

Review

Emerging Battery Technologies: The Main Aging Mechanisms and Challenges

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Abstract

New-generation batteries are attracting increasing interest in response to today's energy storage challenges, as evidenced by the steady rise in scientific publications on the topic. However, their industrial deployment remains limited due to the complexity of aging mechanisms, which are still poorly understood and difficult to control. While several promising developments have emerged in laboratory settings, they remain too immature to be scaled up. These aging processes, which directly affect the performance, safety, and lifespan of battery systems, also determine their technical and economic viability. This review offers a comparative analysis of aging phenomena—both specific to individual technologies and common across systems—drawing on findings from accelerated testing, post-mortem analyses, and modeling. It highlights critical failures such as interface instability, loss of active material, and mechanical stress, while also identifying shared patterns and the unique features of each technology. By combining experimental data with theoretical approaches, the article proposes an integrated framework for understanding and prioritizing aging mechanisms by technology type. It underscores the limitations of current characterization techniques, the urgent need for harmonized testing protocols, and the importance of standardized data sharing. Finally, it outlines possible avenues for improving the understanding and mitigation of aging phenomena.



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1. Introduction

Climate change is one of the greatest challenges of the 21st century, with far-reaching environmental, economic, and social impacts. The increase in extreme weather events, rising average temperatures, and sea level rise are all clear indicators of this ongoing transformation. In response, the international community adopted the Paris Agreement in 2015, aiming to limit global warming to below 2 °C compared to pre-industrial levels (1850–1900). Achieving this goal requires reaching carbon neutrality by 2050, which implies profound changes in the way we produce and consume energy [1]. Another deadline has been set at European level with the Green Pact. This aims to reduce greenhouse gases by at least 55% by 2030, compared with 1990 levels [2]. In order to reduce CO₂ emissions (which remain the main factor in climate change), it is useful to know which sectors are responsible for the majority of emissions. Transport and energy account for a significant

proportion of global emissions. It is therefore important to adopt more responsible solutions as quickly as possible. Electric vehicles (EVs) and energy storage are essential elements in this transition. According to the International Energy Agency (IEA), the share of CO₂ emissions by sector is 23% for industry and the same for transport. Buildings account for 10%. Electric power generation, in the form of coal, gas and oil, accounts for almost 40%, which is considerable [3].

The energy sector must therefore be urgently decarbonized. Renewable energy sources are a key part of the solution. However, their intermittent nature and the often-misaligned timing between energy production and demand require robust and efficient energy storage systems to ensure grid stability. This need is becoming more pressing as global energy demand continues to rise, alongside the projected share of renewables [4].

Batteries will play an important role in energy storage, in particular to compensate for the intermittent nature of renewable energies. But it is also electric mobility that needs rapid development of batteries and battery production. The EV market is growing rapidly, with forecasts of 40–50% of global electric car sales by 2030 in the Stated Policies Scenario (STEPS) [5]. This scenario was developed by the IEA. It aims to reflect the likely evolution of the energy system, based on current policies and those currently being developed. Companies and governments are investing heavily in charging infrastructure and R&D to develop more efficient, durable, and aging-resistant batteries in order to be prepared for the scenarios adopted. In its annual report, the IEA presents the evolution of battery demand in TWh according to the STEPS and Net Zero Emissions by 2050 Scenario (NZE Scenario) [6]. The need for storage is set to increase rapidly, requiring investment and speed of execution to meet it. So, the development of gigafactories around the world is justified by this consequent demand [7].

The stationary energy storage sector, designed to store surplus renewable energy for later use, is also expanding rapidly in terms of both investment and installed capacity. According to the NZE Scenario, the IEA forecasts a sharp increase in this capacity [8]. Batteries are therefore essential to guarantee a stable and flexible energy supply.

Batteries play a vital role not only in portable electronic devices but also in emerging sectors such as the Internet of Things (IoT), carbon-free aviation, and autonomous systems. The batteries needed for these sectors have to be capable of operating under a wide range of conditions, and be high-performance, compact and lightweight. As a result, the areas of research into these systems are many and varied.

At present, lithium-ion (Li-ion) technology is the most widely used. By 2023, 45% of stationary Li-ion batteries will be used in the automotive sector, 25% in communications equipment, 20% in consumer electronics and the remaining 10% in other applications. In the automotive sector, two technologies stand out: NMC (Lithium nickel manganese cobalt oxides) batteries and LFP (lithium iron phosphate) batteries. According to the IEA [9], NMCs will account for over 60% of the market by 2022, compared with 30% for LFPs. Other battery technologies do not yet appear to be sufficiently developed, and their share of the various markets is often quite small. However, the IEA predicts that sodium-ion batteries will account for almost 10% of storage applications by 2030.

