceramic electrolytes can be brittle, making them susceptible to cracking under mechanical stress [310], which is a concern in the demanding environment of an electric vehicle. While solid electrolytes are generally expected to suppress the formation of lithium dendrites, this problem can still occur in solid-state batteries that utilize lithium metal anodes [311], potentially leading to short circuits and battery failure.

The current state-of-the-art of these SSBs, developed by enterprises worldwide, has achieved a specific energy of over 250 Wh/kg, generally about 370 Wh/kg (peaking at 417 Wh/kg), an energy density of over 900 Wh/L, a capability of 4 C fast charge, and cycle life greater than 500 cycles and even up to 4000 cycles [193,286,298].

Based on the current state of development and the timelines announced by various companies, the initial commercialization of solid-state batteries in electric vehicles is anticipated in the late 2020s, with some manufacturers targeting the period between 2026 and 2029 for their introduction in higher-end or limited production models [312]. However, widespread adoption across a broader range of electric vehicle segments is more likely to occur in the early to mid-2030s as the technological and manufacturing challenges are effectively addressed and the production costs are significantly reduced to make the technology economically viable for the mass market [313]. Semi-solid-state batteries, where liquid and solid electrolytes are used together to enhance electrode–electrolyte interface performances, may serve as a transitional technology in the interim.

3.10.2. Sodium-Ion Batteries

Non-lithium metal-ion batteries have attracted increasing interest in the last four years, as shown in Figure 6.

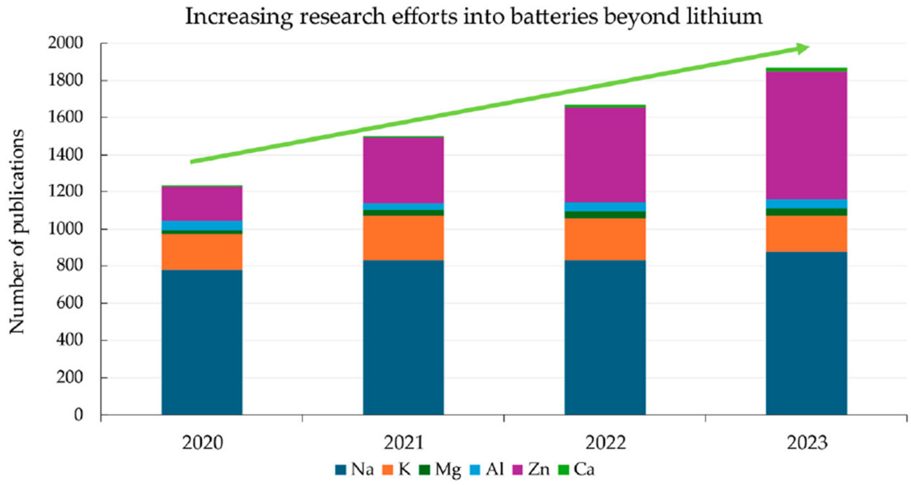

Figure 6. Trend in number of publications regarding non-lithium batteries in the last years. Reproduced from [314] under CC BY 4.0 terms.

The main requirement that alternative chemistries must satisfy is the use of more abundant and easier-to-recycle raw materials. In fact, besides comparable (or at least not significantly worse) performance in terms of energy density, power density, and cycle life, alternative chemistries should have improved safety and environmental sustainability.

Sodium has a low cost and is highly abundant. SIBs function on a very similar principle to LIBs but utilize sodium ions (Na+) as the charge. The fundamental construction of a SIB closely mirrors that of a LIB, making it a promising alternative [315,316]. The main disadvantage of sodium compared to lithium is the higher density, which, combined with a less negative standard electrode potential (−2.71 V of sodium versus −3.040 V of lithium), results in a lower energy and power density than LIBs, making SIBs less attractive for the transportation sector.

The anode is often made of a disordered carbon material known as hard carbon (HC), which has been shown to effectively intercalate sodium ions. Graphite-based anodes are not compatible with sodium-ion, mainly because of the larger ionic diameter of sodium (1.06 Å) versus lithium (0.67 Å) that results in a less ionic diffusivity and causes structural distortion of the active electrode material during intercalation. The use of HC materials in SIBs has already been commercialized, and extensive research is focused on enhancing their rate capability and overall performance. Specifically, research groups are exploring strategies such as heteroatom doping to create porosity and introduce defects on the surface, which can increase the number of active sites [317,318].

Other intercalation materials suitable as anodes in SIBs are titanium-based materials. Among them, titanium-based oxides exhibit considerable potential, due to the various crystalline phases, significant structural stability, and high abundance [319].

Transition metal chalcogenides (TMCs) are also explored as potential negative electrodes for SIBs, since they can provide high capacity [320].

Regarding electrolytes, the most common for SIBs are organic carbonate-based electrolytes and ether-based electrolytes. Carbonates generally use fluoroethyl carbonate (FEC) as an additive to improve the SEI formation [321], and are suitable for high-voltage cathodes since they are more stable than ethers at high voltage. However, in cells with hard carbon as an anode, ethers show better long-term cycling stability. The latter are also more suitable for low-temperature applications [314,322].

A promising solution to increase the energy density of sodium-ion batteries (SIBs) involves replacing the insertion-type anodes with ultra-thin metallic sodium, which has a density of 1166 mAh/g [323]. The metallic sodium anode can be used in the form of a foil deposited on the electrode. However, this foil may contain excess metal, which can decrease the overall energy density. Additionally, metallic sodium is highly reactive to air, and its softness and stickiness complicate the manufacturing process. In an alternative method, the anode is formed during the initial charging process using sodium sourced from the cathode material. This approach benefits from the absence of air during production, eliminating concerns about excess sodium [324]. However, this method may reduce the total capacity that the cathode can provide due to the formation of SEI. Li et al. [325] developed AFNBs that used a layered oxide-based cathode ($Na[Cu_{1/9}Ni_{2/9}Fe_{1/3}Mn_{1/3}]O_2$) and an aluminum current collector coated with graphitic carbon on the anode side, reaching an energy density of 200 Wh/kg with a cycle life of 260.

Typical SIB cathode materials are layered transition metal oxide (LTMO), polyanionic compounds, Prussian blue analogs (PBAs), and organic polymer.

In LTMO, Na+ ions intercalate between the layers through the trigonal prismatic or the octahedral vacancies, and their formula is generally represented as Na_xTMO_2, where $0 < x < 1$ and TM represents 3D transition metals [314]. The use of these cathode materials, already developed for LIBs, could reduce the initial investment required for SIBs production. However, the large size of sodium-ions leads to a great volume expansion during cycling, resulting in reduced stability and lower cycle life, especially at high C-rate. Strategies such as structural modifications can improve LTMO performance [326]. Wang et al. [327] synthesized a transition-metal oxide cathode based on P2-Na_xMnO_2 doped with potassium: $Na_{0.612}K_{0.056}MnO_2$ to reinforce the Mn-O bonds and reduce the phase transition during cycling. When coupled with a presodiated hard carbon, they reached a full cell energy density of 314.4 Wh/kg (based on the total mass of active anode and cathode materials), with a specific capacity of 230.6 mAh/g. Sathiya et al. [328] gradually replaced manganese with a non-transitional metal ion, Sn^{4+}, into a $NaNi_{0.5}Mn_{0.5-\gamma}Sn_\gamma O_2$ cathode (γ = 0–0.5) to reduce cathode phase transition and increase cycling performance. When coupled with a hard carbon anode, the energy density of materials decreases from 335 Wh/kg for the lightest $NaNi_{0.5}Mn_{0.5}O_2$ to 270 Wh/kg when substituting all the Mn with Sn. However, with a γ between 0.3 and 0.5, they improved the cycling stability of the cell. Zheng et al. [329] synthesized a Mn-based layered oxide cathode with a high-temperature thermal shock strategy (NMO-HTS) to suppress Mn ion vacancy within transition material layers. The average discharge is 2.65 V, and the rate capability is 180 mAh/g at 1C and from 28 to 67 mAh/g at 20 C. The full cell, with NMO-HTS cathode and hard carbon anode, reached an energy density of 248 Wh/kg based on the weight of both electrodes.

Among polyanionic compounds, the sodium superionic conductors (NASICON) are among the most promising materials due to their significant structural stability and high ionic conductivity [330,331]. The NASICON molecular formula is generally represented as $Na_xMM'(XO_4)_3$, where M or M′ = V, Fe, etc., X = P or S, x = 0–4. Deng et al. [332] optimized a $Na_3V_2(PO_4)_2F_3$ (NVPF) cathode, obtaining an electrode energy density of 446.4 Wh /kg at 1 C with a high reversible capacity (120.8 mAh/g at 1 C), good rate capability (89 mAh/g at 30 C) and long cycle life (81.3%@10 C after 1700 cycles). The presence of vanadium can pose a challenge, since this metal is scarce in the EU, with China being its primary producer. Zhang et al. [333] developed another NASICON-type $Na_4MnCr(PO_4)_3$ cathode with an excellent energy density of 566.5 Wh/kg (greater than that of $LiFePO_4 \approx 530$ Wh/kg), a reversible capacity of 160.5 mAh/g.

PBA compounds are of interest for their three-dimensional open framework, adjustable structures, and chemical composition, and recent advancements have demonstrated promising enhancements in electrochemical performance and synthesis efficiency. PBAs have a typical structure of a double perovskite framework with $(C{\equiv}N)^-$ anions bridging MN_6 (M = Fe, Mn, Co, Ni, Cu, Zn, and Ti) and FeC_6 octahedra, while Na^+ ions and H_2O occupy the interstitial sites [334]. Within PBAs, sodium manganese hexacyanoferrate ($Na_xMnFe(CN)_6$) is one of the most promising, thanks to its high energy density, non-toxicity, and abundance of its metal components, Mn and Fe. Tang et al. [334] synthesized the cubic and monoclinic structures of ($Na_xMnFe(CN)_6$). The cubic structure achieves better electrochemical performances, with a specific capacity of about 120 mAh/g at 3.5 V vs. Na^+/Na, and a capacity retention of 70% over 500 cycles. PBAs are already used in production SIB cells fabricated by the company Novasis Energies, Inc., providing cell-specific energy between 100 and 130 Wh/kg and volumetric energy density of 150–210 Wh/L [335]. The interstitial water presence is one of the main drawbacks since it compromises the cell performance, and it is difficult to remove [325].

Organic polymers are seen as potential cathode materials for SIBs due to their lightweight nature, flexibility in design, and potentially lower cost compared to traditional inorganic materials [336]. Examples of aromatic functional groups that can be used include imides, quinones, conjugated polymers, and aromatic carboxylates. The design flexibility includes the possibility to modulate the material's physical properties, such as flexibility and electronic conductivity [337]. These materials can achieve a higher capacity than metal oxides and polyanions, but this comes at the cost of a lower voltage range and reduced stability [316].

Table 10 presents the specific energy and capacity of various non-commercial SIBs based on the composition of the anode and cathode, demonstrating performance comparable to LIBs.

It is noteworthy that several studies confirmed that the construction of high-performance SIBs shows a low dependence on cobalt [338]. The main technical challenge with SIBs is their limited reversibility, which results from unstable electrode materials during cycling and uncontrollable side reactions at the electrode/electrolyte interface. Research shows that capacity fading and poor cycling stability are linked to these issues [339]. Additionally, the formation of the SEI layer is still not fully understood. The dynamic process of SEI formation and its chemical composition are critical for ion mobility and the stability of the electrolyte and electrodes, significantly influencing the cells' electrochemical performance [340,341].

The safety performance of SIBs is still under investigation. If future research confirms that sodium batteries are indeed safer than LIBs, their commercialization could increase significantly since one of the key motivations for developing batteries beyond lithium is the potential to enhance safety features. However, sodium, like other alternative ions, is unstable in ambient air and reacts vigorously with water.

Among the components contributing to the overall stability of the cell, electrolytes play a particularly important role in ensuring cell safety. Since organic electrolytes commonly used in SIBs are inherently flammable, it is crucial to thoroughly evaluate the safety aspects associated with them. Yue et al. [342] compared the risk of thermal runaway in SIBs and LIBs, finding that the hazard associated with sodium-ion batteries using transition metal cathodes was lower than that of NCM LIBs but higher than that of LFP batteries. Buthia et al. [343] reported in their review the onset and maximum temperatures related to thermal runaway in both LIBs and SIBs with various chemistries. They noted that all SIB chemistries exhibit a lower maximum temperature compared to LIBs, although their onset temperatures are similar. Additionally, the authors emphasize that the risks of thermal runaway in SIBs can vary depending on the cathode material used. Specifically, cathodes made from layered oxides present a greater risk than those made from Prussian blue analogs, while polyanionic compounds are considered less risky.

Table 10. Electrochemical properties of some non-commercial SIBs.

Cathode	Anode	Specific Energy [Wh/kg]	Specific Capacity [mAh/g]	Source
$Na_{0.612}K_{0.056}MnO$	Presodiated HC	314.4	230.6	[327]
$NaNi_{0.5}Mn_{0.5-\gamma}Sn_{\gamma}O_2$	HC	335–270 with γ = 0–0.5	-	[328]
NMO-HTS	HC	248	180	[329]
$Na_3V_{1.8}(CrMnFenAl)_{0.2}(PO_4)_3$	HC	202	-	[344]
$Na_xMnFe(CN)_6$	TiO_2	111	120	[334]
PBA	HC	100–130	-	[335]
$Na[Cu_{1/9}Ni_{2/9}Fe_{1/3}Mn_{1/3}]O_2$	Anode Free	200	-	[325]

3.10.3. Potassium-Ion Batteries

Potassium has garnered significant scientific interest due to its membership in the same group as lithium and sodium. It exhibits a standard electrode potential of −2.931 V, which is more negative than that of sodium (−2.71 V). Additionally, potassium is one of the most abundant elements in the Earth's crust. However, the diffusion of potassium ion batteries (PIBs) is hindered by the larger ionic radius compared to sodium, which leads to an increased volume expansion during ion intercalation in the electrode materials.

The larger radius of K^+ implies a smaller charge density, which corresponds to a weaker solvent shell, also compared to Na^+, and consequently to a minor solvation energy. Since in the intercalation mechanism, the ion desolvation is a key feature, PIBs could show high-rate capability and high power [314].

A common cathode used in PIB full cells is the organic compound perylenetetracarboxylic dianhydride (PTCDA), which is compatible with common organic electrolytes. Other cathodes include LTMO, polyanionic compounds, and PBA.

Regarding the PBAs, similarly to sodium ion, the interstitial water presence gives rise to unwanted reactions such as thermal instability and capacity decay during cycling. Liao et al. [345] focused on a cathode of metal hexacyanoferrates (HCFs), because of their low cost and high energy density, and developed a method to obtain nanoplate of (100) face-oriented potassium magnesium hexacyanoferrates (KMgHCF) with low $[Fe(CN)_6]$ vacancies, high crystallinity and no crystal water. When coupled with an anode composed of graphite and dipotassium terephthalate (K2TP), they obtained a full cell with a 3.45 V average discharge voltage, with a specific capacity of 83 mAh/g, and an energy density of 214.8 Wh/kg.

Research on anodes for PIBs primarily focuses on carbon-based materials, including graphitic carbon, soft carbon, and hard carbon. Although Na^+ cannot intercalate in graphite, K^+ can. This phenomenon is related to the enthalpy of formation rather than simply the size of the ions [346].

In general, electrolytes used in PIBs include carbonate or ether-based electrolytes, while aqueous electrolytes are not common due to the limited electrochemical stability window.

Zhang et al. [347] reported the carbonaceous anodes as a bottleneck of PIBs capacity, so they focused on the development of a carbon anode, doped with nitrogen, that possesses a 3D framework (3D-NTC), to enhance the electrode capacity. Also, Wang et al. [348] focused on the anode development, using a facet growth mechanism with $(BiO_2)CO_3$ nanocrystal and amorphous iron oxide obtaining outstanding results. Ji et al. [349] found that a magnet, the $KFeC_2O_4F$, can be used as a cathode in PIBs, with a discharge capacity of 112 mAh/g and an excellent capacity retention of 94% after 2000 cycles. The reported results are summarized in Table 11 for the full cells.

Table 11. Electrochemical properties of some PIBs.

Cathode	Anode	Specific Energy [Wh/kg]	Specific Capacity [mAh/g]	Authors
PTCDA	3D-NTC	187	241	[347]
PTCDA	$(BiO_2)CO_3$	732.8	-	[348]
$KFeC_2O_4F$	Soft Carbon	235	112	[349]
KMgHCF	Graphite and K2TP	214.8	83	[345]

3.10.4. Magnesium-Ion Batteries

Magnesium is one of the ten most abundant elements on Earth (1000 times more abundant than lithium), and it is the third most used metal in industry. It has a good specific density (2205 mAh/g of Mg vs. 3861 mAh/g of Li), a high density per unit of volume (3833 mAh/mL of Mg vs. 2062 mAh/mL of Li), and a discrete redox potential (−2.372 V of Mg/Mg^{2+} vs. SHE). These advantages, together with the reputation of dendrite-free plating of Mg onto Mg metal [350], make magnesium ion batteries (MIBs) of interest. Nevertheless, many challenges must be faced to achieve a satisfactory performance, and research is still at an early stage.

The main drawbacks of MIBs are the sluggish kinetics of Mg ions and the difficulty in finding electrolytes compatible with both electrodes and SEI formation when using common solvents. The magnesium ion, Mg^{2+}, has a smaller ionic radius than Li+ and a double valence state that results in a higher charge density and therefore in slow diffusion inside the electrodes and high desolvation energy in the electrolytes [322,351].

As a result, the chemistry of the magnesium ion battery is different and more complicated than that of other alkali metals already used for secondary batteries, and the TRL is still low [352]. Uncommon electrolytes are used in MIBs, the two best performing electrolytes are the "All Phenyl Complex" (APC) from Aurbach et al. [353] and the "Magnesium Aluminum Chloride Complex" (MACC) by Doe et al. [354]. Also aqueous electrolytes are used, but, similar to the common organic electrolytes, they tend to passivate pure Mg anodes [355].

The most common cathodes are inorganic oxides, polyanionic, and sulfide compounds. Metal oxides can store Mg^{2+} ions both by intercalation and by conversion [316]. Within the sulfide compounds, the benchmark is the Chevrel-phase Mo_6S_8 [356,357].