To meet the growing performance demands, batteries must offer sufficient autonomy and appropriate energy density. Today's Li-ion batteries typically offer between 120 and 300 Wh/kg, depending on the application [10]. Advances in electrode structure, electrolytes, and battery management systems continue to enhance this performance. However, for more energy-intensive applications such as aviation or heavy mobility, higher energy densities are required. Research into new chemistry is therefore booming. The aim is to go beyond the limits of today's batteries, such as the 400 Wh/kg threshold, to meet the

needs of more demanding applications. New technologies such as lithium-sulfur (Li-S) or all-solid batteries may offer promising solutions for achieving these goals [10].

Another criterion to consider is cell life and ageing. However, battery durability, defined as their ability to maintain their electrochemical performance (capacity, power, safety, etc.) over numerous charge cycles and long periods of storage, remains one of the main obstacles to the widespread adoption of advanced storage technologies. Indeed, aging mechanisms, whether related to electrode degradation (passivation formation, loss of active material, electrolyte dissolution), changes in the electrode/electrolyte interface, or thermal and mechanical phenomena, cause a gradual loss of capacity and energy efficiency. These phenomena, which are often non-linear and dependent on conditions of use (temperature, current, state of charge, etc.), are still poorly understood for many emerging chemistries such as lithium-sulfur, solid lithium, and sodium-ion batteries. This uncertainty about lifespan and reliability is therefore a major technological barrier, limiting industry confidence and delaying the commercialization and widespread adoption of these new generations of batteries. The criteria for battery replacement must also be adjusted to reduce the economic and ecological impact. Premature replacement represents a real cost, particularly for electric vehicles and stationary storage systems. Since battery recycling remains underdeveloped at an industrial scale, managing end-of-life batteries poses both ecological and health-related challenges due to the presence of toxic materials. In addition to the development of these channels, there is also the question of the recovery of certain materials, where recycling costs more than the purchase of new materials, making it uneconomic to recycle them. This is why a better understanding of degradation mechanisms could improve battery longevity while reducing operating costs and environmental impact.

Additionally, Li-ion batteries rely heavily on critical metals such as lithium, cobalt and nickel. These elements are not only costly but also subject to geopolitical tensions and supply chain volatility [11]. These metals therefore raise concerns not only about their long-term supply, but also about the environmental impact of their extraction. As a result, alternatives are increasingly being developed to improve battery durability and reduce dependence on critical metals. As a result, alternatives are increasingly being developed to improve battery durability and reduce dependence on critical metals. Less expensive and more abundant alternatives are being developed, such as sodium-ion (Na-ion), zinc-cadmium (Zn-Cd), and zinc-air (Zn-air) batteries, although the latter still face strong limitations in rechargeability and stability.

Despite the widespread use of Li-ion batteries, they are not without risks, particularly in the event of overcharging, short-circuiting or thermal runaway. Fires have already been observed, leading to ever stricter safety standards and the search for new, less dangerous technologies [12]. Emerging technologies such as solid-state batteries (SSB), which use a solid electrolyte instead of liquids, could offer significant improvements in terms of both safety and energy density.

As mentioned earlier, battery recycling is also a major challenge. While progress is being made, most Li-ion batteries are not yet recycled efficiently, leading to resource losses and pollution. In its draft regulation on batteries, the European Commission has proposed minimum recycling efficiency targets of 65% of battery weight by 2025 and 70% by 2030. A minimum recovery rate for the main metals (CO, Ni, Li, Cu) has also been set [13]. Furthermore, battery design and architecture must evolve to facilitate recycling processes and support the development of a truly circular economy.

Despite the progress achieved in lithium-ion battery (LIB) technology, several limitations remain, particularly regarding energy efficiency and safety. Long-term performance is hindered by aging mechanisms, especially under conditions of rapid charging/discharging and elevated temperatures. Questions of long-term durability and sustainability are there-

fore raised, as well as the prospect of a second life provided that safety standards are validated. These limits are critical in applications where high energy density and long life are essential. To meet these challenges, technologies with significant potential for improvement are being developed [14]. SSBs, which have already been presented; Li-S batteries, which show promise thanks to their high specific capacity and potentially low production cost, but still have to overcome challenges linked to stability and service life, particularly in terms of polysulfide formation management; Sodium-ion batteries, or NIBs, which have a lower energy density than LIBs, but offer a sustainable and less expensive alternative thanks to the abundance of sodium, enabling manufacturing costs to be reduced in the long term [15]; and other technologies such as Zn-air or Magnesium-ion (Mg-ion) batteries, which offer advantages in terms of energy density and durability, although they still require a great deal of research to overcome current limitations [10]. Investment in new battery technologies is on the increase, with the hope of being one of the first on the market. However, new technologies are still hampered by their relatively short lifespan and long-term instability. Nevertheless, there have been a number of notable advances. The development of solid electrolytes for batteries is a very promising area of research. These electrolytes make it possible to replace flammable liquid electrolytes with solid materials, offering greater safety, higher energy density and longer life. Hybrid electrolytes, combining solid and liquid aspects, are also being studied to optimize performance while reducing costs. For example, the development of solid electrolytes, such as those based on lithium, zirconium and chlorine, improves the safety, energy density and longevity of SSBs. These electrolytes offer a triple function, surpassing the performance of current LIBs [16]. New negative electrode concepts are crucial to increasing battery energy density. Silicon negative electrodes can store much more lithium than the graphite negative electrodes generally adopted, thus increasing battery capacity [17]. Research into lithium metal (LiM) negative electrodes is also promising for next-generation batteries, although they still present stability and dendrite management challenges. Finally, as mentioned earlier, cyclic instability is a real problem, as it blocks access to stable, long-life technology with rapid degradation. Innovative strategies, such as adding protective coatings or optimizing electrode structure, are being explored to stabilize cycling and thus extend lifetime. One example is the use of functionalized nanotubes to increase the stability and capacity of Li-S [18].

The objective of this article is threefold:

1. To provide an overview of emerging battery technologies, with a focus on advanced LIBs, SSBs, Li-S batteries, and NIBs. Each technology offers distinct advantages for specific applications while posing unique technical challenges, which make them central to current research efforts.
2. To analyze the specific aging mechanisms associated with each battery type. For instance, Li-S batteries are affected by sulfur dissolution, NIBs by electrode expansion, and SSBs by interface instability between electrodes and electrolytes. Understanding these mechanisms is key to improving performance and extending battery life.
3. To propose avenues for improvement, based on current research. Potential solutions include electrode coatings, innovative electrolyte design, and improved mechanical stress management within cells.

Unlike previous reviews that focus on a single chemistry, this paper provides a cross-comparative analysis of degradation pathways across advanced LIBs, SSBs, Li-S, and Na-ion systems. This transversal perspective highlights both shared and unique mechanisms, while identifying knowledge gaps and standardization needs that remain underexplored in the literature. A schematic overview of the manuscript structure is presented in Figure 1,

illustrating the logical flow from emerging battery technologies to their respective aging mechanisms, comparative analysis, and proposed mitigation strategies.