For anodes, the principal materials under investigation are metallic magnesium, alloy-based, and carbon-based materials. Metallic magnesium could allow the high energy density that MIBs promise. While alloy-based materials, mainly bismuth, tin, and antimony, are used to avoid the passivation layer formed from Mg metal in the presence of a common electrolyte [358,359]. In Table 12, we summarize some electrochemical properties of MIBs.

Table 12. Electrochemical properties of some MIBs.

Cathode	Anode	Specific Energy [Wh/kg]	Specific Capacity [mAh/g]	Source
$NaV_2O_2(PO_4)_2F$ @rGO	$Mg_{0.79}NaTi_2(PO_4)_3/C$	76	-	[360]
Te @CSs	Mg metal	337	387	[361]
$Mg_{0.75}V_{10}O_{24}\cdot 4H_2O$	PTCDA	67	-	[362]

Dominko et al. [353] calculated the performance between various cathodes, considering as anode either a Mg foil or an alloy (Mg_2Sn) and taking into account many parameters such as conductive additive, binder, current collectors, porosity of electrodes and separator, etc. All combinations based on insertion cathodes have an operating voltage below 2 V, and their performance is lower than that of LIBs (~685 Wh/L and 180 Wh/kg). Organic materials can increase gravimetric density up to 250 Wh/kg, but only the sulfur conversion cathode can have an energy density comparable to LIBs. Wang et al. [361] developed an intercalation cathode based on tetragonal $NaV_2O_2(PO_4)_2F$ reduced graphene oxide (rGO) obtained by a electrochemical desodiated method, that shows an average working voltage of 3.3 V vs. Mg^{2+}/Mg and 30.3 mAh/g at 5 mA/g. When coupled with a $Mg_{0.79}NaTi_2(PO_4)_3/C$ anode material to build a full cell, they obtained a 76 Wh/kg energy density with a power density of 1300 W/kg, with a working voltage between 0.3 and 2.2 V. Chen et al. [362] developed a conversion-type cathode based on Tellurium (Te) encapsulated on carbon spheres (CSs). When coupled with Mg metal anode, the electrode capacity is up to 387 mAh/g with an energy density of 337 Wh/kg. Ma et al. [363] developed a lamellar $Mg_{0.75}V_{10}O_{24}{\cdot}4H_2O$ (denoted as MVOH), which contains abundant lattice H_2O that led to fast Mg^{2+} migration through a complex shuttle mechanism. When coupling this cathode with a perylene-3,4,9,10-tetracarboxylic dianhydride (PTCDA) anode in an aqueous solution electrolyte, they achieved a 67 Wh/kg energy density with a cycle life of 5000 cycles and a maximal power density of 2 kW/kg.

3.10.5. Lithium–Sulfur Batteries

Lithium–sulfur (LiS) batteries represent another promising emerging technology that utilizes a lithium metal anode and a sulfur-based cathode. LiSs potential for exceptionally high energy density, which can be two to five times greater than that of current LIBs, makes them a remarkable candidate for automotive applications [363]. Another major benefit is the potential for lower costs. Sulfur, a primary component of Li-S batteries, is an abundant and inexpensive material compared to the cobalt and nickel used in many lithium-ion batteries. Furthermore, Li-S batteries are considered to be potentially more environmentally friendly due to the abundance of sulfur and the less resource-intensive processes associated with its extraction compared to some of the metals used in traditional batteries [364].

Like conventional lithium-ion batteries, they typically employ a liquid organic electrolyte to facilitate the movement of ions. The generation of electrical energy in an LiS battery occurs through an electrochemical reaction where lithium at the anode is oxidized, releasing lithium ions that then travel through the electrolyte to the sulfur cathode. At the cathode, elemental sulfur undergoes a complex, multi-step reduction process. This process involves the formation of various intermediate compounds known as lithium polysulfides (Li_2Sn), which have different chain lengths (with n ranging from 3 to 8). The discharge process continues until the sulfur is fully reduced to lithium sulfide (Li_2S). During charging, this reaction is reversed, with lithium sulfide being oxidized back to elemental sulfur, and lithium ions returning to the anode [365]. This chemical transformation involves a multi-electron transfer process, resulting in a significantly high theoretical energy density estimated to be between 2500 and 2600 Wh/kg [366]. Intermediate lithium polysulfides are soluble in the electrolyte, allowing them to diffuse between the cathode and anode. This polysulfide shuttle creates performance challenges, leading to a decrease in battery capacity and Coulombic efficiency [367]. Additionally, the cycle stability of LiS batteries is compromised by the poisoning of the lithium metal negative electrode, which hampers their practical application [368]. Other issues include the low conductivity of active materials, significant volume changes during redox cycling, and the formation of dendrites [365].

Table 13 summarizes the performance metrics reported in several recent research articles and company announcements concerning LiS batteries in 2023 and 2024. It highlights the advancements in energy density, capacity density, and voltage achieved through various materials and experimental conditions.

Table 13. Electrochemical properties of some LiS batteries.

Energy Density (Wh/kg)	Capacity Density (mAh/g)	Average Discharge Voltage (V)	Cell Characteristics	Source
395	-	-	9.5 Ah pouch cell	[369]
>550 (pack), up to 700 (cell)	-	-	Low electrolyte-to-sulfur ratio pouch cells	[370]
-	>250 (pouch cell), >3 mAh/cm^2	-	Catholyte, sulfur-free carbon nanofiber cathode	[371]
2500 (theoretical)	1672 (theoretical)	~2.1	Theoretical values	[372]
~542.7 (estimated All-solid-state)	-	~2.0	All-solid-state, 90% sulfur utilization, 60 wt% sulfur in cathode	[373]
2400 (theoretical with Li anode)	1675 (theoretical cathode), 3860 (theoretical anode)	-	Theoretical values	[374]

Analysis of the data reveals a clear trend towards achieving higher energy densities in practical LiS battery cells. These advancements are often associated with specific material choices and cell designs, such as the use of pouch cell formats and optimized electrolyte-to-sulfur ratios. While theoretical values for energy and capacity density remain much higher, the gap is gradually being narrowed by ongoing research. The average discharge voltage for LiS batteries remains consistently around 2.0–2.1 V, as dictated by fundamental chemistry. The table underscores the dynamic nature of the field, with continuous improvements being reported through innovative approaches.

To improve LiS performance in terms of cell cyclability, rate capability, safety, and lifespan, electrolyte additives can be used [375]. Material engineering is actively studied to prolong the lifespan of LiS [365], along with different protection strategies for the anode to avoid dendrite formation [376]. Other research areas include the development of nanostructured sulfur cathodes [377,378], the creation of protective coatings [379], the use of MXene to anchor polysulfides [380], and the advancement of all-solid-state LiS batteries [368].

While lithium–sulfur batteries hold significant promise, their widespread commercialization in electric vehicles is still some years away.

3.10.6. Zinc-Based Batteries

Zinc-based batteries (ZBs) represent a diverse category of electrochemical energy storage systems that utilize metallic zinc as the primary negative electrode material. Zinc is an abundant, inexpensive, and non-toxic material, making it a more sustainable and cost-effective option compared to lithium and other critical battery materials [381].

Unlike lithium-ion batteries, which primarily rely on the intercalation of lithium ions into electrode materials, zinc-based batteries often operate through different mechanisms, such as the dissolution and deposition of zinc metal or oxygen reduction reactions, depending on the specific type of zinc battery. There are several main types of zinc-based batteries being explored for various applications, including zinc-ion batteries (ZIBs), which typically use aqueous electrolytes and involve the reversible shuttling of zinc ions between the zinc anode and a cathode made of materials like manganese oxide or vanadium oxide [382]. Aqueous electrolytes are non-flammable and eliminate the risk of thermal runaway associated with the organic electrolytes used in LIBs.

Another prominent type is zinc–air batteries (ZABs), which are open-system batteries that utilize zinc as the anode and oxygen from the ambient air as the cathode. These batteries generate energy through the reaction of zinc with oxygen and can be recharged either electrically or by physically replacing the spent zinc anode [383,384]. They have a very high theoretical energy density, potentially exceeding that of LIBS.

Despite their promising attributes, zinc-based batteries face several challenges that currently limit their widespread use in electric vehicles. To enable large-scale practical applications, several challenges must be overcome, including limited discharging capacity, low operating voltage, low energy density, short cycle life, and complex energy storage mechanisms, which require methodologies that depend on the specific redox mechanism [385,386]. ZIBs generally have a lower energy density compared to high-performance lithium-ion batteries, which could restrict the driving range of EVs powered solely by ZIBs. A significant technical hurdle for both ZIBs and ZABs is the zinc anode, which is susceptible to corrosion, the formation of dendrites (needle-like zinc structures that can cause short circuits), and hydrogen evolution reactions, all of which can severely compromise the battery's Coulombic efficiency and cycling stability, hindering their broader adoption [382,387]. ZABs have faced challenges related to their rechargeability, often requiring physical replacement of the zinc anode [388], and can suffer from slow discharge rates [389]. For the same energy capacity, ZB packs can also be bulkier compared to lithium-ion packs [381]. Additionally, some ZBs chemistries have a lower nominal voltage compared to lithium-ion batteries [390].

ZBs are already utilized in various niche applications, including hearing aids and some stationary storage systems. Commercialization for electric vehicles, particularly zinc–air batteries, is expected to begin within this decade, potentially targeting smaller vehicle segments like two- and three-wheelers initially [391].