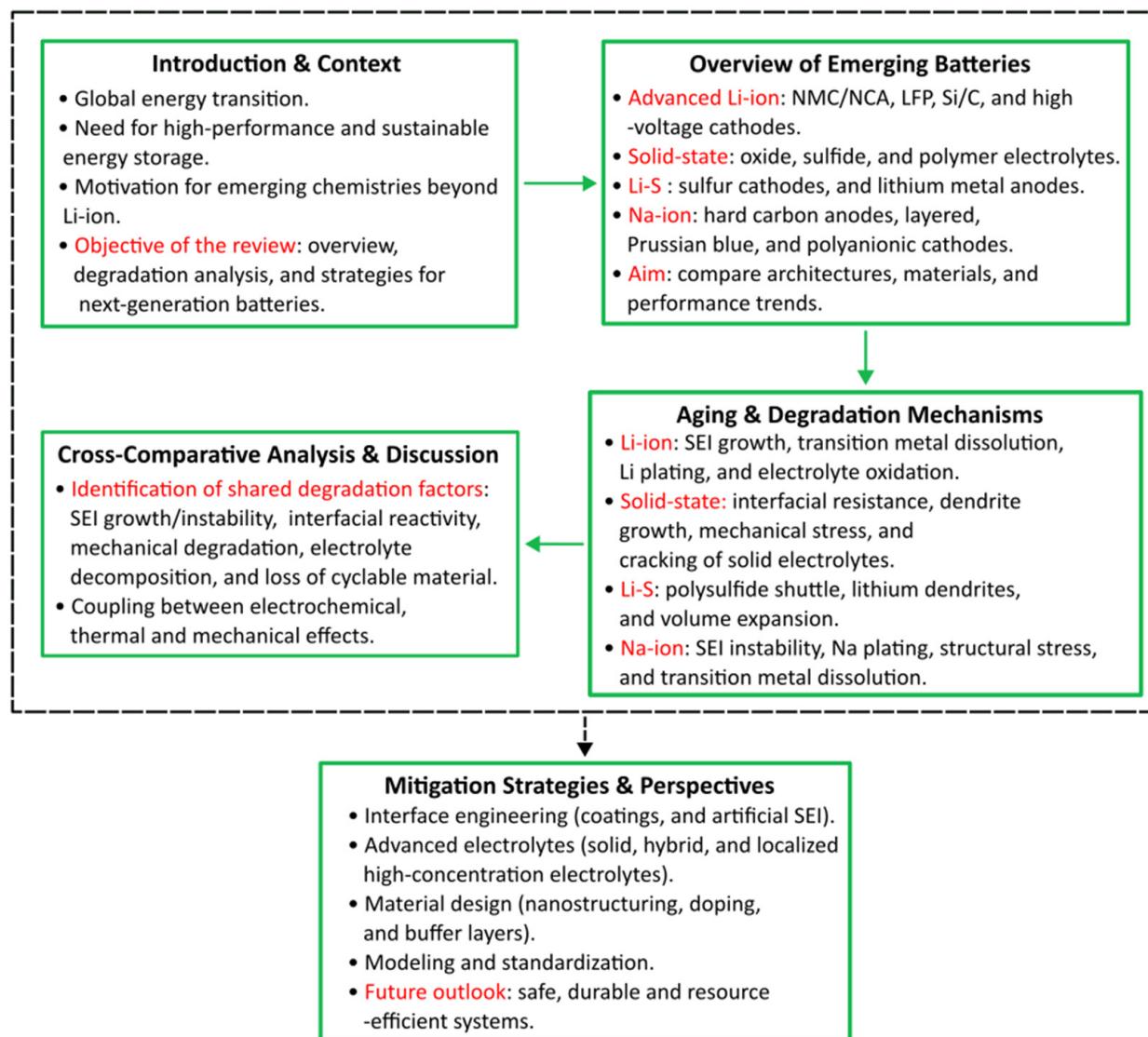


Figure 1. Schematic overview of the manuscript structure and main discussion points.

2. Overview of New-Generation Batteries

As part of the energy transition, innovation in battery technology is crucial to overcoming current limitations. New generations of batteries aim to improve energy density, safety, durability and reduce costs. An overview of the main emerging technologies.

2.1. Advanced Lithium-Ion Batteries

Advanced LIBs are based on the same architecture as conventional LIBs, with a graphite or silicon-enriched negative electrode, a positive electrode based on transition metal oxides (NMC, NCA, LNMO, etc.) and a liquid electrolyte. Six main types of lithium-ion batteries are currently in use, forming the technological foundation for further development [19]. These systems already provide a basis on which to work.

The aim is therefore to optimize these materials to improve the overall characteristics of the cells. Other research focuses on the use of new materials or partial modification of existing systems. Increasing operating voltage and developing high-capacity negative electrodes, such as Si/C composites, are among the avenues being explored. These advances

mean that LIBs remain the dominant technology for EVs and stationary storage, despite the challenges associated with this technology. At the core of their operation, LIBs store and release energy through the intercalation and de-intercalation of lithium ions between the electrodes. During discharge, Li^+ ions migrate through the electrolyte of the negative electrode and insert themselves into the structure of the positive electrode. At the same time, electrons circulate in the external circuit. During charging, this process is reversed: Li^+ ions return to the negative electrode, restoring the system's energy potential.

2.1.1. NMC and NCA

Positive electrodes based on nickel, manganese and cobalt (NMC) and nickel, cobalt and aluminum (NCA) are among the most widely used in high-performance batteries. The evolution of compositions is aimed at increasing energy density and reducing dependence on cobalt. These technologies offer several significant advantages. Most notably, they deliver high energy densities, typically in the range of 250 to 300 Wh/kg. One of our major projects is therefore to gradually increase this density. Since 1991, when Li-ion was first marketed, energy density has risen from 80 Wh/kg to almost 300 Wh/kg [20]. A target of 500 Wh/kg has also been set for the United States and Europe with the "Battery 2030" project [21]. More recently, ultra-nickel-rich compositions such as NMC90-5-5 have attracted attention due to their even higher specific capacity and reduced cobalt content. However, such materials present pronounced surface instability, rapid gas evolution, and accelerated microcracking, which still limit their practical adoption despite promising laboratory results [22,23]. These batteries offer a good compromise between capacity, stability and safety, with a gradual reduction in cobalt in recent formulations (Table 1).

Table 1. Evolution and composition of NMC and NCA batteries.

Composition	Ni/Mn/Co Content	Note
NMC111	1/1/1	First generation LIBs
NMC532	5/3/2	Energy density improvement
NMC622	6/2/2	A compromise between stability and performance
NMC811	8/1/1	High energy density, but a little more unstable
NMC90-5-5	9/0.5/0.5	Good energy density but structurally unstable
NCA	80–90% Ni	Tesla batteries, long autonomy

However, these technologies also present notable limitations. Indeed, the thermal risks of these batteries are quite high, and safety can be improved, especially when the nickel content is high. Nickel has the capacity to offer higher energy density, but reduces stability [24]. They are also rather sensitive to rapid cycling and high temperatures, which accelerate degradation. A limit close to 2000 charge/discharge cycles on average for NMC or NCA batteries [25]. Finally, dependence on critical metals such as nickel and cobalt are a real problem for product sustainability, both in terms of supply and cost. While Ni-rich NMC and NCA systems clearly push energy density higher, their long-term stability and safety remain debated. Some reports highlight promising lifetime under moderate conditions, whereas others reveal rapid degradation at high voltages or elevated temperatures. These discrepancies emphasize that the true potential of Ni-rich cathodes strongly depends on cycling protocols and electrolyte formulations, making cross-study comparison difficult.

2.1.2. Doped or Nanostructured LFP

Lithium-iron-phosphate batteries are renowned for their safety and long service life. However, they suffer from lower energy density. Improvements via doping or nanostructures are helping to optimize performance. High thermal stability and excellent safety make these batteries particularly viable for automotive applications [26]. These attributes make LFP particularly attractive for automotive and stationary storage applications. In addition, its long service life is due to good stability during cycling, which can be further improved by doping or nanostructuring the electrodes, which will surely enable us to exceed the current service life of 4000–6000 cycles [27–29]. The absence of nickel and cobalt tends to reduce its cost compared with NMC batteries [14]. Although LFP is often considered more stable and safer than NMC, its lower energy density remains a critical drawback [30]. Some studies suggest that nanostructuring narrows this gap, but others report limited improvement when evaluated under practical conditions. This raises questions about whether such material engineering strategies can realistically overcome intrinsic energy density limitations.

2.1.3. Silicon-Based Negative Electrodes and Si/C Composites

The addition of silicon to negative graphite electrodes increases the specific capacity of batteries but still poses challenges in terms of overall stability. Silicon boasts a theoretical specific capacity of approximately 3600 mAh/g, significantly higher than that of graphite (370 mAh/g) [31]. It improves battery autonomy with higher energy density and better cycling performance [31]. On the other hand, volume expansion (of the order of 300%) during cycles leads to numerous problems, such as cracks and electrode degradation [31,32]. During this volume expansion, sputtering of the SEI (Solid Electrolyte Interphase) renders this layer unstable and loss of electrochemical contact is sometimes observed [31]. These phenomena are illustrated in Figure 2.

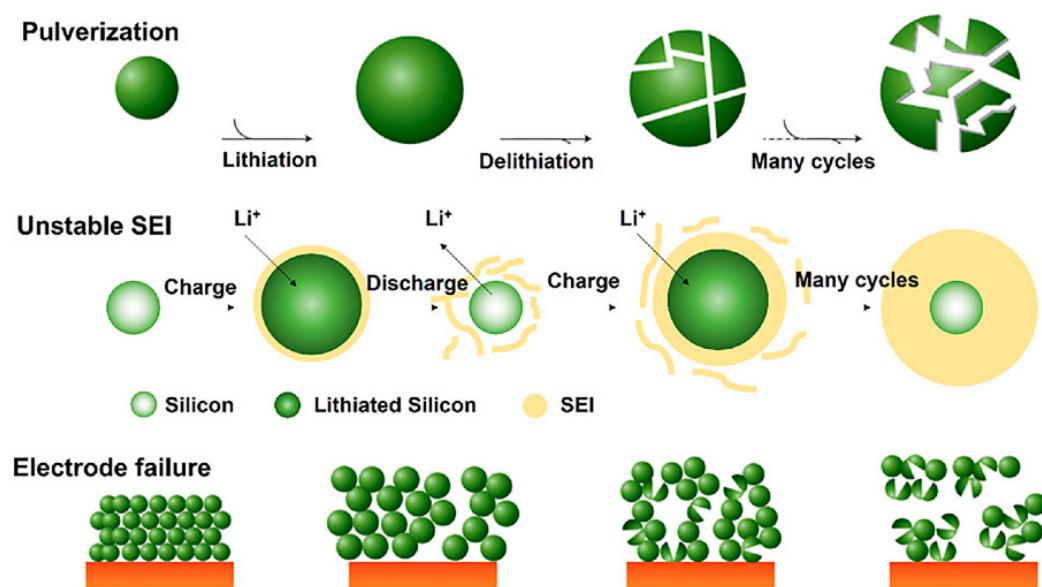


Figure 2. Degradation modes of negative silicon electrodes during cycling. Reproduced under terms of the CC-BY license [33]. Copyright 2023, MDPI.

Thus, a reduced number of cycles (generally around 500–1000 cycles) is observed compared to graphite negative electrodes alone. However, enriched negative electrodes represent an interesting and promising area of research in the development of better negative electrodes for LIBs [31]. Despite the strong appeal of silicon enrichment, practical demonstrations rarely achieve both high capacity and long-term stability simultaneously.