Figure 7 depicts a maturity roadmap of lithium-ion alternative battery chemistries presented in this section.

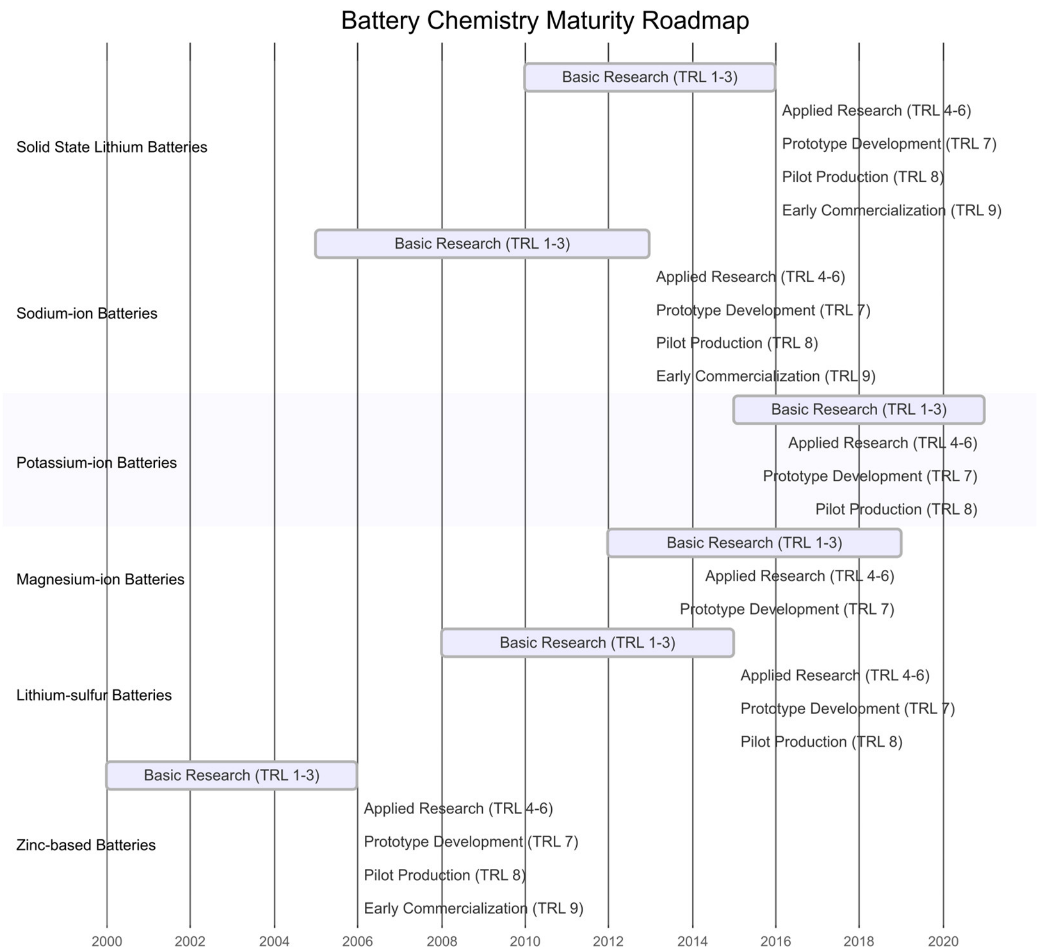

Figure 7. Maturity roadmap for some lithium-ion alternative battery chemistries.

4. The Sustainability Issue

Batteries are one of the key enablers for sustainable development, green mobility, clean energy, and climate neutrality. For the widespread adoption of electric power across industries like transportation, sustainable battery practices are vital. To truly benefit from a low-carbon economy driven by electrification, we must tackle the environmental burdens of battery manufacturing, specifically CO_2 output, resource scarcity, and ethical material procurement. Achieving sustainable consumption and production necessitates a swift transition to well-engineered batteries that are clean, circular, and long-lasting [392]. Accordingly, a harmonized regulatory framework governing the entire lifecycle of batteries placed on the market ought to incorporate the following sustainability stipulations:

- Minimizing the carbon footprint across the entire value and production chain;
- Ensuring ethical and responsible raw material acquisition;
- Fostering a circular design that incorporates recycled content and enables reuse, repurposing, remanufacturing, and final recycling;
- Providing transparent communication and tracking of performance and material/chemical contents for end users and supply chain stakeholders.

From the perspective of EU environmental policy, batteries are considered highly valuable and strategic products. According to the recent Battery Regulation [35], batteries must be designed and manufactured to optimize performance, durability, and safety while minimizing their environmental impact. Specific sustainability requirements have been established for EV batteries, as this market segment is expected to grow significantly in the coming years.

A “battery passport” is mandated by the Regulation to increase transparency throughout battery supply and value chains for all stakeholders. This passport will monitor and trace batteries and disclose vital information such as the carbon footprint of their production, the origin of their components, potential for repair and repurpose, and dismantling instructions. It will also detail the treatment, recycling, and recovery pathways for batteries at the end of their usable life.

The battery passport also presents challenges that could lead to drawbacks if left unmitigated [393,394]. The regulation requires actors to collect, integrate, and certify extensive data throughout the battery lifecycle. This requires transparent and efficient communication between actors to ensure everybody along the supply chain can provide the information needed. Passport issuers are expected to face mainly technical and system challenges, thus requiring industry collaboration, investment in emerging technologies, and support from authorities to ensure standard enforcement. Conversely, small- and medium-sized enterprises are anticipated to encounter primarily capability and resource challenges, necessitating early internal alignment, standardized requirements, and financial aid.

The involvement of numerous supply chain actors makes it difficult to access data on aspects like the metallic composition of batteries and the specifics of their manufacturing processes. Moreover, determining the state of health of batteries can also be complicated. Adding to these challenges, companies are unwilling to disclose data unless they have assurances through non-disclosure agreements. Although these unresolved issues might lessen the overall effectiveness of the passport, its benefits are still expected to be greater than its drawbacks.

4.1. Life Cycle Emissions

Encompassing all greenhouse gas (GHG) emissions produced across the supply chain’s diverse phases, the life cycle emissions of batteries originate with the mining and processing of ores. This initial step yields precursor materials crucial for creating the battery’s active components: cathode and anode materials. Subsequently, these active materials, along with other elements like the electrolyte, separator, current collector, and casing, are utilized in battery cell production. Ultimately, individual cells are assembled into battery modules or packs, which also incorporate vital components such as battery management systems, electronics, and cooling systems. Notably, the carbon footprint of batteries (CFB) stands as one of the sustainability metrics that must be calculated and communicated, as detailed in Article 7 of the EU Regulation [35].

Quantifying the overall greenhouse gas impact of a battery over its anticipated service life, the CFB is expressed in g CO_2 equivalent per kWh of total energy output. The Regulation mandates CFB declaration for specific battery types placed on the Union market: rechargeable industrial batteries with a capacity over 2 kWh, light means of transport (LMT) batteries, and EV batteries. Subsequently, these CFB declarations will be utilized to establish CFB performance classes and the CFB thresholds that batteries must adhere to when entering the European market. A CFB model is constructed from processes that combine elementary flows with their associated characterization factors, along with activity data connected to the respective life cycle inventory or carbon footprint of the process. Notably, both activity data and elementary flows can originate from processes and their constituent sub-processes, with information potentially being company-specific or derived from secondary sources like databases.

Figure 8 represents the system boundaries of the carbon footprint of a generic EV battery. Each square represents a process, while each arrow represents activity data. The different colors indicate in which life cycle stage each process belongs, while red arrows and red borders indicate if a process/activity data shall be company-specific.

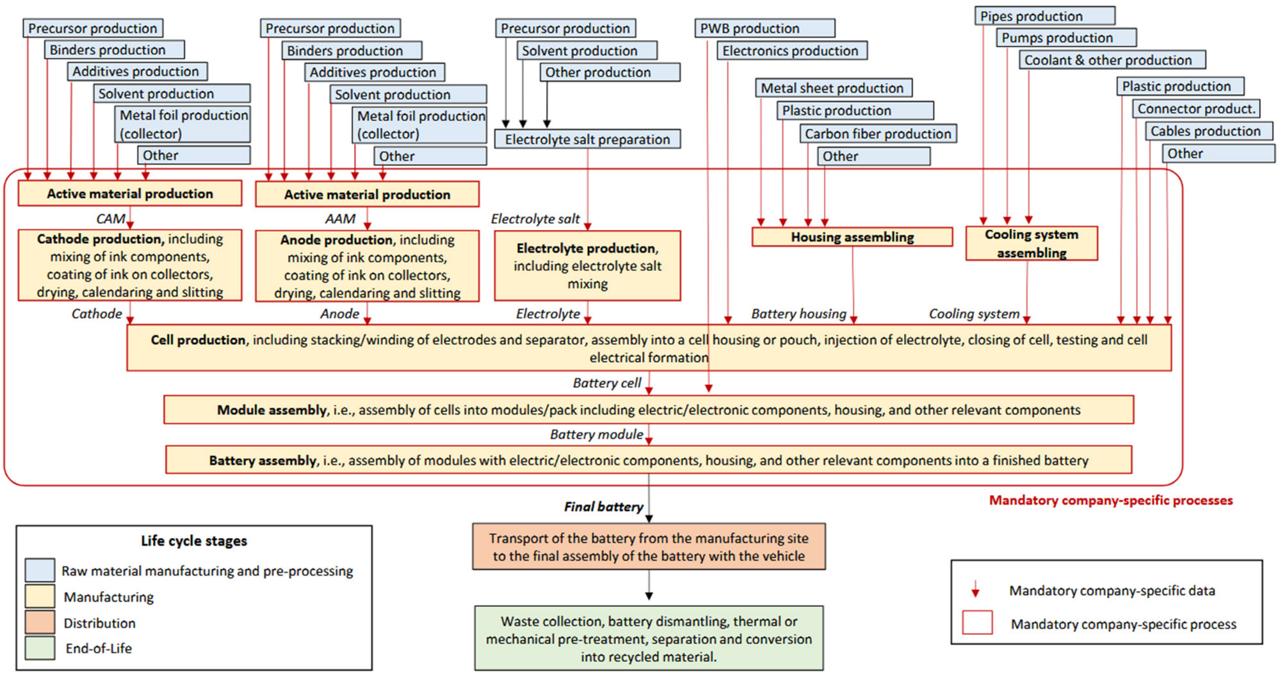

Figure 8. System boundaries of the carbon footprint of a generic EV battery. PWB: printed wiring. CAM: cathode active material, AAM: anode active material. Reproduced from [395] under CC BY 4.0.

Resulting from extensive discussions and representing a consensus among numerous stakeholders on how to calculate the carbon footprint of EV batteries, the CFB rules aim to be broadly applicable. Although methodological guidelines for determining the CFB of EVBs have been proposed, aligning with the Product Environmental Footprint Categories Rules for Batteries (PEFCR) [395], these guidelines also maintain a general approach. This generality would enable the application of the CFB rules not only to batteries currently available but also to those potentially entering the market in the near future.

According to the PEFCR for batteries, the benchmark value for climate change (measured in kg CO_2eq) for e-mobility lithium-ion batteries (excluding the use phase) is 0.42 kg CO_2eq/kWh [396].

Life cycle emissions from batteries are significantly determined by their chemical composition. In the case of NMC batteries, the prevalent chemistry in the US and EU, the processing of critical minerals is the largest emission contributor, accounting for 55% of the total. This contrasts with LFP batteries, the primary type in China, where critical mineral processing represents about 35% of emissions. This difference results in NMC batteries having greater overall life cycle emissions than LFP batteries, primarily due to the higher emissions from critical mineral processing. A key factor in the elevated emissions of NMC batteries is the use of nickel, an element absent in LFP batteries. Notably, half of all nickel is currently mined in Indonesia, and about two-thirds undergoes refining in Indonesia and China, utilizing energy-intensive methods that predominantly rely on coal.

Given the diversity of battery chemistries, effective emission reduction in the supply chain necessitates targeted strategies. For NMC batteries, the most impactful approach would be to minimize emissions from critical mineral processing. This could involve several actions, such as sourcing less carbon-intensive nickel, improving the carbon efficiency of existing nickel processing, increasing the proportion of recycled materials in batteries, or even reducing the nickel content in NMC batteries while preserving high energy density through the adoption of high-manganese NMC chemistries.

While LFP battery cell manufacturing currently contributes the most to their lifecycle emissions—nearly 50% compared to just 15% for NMC—future trends suggest a decrease in overall battery emissions. This anticipated reduction stems from progress in areas like increased battery pack energy density, the ongoing decarbonization of electricity grids, and a greater supply of cathode active materials derived from recycling. Notably, strategies for reducing LFP battery emissions should therefore focus on lowering the carbon footprint of cell production through enhanced electrification and the use of low-emission power. Additionally, the steam utilized in many cell manufacturing plants presents an opportunity for emissions reduction by sourcing it from low-carbon alternatives, such as waste heat from nuclear or other industrial facilities, or renewable fuels like biogenic waste.

Furthermore, as the volume of end-of-life EV batteries suitable for recycling increases after 2035, recycling is expected to become an even more crucial factor in decreasing battery emissions, offering advantages for material-intensive chemistries such as NMC.

4.2. Recycling

The increasing demand for batteries is driving a heightened need for critical raw materials. Specifically, the global need for raw materials used in batteries—such as nickel, graphite, and lithium—is projected to rise significantly by 2040, with anticipated increases of 20 times for nickel, 19 times for graphite, and 14 times for lithium, compared to 2020 levels, as shown in Figure 9. This rising demand is primarily due to the rapid growth of EVs and, to a lesser extent, energy storage applications. Therefore, as the demand for batteries grows, so does the need for effective battery recycling to ensure a sustainable and competitive industry. In this regard, the battery passport introduced by the EU Regulation [35] constitutes a key instrument.

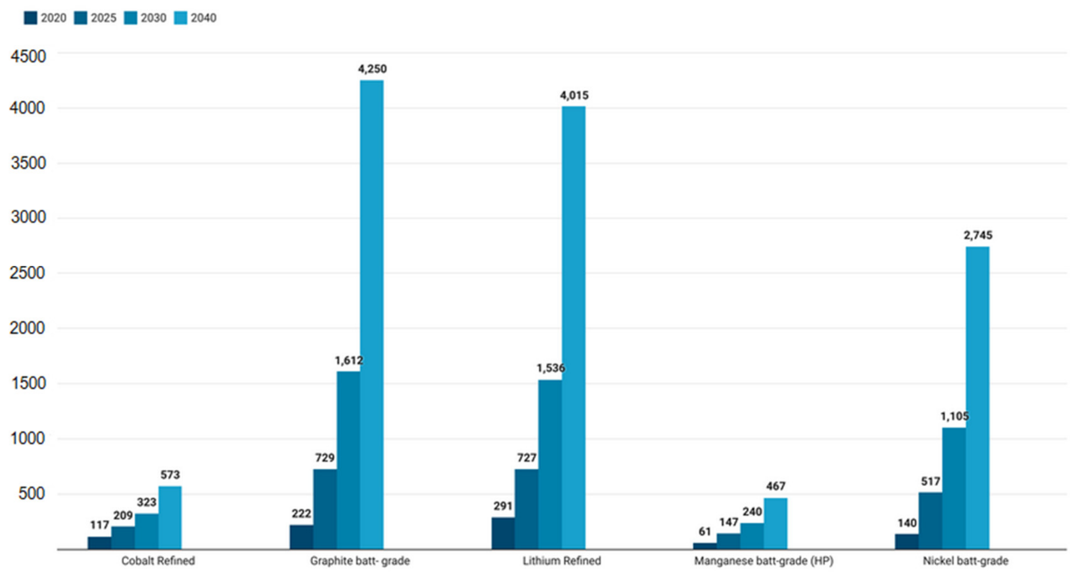

Figure 9. Forecast of battery demand globally from processed raw materials (kt) [397].

Globally, according to a recent study of the Battery Pass consortium [398], the recycling pre-processing and treatment costs could be reduced by ~10–20%, as a result of the combination of the following factors:

- Access to detailed battery composition and chemistry information eliminates costly sampling procedures, allowing for more efficient and lower-cost sorting while minimizing contamination risks. Sampling costs could potentially decrease by 50% to 80%.
- A detailed dismantling manual can reduce disassembly time and costs of battery packs by 20–40%.

- Additionally, dismantling manuals can facilitate the automation of parts of the dismantling process, particularly for heavy and hazardous operations, resulting in a further 20–30% reduction in dismantling costs.
- Optimizing the recycling treatment process and potentially reducing material and processing costs by 10–20% could be achieved through a homogenous battery recycling feedstock. This consistent input, pre-processed to eliminate unwanted materials, would streamline the feed-in process (batch sequencing) and allow for finer control over process parameters.

Improved recycling efficiency offers a dual advantage: not only does it reduce costs associated with pre-processing and treatment, but it also enables the retrieval of additional active materials, thereby lowering carbon emissions.

In particular, the production of cathodes is identified as a significant contributor to the overall environmental impact of LIBs [399].

The proportion of mined lithium allocated for EV batteries has quadrupled in the past five years, reaching 60% in 2022. That same year, demand for lithium exceeded supply, even with a remarkable 180% increase in production since 2017. Similarly, the shares of cobalt and nickel used for electric vehicle batteries have also risen in the same period, increasing from 10% and 2% to 30% and 10%, respectively [47].

Essential for the clean energy transition, both cobalt and lithium are unfortunately vulnerable to supply shortages and present considerable risks to their supply, although these risks are rooted in somewhat different circumstances. Figure 10 offers a geographical perspective on the reserves and supply chain of both cobalt and lithium, encompassing all stages [400].