Inconsistent results across studies highlight the difficulty of balancing volume expansion and SEI stabilization, suggesting that Si/C solutions may remain constrained to niche or blended applications rather than full replacement of graphite in the near term.

2.1.4. LNMO High-Voltage Spinel Cells

High-voltage spinels are considered very promising due to their high theoretical energy density, close to 650 Wh/kg [34,35]. Lithium nickel manganese oxide (LNMO) spinel positive electrodes, particularly those based on $\text{LiNi}_{0.5}\text{Mn}_{1.5}\text{O}_4$, offer a high-voltage alternative to traditional LIB systems. LNMO operates at approximately 4.7 V vs. Li/Li^+ , compared to around 3.7 V for standard NMC chemistries. This means greater energy density, improved power and a battery pack with fewer cells. But the choice of electrolyte will be complex, as it is hard to find a stable electrolyte above an operating voltage of 4 V that will not decompose [35,36]. Cyclability remains moderate for the time being, with an average of 300 to 1000 cycles for a capacity retention of over 80% [34,35]. The absence of cobalt and the abundant presence of manganese are also assets that can lead to low electrode cost [32]. Finally, LNMO spinels offer good thermal and chemical stability [35,36]. Increased sensitivity to parasitic effects at high voltages is observed, with dissolution of species such as manganese leading to fairly rapid loss of capacity [35,36]. LNMO offers attractive high-voltage performance, yet cycling stability remains highly variable depending on electrolyte formulation. Some groups report stable operation over hundreds of cycles, while others observe rapid capacity fade due to Mn dissolution. This inconsistency illustrates the critical role of electrolyte selection and highlights a gap in achieving reproducible performance benchmarks.

2.1.5. Li-Rich Manganese-Based Positive Electrode Materials

Lithium-rich manganese-based cathode materials (LRM) are considered very promising for next-generation lithium-ion batteries for many reasons. Their high theoretical energy density over 900 Wh/kg [37,38] thanks to a relatively high average voltage make them good candidates for industrial applications. It is also a high specific capacities, over 250 mAh/g [37–41], far exceeds conventional NMC-type positive electrodes which makes them interesting. The resources for these electrodes are more abundant and less expensive, unlike cobalt, which is used in several other electrodes such as NMC. The electrodes are therefore more economical and durable. Finally, safety is enhanced with good thermal stability. However, certain drawbacks exist, particularly when high energy densities are desired. These mainly include irreversible decomposition of the electrolyte, dissolution and migration of transition metals, surface corrosion, etc. [39,40]. It has also been observed that when oxygen is released, irreversible structural changes occur or significant secondary reactions take place. These limitations have restricted the industrial-scale development of these materials [39,40]. To overcome these limitations, several improvement strategies have been developed. First, there is doping and substitution. Introducing new elements improves performance, structural stability, and cyclability [37,41,42]. The irreversible migration of transition ions and the continuous degradation of voltage are weaknesses for these electrodes. To address this, a solution is proposed by introducing several different elements at the metal sites. This multiplicity increases the configuration entropy, which acts as a stabilizer. As a result, there is a reduction in voltage fade, energy retention nearly twice that of a conventional Li-rich positive electrode, and improved cyclability [43,44]. This design removes barriers for these electrodes. Thus, despite their inherent challenges, lithium-rich manganese cathodes appear to be very promising candidates for next-generation lithium-ion batteries, with recent improvement strategies paving the way for their large-scale industrial deployment. Although recent strategies such as doping or entropy stabilization

have shown clear improvements, many reports remain at laboratory scale with limited validation under practical cycling conditions. This raises doubts about whether the observed enhancements can translate to commercial cells, especially given the persistent issues of voltage fade and oxygen release.

2.2. Solid-State Batteries

Solid electrolyte batteries are distinguished mainly by the replacement of the liquid electrolyte by a solid electrolyte, such as a polymer, sulfide or oxide. This fundamental change offers significant safety advantages, as it eliminates flammable liquid components. Moreover, it enables the use of a lithium metal negative electrode, which could greatly increase the energy density of the cell. This battery operates in a similar way to LIBs, by means of an intercalation/extraction mechanism, except in the case where the negative electrode is lithium metal. In this case, when discharging, Li^+ ions from the partial dissolution (stripping) of the negative electrode intercalate well into the positive electrode. During charging, however, these same ions leave the positive electrode (extraction) and are deposited directly on the negative electrode (plating). The phenomenon of plating/stripping is observed. These technologies still face a number of challenges, notably dendrite formation and improved ionic conductivity. Several industrial players are currently working on advanced prototypes, with a view to commercialization in the next decade.