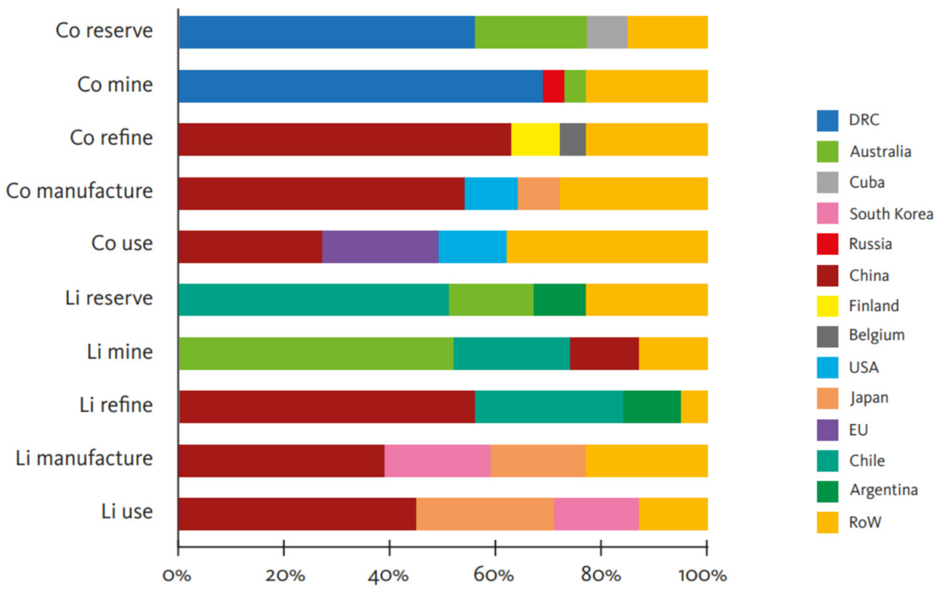

Figure 10. An overview of the geographical location of cobalt and lithium reserves and supply.

While secondary supply through recycling offers an alternative source of materials, its impact on overall supply is expected to be quite small by 2030. Looking ahead, the recycling of LIBs, particularly from electric vehicles, will be crucial for unlocking substantial volumes of recycled cobalt and lithium. Figure 11 presents the projected annual production capacity for lithium and cobalt, factoring in this secondary supply stream.

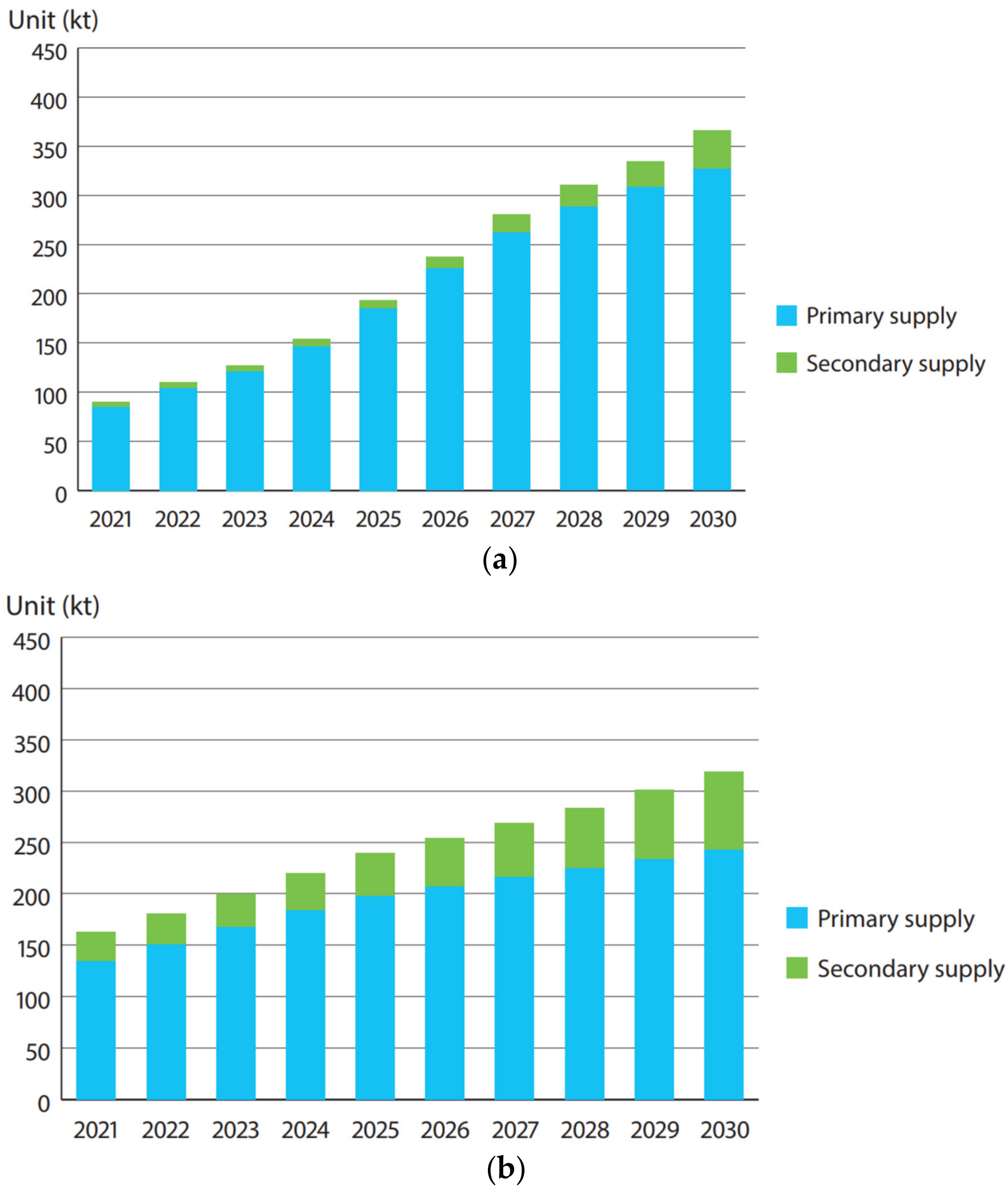

Figure 11. Annual lithium (**a**) and cobalt (**b**) supply growth by 2030. Source: Benchmark Mineral Intelligence (https://www.benchmarkminerals.com/ accessed on 31 March 2025).

Given the complexity of the battery ecosystem, to analyze the actual economic and environmental impacts derived from the implementation of the battery passport digital framework requires advanced simulation tools, for instance, based on Agent-Based Modeling. The latter is a relatively contemporary approach when compared to System Dynamics and Discrete Event Modeling. By means of these advanced tools, the entire lifecycle of LIBs, including end-of-life strategies such as reuse, remanufacturing, and repurposing, can be explored and evaluated.

As a result of the introduction of the battery passport, it is estimated that European recyclers could recover between ~4 and 8 kilotons of additional cathode active materials each year, starting in 2045 [398].

Compared to other battery technologies, such as lead–acid or sodium–nickel chloride batteries, LIBs generally have a lower environmental impact over their life cycle, especially for their superior performance in practical applications [401,402] although the results depend on the life-cycle assessment method applied [403,404].

Among LIBs, LFP batteries stand out because they use iron and phosphorus instead of the nickel, manganese, and cobalt found in NCA and NMC batteries. This shift also offers both cost and long life, although the overall environmental impact could be higher than for other LIB technologies [405]. Additionally, the presence of phosphorus in LFPs, which is also used in food production, could lead to competing demands for this resource as battery demand continues to rise.

Adopting batteries that require fewer critical minerals may be beneficial to mitigate the demand for critical raw materials and enhance sustainability, resilience, and supply chain security. Additionally, supporting the development of vehicle designs with optimized battery sizes and battery recycling practices could help address these challenges [22,406]. Therefore, there is a rapidly growing focus on the necessary technological and knowledge advancements in the field of EV battery recycling. The total recycling amount of copper, lithium, nickel, and cobalt by 2040 could decrease the demand for the extraction of mentioned minerals from their primary resources by approximately 10% [61]. Moreover, enhancing circularity along the battery value chains has the potential to decrease the EU's supply dependency. It is estimated that by 2040, recycling could contribute to up to 51% and 42% of cobalt and nickel EU demand, respectively [397].

Since the volume of EOL batteries, in particular LIBs, is projected to increase dramatically, robust recycling solutions are needed. China is at the forefront of global battery recycling, holding approximately 80% of pretreatment capacity and nearly 85% of material recovery. By 2030, if all planned initiatives are realized, North America and Europe are expected to contribute 10% and 5% to global recycling capacity, respectively. South Korea aims for a recovery capacity of nearly 600 kilotons, which would account for over 5% of global material recovery.

The trend of reusing EOL batteries significantly helps reduce their environmental impact [61]. This process involves disassembling and repurposing spent EV batteries, which still retain 80–85% of their original energy capacity, for use in renewable energy technologies. After the reuse phase, these batteries can ultimately be recycled.

There are various types and combinations of recycling processes for LIBs. Currently, hydro- and pyrometallurgical processes dominate the global industrial landscape for recovering valuable metals [407]. Hydro-metallurgical processes are complex and involve high costs for chemicals and wastewater treatment, although they achieve high recovery efficiency. On the other hand, pyrometallurgical processes have disadvantages, such as high-energy consumption and toxic gas emissions, but they are the most used methods. Novel technologies are being developed, such as the direct repair and regeneration of cathode and functional materials. However, their actual costs and environmental impacts still require thorough evaluation.

5. Conclusions

While LIBs have improved energy density, the driving range of current EVs remains a concern for consumers. Many potential buyers experience "range anxiety", fearing their vehicle will run out of charge before reaching a destination, especially during long trips or in areas with limited charging infrastructure, and recharging an EV battery still takes significantly longer than refueling a gasoline car. The maximum theoretical energy density of conventional LIBs using graphite anodes is nearing its limits, indicating the need for alternative technologies for further range improvements.

The high cost of LIBs contributes significantly to the price of electric vehicles. This is primarily due to expensive materials like cobalt and nickel, as well as the complex manufacturing processes involved. Additionally, conventional LIBs use flammable liquid electrolytes, posing risks of thermal runaway and associated safety concerns. These issues necessitate complex safety systems that increase the overall cost and weight of EVs.

Moreover, the production of LIBs relies on critical materials that are geographically concentrated, raising ethical and environmental concerns. This creates vulnerabilities in the supply chain, potentially leading to price fluctuations and geopolitical risks. Therefore, there is a pressing need to diversify battery chemistries and reduce reliance on these essential materials. For emerging technologies to gain traction in the market, they must offer clear and significant advantages in key areas such as cost efficiency, improved safety, and superior performance.

Transitioning from an established technology like lithium-ion requires substantial investment in new manufacturing processes and the development of robust supply chains for new materials. Therefore, any emerging battery technology aiming to capture a significant share of the automotive market must provide a compelling value proposition that surpasses the existing advantages and infrastructure associated with lithium-ion batteries.

Based on the current state of development and the projected timelines from various companies and research institutions, the future of electric vehicle (EV) batteries is likely to feature a diverse range of technologies. Lithium iron phosphate (LFP) batteries, a cobalt-free variant of lithium-ion batteries, are gaining significant traction due to their cost-effectiveness and safety benefits.

In the near to medium term, silicon anode technology is expected to be integrated into existing lithium-ion batteries, which could incrementally improve their energy density and charging speeds. However, addressing the challenge of silicon's volume expansion during charging and discharging cycles is crucial.

Solid-state batteries hold significant promises for improved energy density, safety, and charging speeds in the long term, particularly for high-performance EVs. The potential lower cost, improved sustainability, and lower lifespan compared to LIBs can help the EU achieve its EU2030 targets [408]. Nonetheless, further breakthroughs in cost-effective manufacturing and solutions to technical challenges such as scalability and interfacial resistance are necessary. While LIBs will likely dominate the EV market in 2030, SSBs are expected to move beyond the pilot and demonstration phases. Market forecasts suggest that the solid-state battery market could reach a significant value by 2030 [409]. If European companies can become leaders in SSB technology development and production, it could significantly boost the EU's competitiveness in the global battery market and contribute to job creation within the EU.

Sodium-ion batteries are also emerging as a vital option for the lower-cost and standard-range EV segments, especially as their energy density improves. Additionally, these batteries utilize abundant and sustainable materials, which helps reduce the European Union's dependence on critical raw materials with concentrated supply chains. This aligns well with the goals of the Critical Raw Materials Act (CRMA) and promotes a secure and resilient battery value chain. The potentially lower cost and enhanced safety can boost the adoption of EVs. The commercialization of SIB technology is still in its early stages compared to LIBs. However, given the increasing focus on supply chain diversification and cost reduction, SIBs are expected to gain a notable foothold in the EU market by 2030 [410]. The development of a strong domestic SIB manufacturing industry within Europe will be key to realizing the full potential of this technology [411].

Table 14 reports a short comparison of relevant parameters for emerging technologies.

The overall outlook for the adoption of these emerging technologies in the automotive sector is positive, though it requires ongoing investment in research and development. This investment should focus on addressing the key limitations of each technology to accelerate their commercialization.

Table 14. Comparison among emerging battery technologies.

Technology	Energy Density (Wh/kg)	Energy Density (Wh/L)	Power Density (W/kg)	Charging Speed (Typical)	Cycle Life (Typical)	Safety Characteristics	Estimated Cost (per kWh)	Estimated Commercialization Timeline for Automotive
Solid-State	200–500+	400–800+	Up to 1000+	10–30 min	1000–5000+	Non-flammable solid electrolyte, reduced thermal runaway	Higher	Late 2020s–Mid 2030s
Silicon Anode (Li-ion)	250–400+	500–800+	Up to 1000+	10–30 min	300–1000+	Similar to Li-ion	Similar	Late 2020s onwards
Sodium-Ion	100–160	200–300	Up to 500	30–60 min	2000–5000+	Lower thermal runaway risk, better low-temp perf.	Lower	2025 onwards
Lithium-Sulfur	300–600+	300–500+	Up to 500	Varies	100–500+	Lithium metal anode poses dendrite risk	Lower	2030 and beyond

Government funding for battery technology development has increased across all major global economies, though their strategic approaches and specific goals differ significantly [412]. China initially focused on its domestic EV market demand, but has shifted towards a supply side strategy to solidify its global market leadership. Japan, a former battery technology leader, is now expanding lithium-ion production while exploring advanced technologies like fluorine shuttle batteries. South Korea aims to spearhead the international battery industry through substantial R&D investment focused on near-term commercialization.

The United States employs a balanced strategy combining supply- and demand-side measures with an open technological approach, aiming for R&D leadership and independence from China by targeting cost and sustainability performance. In contrast, the EU prioritizes supply side policies with ambitious sustainability and recycling targets to become a leading provider of sustainable battery technologies and ensure supply chain resilience. Initiatives like the European Battery Alliance and the European Green Deal aim to establish a competitive and sustainable European battery ecosystem. The Automotive Skills Alliance supports the reskilling of European automotive workers for the sector's future needs.

Developing a robust European battery supply chain is crucial for reducing reliance on external suppliers and securing supply for future mobility and energy demands. Addressing the sustainable, ethical, and diversified sourcing of raw materials is critical due to increasing global demand and competition, where Europe faces strong Asian competition and higher production costs. Europe's nascent battery production sector offers a competitive edge, allowing for the immediate adoption of advanced technologies to build a state-of-the-art supply chain without extensive industrial retrofitting.

Europe could achieve battery cell self-sufficiency by 2026 and largely meet its demand for key components and lithium by 2030. However, over half of European gigafactory plans still face delay or cancellation, necessitating stronger government intervention. Key industrial policy should ensure investment, provide EU-level funding, and favor best-in-class "made in EU" projects. Finland, the UK, Norway, and Spain have the most at-risk capacity, while France, Germany, and Hungary have shown the most progress in securing it [413].

Maintaining competitiveness requires emphasizing efficiency and innovation, alongside training a skilled workforce across the battery value chain, including material chemistry, production, recycling, and data management. Continuous investment in R&D is essential for the rapid integration of innovations into European production processes.

Establishing common European standards is vital to ensure battery quality, safety, and sustainability, while also facilitating recycling, reuse, and repair processes to promote a circular economy. In particular, the battery passport, recently introduced by EU Regulation, supports the collection and sharing of product-related data among supply chain actors, addressing existing information gaps for products and components throughout global supply chains, thus becoming a key enabler for circular business models. Europe's leadership in setting high environmental and social standards can provide a competitive advantage in developing more sustainable batteries and recycling methods.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

3D-NTC	Three-dimensional nitrogen-doped turbostratic carbon
AFNB	Anode free sodium batteries
APC	All phenyl complex
BEV	Battery electric vehicle
BMS	Battery management system
BOL	Begin of life
BTMS	Battery thermal management system
CA	Cyanoacrylate
CS	Carbon sphere
CSE	Composite solid electrolytes
EOL	End of life
EUCAR	European Council for Automotive R&D
EV	Electric vehicle
FEC	Fluoroethylene carbonate
HC	Hard carbon
HCF	Hexacyanoferrates
HE-NMC	High-energy lithium nickel manganese cobalt oxide
HLM	High lithium manganese oxide
HTS	High temperature thermal shock
HV-LNMO	High-voltage lithium nickel manganese oxide
ISE	Inorganic solid electrolyte
KMgHCF	Potassium magnesium hexacyanoferrates
K2TP	Dipotassium terephthalate
LCO	Lithium cobalt oxides
Li+	Lithium ion
LIB	Lithium-ion battery
LiS	Lithium–sulfur
LMO	Lithium manganese oxide
LFP	Lithium iron phosphate
LLZO	$Li_7La_3Zr_2O_{12}$
LTO	Lithium titanate oxide
MACC	Magnesium Aluminum Chloride Complex
MIB	Magnesium ion battery
MF	Muffle furnace-sintered
MOF	Metal–organic framework
MVOH	$Mg_{0.75}V_{10}O_{24}\cdot 4H_2O$

NaNiCl	Sodium–nickel chloride
NaS	Sodium–sulfur
NASICON	Sodium superionic conductors
NaxMnFe(CN)6	Sodium manganese hexacyanoferrate
NCA	Lithium nickel cobalt aluminum oxide
Ni-Cd	Nickel–cadmium
Ni–Fe	Nickel–iron
Ni-H2	Nickel–hydrogen
Ni–MH	Nickel–metal hydride
Ni–Zn	Nickel–zinc
NMB	Sodium metal batteries
NMC	Lithium nickel manganese cobalt oxide
NMO	Sodium manganese oxide
NVP	$Na_3V_2(PO_4)_3$
OEM	Original equipment manufacturer
OLE	Organic liquid electrolyte
PAN	Polyacrylonitrile
PBA	Prussian blue analog
PEGMEA	Poly-ethylene glycol methyl ether acrylate
PEO	Poly-ethylene oxide
PHEV	Plug-in hybrid electric vehicle
PIB	Potassium ion battery
PTCDA	Perylenetetracarboxylic dianhydride
PMMA	Poly-methyl methacrylate
PVDF	Poly-vinylidene fluoride
PVDF-HFP	Poly-vinylidene fluoride-hexafluoropropylene
rGO	Reduced graphene oxide
SC	Single crystal
SE	Solid electrolyte
SEI	Solid electrolyte interphase
SN	Succinonitrile
SHE	Standard hydrogen electrode
SIB	Sodium-ion battery
SOC	State of charge
SOH	State of health
SPE	solid polymer electrolyte
SSB	Solid state battery
SSE	Solid state electrolyte
TiO_2	Titanium dioxide
tLi+	Lithium transference number
TM	Transition metal
TMC	Transition metal chalcogenides
TMO	Transition metal oxide
TRL	Technological readiness level
USABC	United States Advanced Battery Consortium
ZB	Zinc-based battery

Appendix A

This appendix details the review searching criteria and analyzes the results.