As mentioned above, 3 types of electrolytes are mainly used. The first ones are solid polymer electrolytes, such as polyethylene oxide (PEO). It is widely studied for their flexibility and ease of shaping [45]. Polymer electrolytes have ionic conductivities in the range of 10^{-6} to 10^{-4} S/cm at room temperature [46]. Sulfide-based electrolytes, such as $\text{Li}_6\text{PS}_5\text{Cl}$, have fairly high ionic conductivity ($>10^{-3}$ to 10^{-2} S/cm), but are not compatible with negative lithium metal electrode [47]. Finally, there are solid oxide electrolytes, such as Lithium lanthanum zirconium oxide (LLZO , $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$) garnet, which offers good thermal and chemical stability, as well as good ionic conductivity in the order of 1 mS/cm [48]. The NASICON (Na Super Ionic Conductor) and LISICON (Li Super Ionic Conductor) structures serve as the foundation for another promising family of solid electrolytes. These materials, which are usually formed as $\text{Li}_{1+x}\text{M}_x\text{M}'_{2-x}(\text{PO}_4)_3$ (where M = Cr, Al, Ga, Sc, Y, In, La and M' = Ti, Ge, Sn, Hf, Zr) or $\text{Na}_{1+x}\text{Zr}_2\text{Si}_x\text{P}_{3-x}\text{O}_{12}$, combine great structural stability with strong ionic conductivity (up to 10^{-4} – 10^{-3} S/cm) [49,50]. In order to reduce reduction processes at the electrode interface, Zr has recently been used in place of Ti or Ge, which has addressed earlier interfacial instabilities. Because of their excellent electrochemical stability and resistance to moisture, NASICON-type electrolytes, such as $\text{Na}_{1+x}\text{Zr}_2\text{Si}_x\text{P}_{3-x}\text{O}_{12}$ are now regarded as important candidates for all-solid-state sodium batteries for Na-based systems. Thus, these oxides offer a promising path toward solid-state Na-ion batteries that are safer and more conductive [49].

These batteries offer a number of advantages, including greater intrinsic safety, due in part to the absence of flammable liquids [47,48]. If the lithium metal negative electrode is introduced into these systems to reduce the dendrite phenomenon, there is great potential for high energy density [47]. Finally, a number of advances have been observed, notably the release of the first production prototypes by Toyota and QuantumScape, and various programs aimed at commercialization around 2030 [51]. These announcements are questionable in light of the scientific obstacles that have been identified, whether they concern interface instability, pressure constraints, or gas emissions. These timelines should therefore be viewed as targets rather than certainties. However, there are a number of limitations to overcome in order to achieve a stable system. Firstly, ionic conductivity is often lower than that of liquid electrolytes, especially at room temperature, which often requires heating [45]. Furthermore, interface instability and the formation of dendrites, even in

solid electrolyte, reduce battery performance and even break the circuit [45,47]. Problems of delamination and mechanical cracking have also been observed in these systems [52]. Pressurizing these systems is an essential aspect of their operation. The challenge lies in managing the pressure to obtain good interfacial contact, as well as the internal pressure that develops during charge and discharge cycles, in order to maintain effective interfacial contact between the materials [53]. To achieve good contact, studies show a reduction in interfacial impedance from ten to a hundred kPa and an improvement up to 400 kPa at 60 °C. Many studies report much higher pressures of several hundred MPa. However, industrial objectives are pushing for pressures below 10 MPa through specific architectures, interface designs, etc. [54]. There is thus a clear discrepancy between laboratory demonstrations, which often require high stack pressures (hundreds of MPa), and industrial roadmaps from companies such as Toyota or Quantum cape, which target below 10 MPa for commercial viability. This gap raises questions about the feasibility of transferring laboratory-scale performance to practical cells. In addition, contradictory reports exist on whether interface coatings can fully suppress dendrite penetration, underscoring the need for more systematic long-term studies.

In summary, solid-state batteries promise a safer and more energy-dense future for electrochemical storage. Although each solid electrolyte class has shown promise, comparisons across reports are complicated by the use of different cell architectures and test conditions. For example, oxide-based systems are often praised for stability but suffer from high resistance at interfaces, whereas sulfides show high conductivity yet raise serious concerns regarding moisture sensitivity and gas release. The absence of standardized testing makes it difficult to objectively compare performance across these materials, which hinders a clear roadmap for industrial adoption. While substantial challenges remain, the first commercially viable fully solid-state battery systems are expected to reach the market between 2030 and 2035.