Appendix A.1. Review Methods

Searching on Scopus with the string "review AND battery AND (automotive OR "electric vehicle" OR "electric vehicles")" in the fields of "article, title, and keywords" yields 3730 documents published between 2019 and 2025 (as of 12 February 2025). The distribution of the publications year by year is shown in Figure A1. In contrast, using the same search criteria in Google Scholar returns 18,600 papers when searching "everywhere in the article". However, limiting the search to the title results in only 176 records. Given that the search options in Google Scholar are either too broad or too narrow for our needs, we will focus on the results from Scopus. We refined our search to focus on the specific topics relevant to our current work, adding new criteria to our previous search string (see Table A1 and Figure A2).

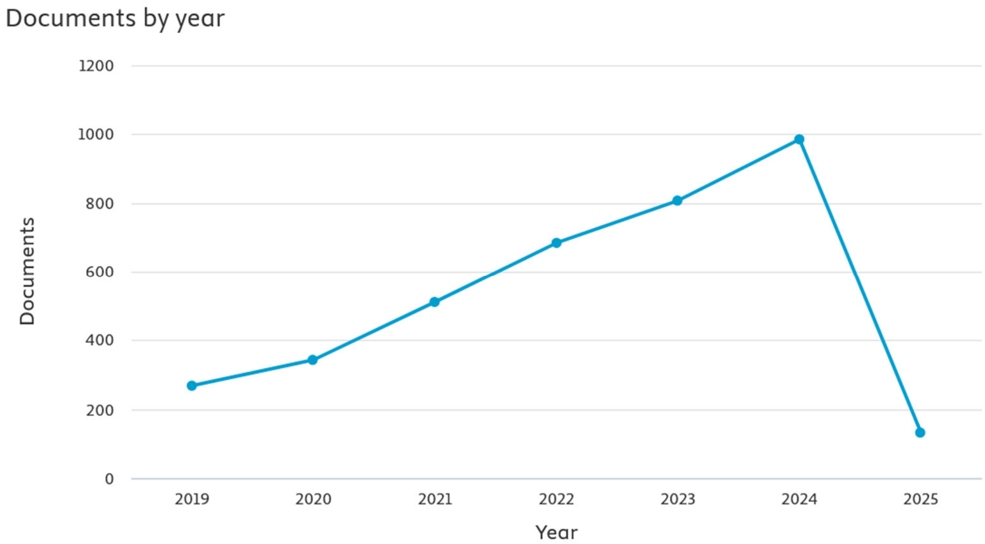

Figure A1. Articles on EV batteries published between 2019 and February 2025 and registered in Scopus.

Table A1. Literature search results with additional criteria.

Additional Criteria	Safety	Life OR Lifespan OR Cyclelife	Cost OR Market	Energy OR Power	Sustainability
No. of articles from 2019	883	984	1331	3039	256
No. of articles from 2023	487	536	672	1550	178

Appendix A.2. Search Results

From Figure A1, it can be concluded that most of the research reviews concentrated on energy and power performance. The second most common topic was battery cost and market aspects, followed by battery life performance and safety. Sustainability is the least explored aspect.

By limiting the search from 2023 up to today, we found 1924 reviews related to battery and automotive topics on Scopus. The trend of topic interests, illustrated in Figure A2, remains mostly the same over the two periods.

Among the results from Scopus, 156 articles discuss the "state of the art", while 269 records meet the search criteria "review AND battery AND automotive AND (emerging OR 'future development')". When we combined the two criteria, we retrieved a total of 402 documents. The percentage distribution of subject areas and the number of articles per country are illustrated in Figures A3 and A4, respectively.

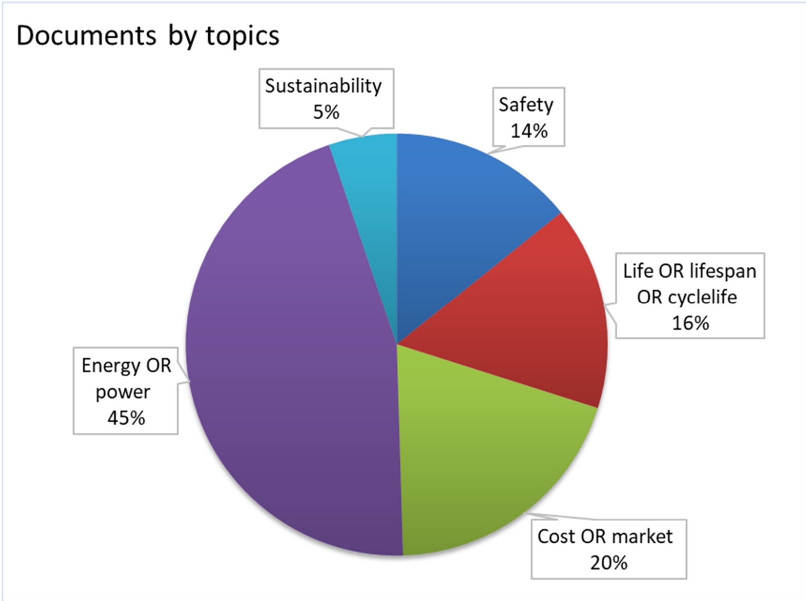

Figure A2. Percentage distribution of articles by topics since 2023.

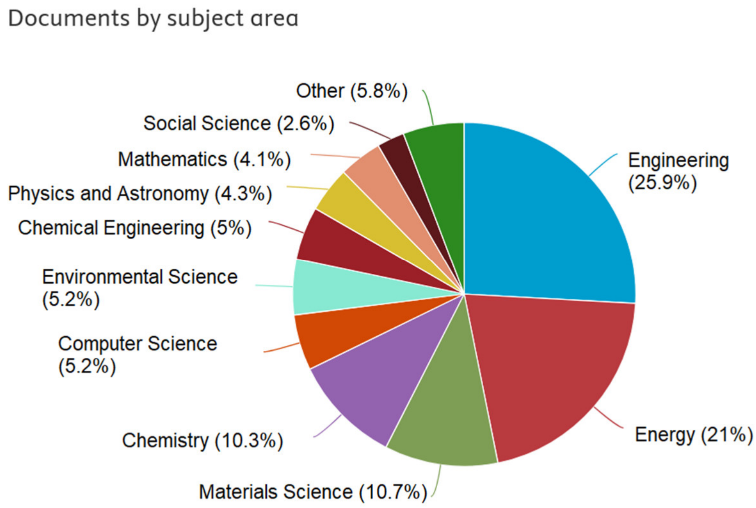

Figure A3. Percentage distribution of article subject areas in the last year (until February 2025).

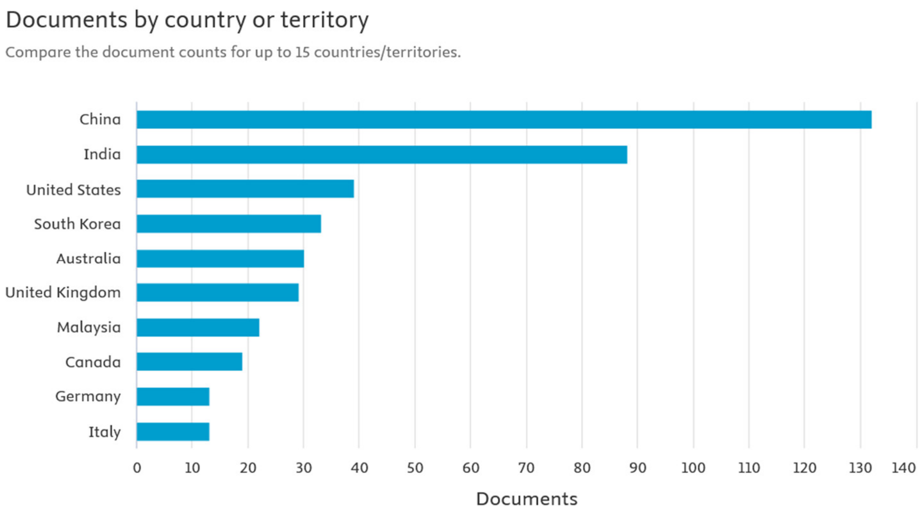

Figure A4. Distribution of articles among countries in the last year (until February 2025).

Most review articles are categorized under engineering and energy, reflecting the focus on automotive applications (Figure A3). The authors of these studies predominantly come from China and India (Figure A4), while the contributions from all European countries exceed those from the United States.

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