2.3. Lithium-Sulfur Batteries

Lithium-sulfur (Li-S) batteries are composed of a sulfur-based positive electrode and a lithium metal negative electrode, offering one of the highest theoretical energy densities among current battery technologies. Battery operation is based on a series of conversion reactions. The basis for the strong appeal of Li-S is the theoretical capacity of sulfur of 1675 mAh/g. Although the potential is very high, practical cells suffer from significant degradation when industrial constraints are imposed. Many journals therefore estimate that, in practice, the values achievable at the cell level would not exceed 350 Wh/kg initially. Moreover, this technology is still limited by cyclability problems, notably the dissolution of polysulfides in the electrolyte, leading to rapid loss of capacity. To overcome these limitations, various strategies are currently being studied. Methods such as encapsulation of the active material or optimization of electrolytes are being considered to stabilize cycling. From a theoretical standpoint, Li-S batteries can reach energy densities exceeding 500 Wh/kg, and even up to 2600 Wh/kg, according to thermodynamic calculations [55,56]. However, the energy density of these systems remains limited due to the low density of sulfur ($\sim 2.06 \text{ g/cm}^3$) and the use of highly porous electrodes requiring a large amount of electrolyte. At the cell level, the volume occupied by the electrolyte and thermal management significantly reduces the volumetric energy density. As a result, some systems are less efficient than certain Li-ion batteries. Therefore, for applications where volume is a critical factor, the mass advantage may be negated. Research is therefore focused on increasing volumetric density by developing denser electrodes or reducing the electrolyte/sulfur ratio [57]. Sulfur is abundant and available at an average of less than 200 USD/ton, which is inexpensive compared to other metals and reduces the criticality of other metals. Recent

advances have shown positive electrodes encapsulated by carbon nanotubes to reduce the “shuttle effect”, one of the main modes of degradation in Li-S batteries [58]. Researchers have also developed electrodes stabilized by chemical bonding to increase the stability of these batteries [59]. However, the challenges associated with this technology are tough. The “shuttle effect” of soluble polysulfides is one of the challenges to be overcome. Low cyclability due to the loss of active sulfur and the growth of insulating by-products make the technology difficult to use at present [59–61]. Finally, as with all-solid-state batteries with lithium metal as the negative electrode, an instability problem has been observed in Li-S [60].

While Li-S batteries offer very high theoretical energy density, practical demonstrations remain inconsistent. Some reports highlight over 500 cycles with promising capacity retention, whereas others observe rapid fading due to polysulfide dissolution. This variability indicates that Li-S research is still at a stage where reproducibility is limited, and solutions proposed in the literature often trade one issue (shuttle effect) for another (volumetric energy loss or electrode instability). Such contradictions underscore the early maturity of this chemistry.

2.4. Sodium-Ion Batteries

Most sodium-ion batteries (NIBs) operate according to the same fundamental principle as lithium-ion batteries (LIBs), relying on intercalation and extraction mechanisms. However, they substitute sodium ions (Na^+) for lithium ions (Li^+). The main advantage of this substitution lies in the abundance and low cost of sodium, which significantly reduces raw material constraints and is expected to lower overall cell production costs. They use positive electrodes inspired by LIBs, such as polyanionic structure, Prussian blues or layered oxides. As for negative electrodes, the most widespread is currently hard carbon. There are also batteries that do not operate using intercalation mechanisms but rather conversion reactions, alloys, etc. Although their energy density is lower, they offer great potential for stationary storage, power applications and certain mobility applications. In terms of performance, commercial cells display an energy range of 100 to 150 Wh/kg, while in the laboratory, some prototypes display a density greater than 200 Wh/kg. This progress is partly possible through the optimization of electrode materials and the electrolyte. Regarding durability, it is not uncommon to see a cycle count of 2000 to 4000 or higher depending on the chemistry. Thus, these technologies are approaching the lifespans of lithium-ion batteries for certain applications. Several companies, including CATL, Natron Energy, and Tiamat, have already announced initial commercial deployments, marking a pivotal step in the maturation of this technology. Some brands are already conducting tests, such as CATL, which has announced the launch of an electric vehicle equipped with a sodium-ion battery with an energy density of 175 Wh/kg. One of the advantages of this technology is its freedom from lithium dependence, thanks to the abundance of sodium [53]. In addition, research into LIBs is being used extensively to develop this technology, notably thanks to the compatibility of positive electrode materials [54,55]. Last but not least, the first industrial deployments will provide a wealth of feedback to further improve this technology. However, energy density is lower than for LIBs, on the order of 100–150 Wh/kg, and problems of SEI instability on hard carbon tend to reduce the durability of NIBs [62].

Na-ion technology is frequently described as a low-cost and sustainable alternative to LIBs, but its performance reports vary significantly depending on the electrode chemistry. While hard carbon is widely considered the most suitable anode, the lack of consensus on SEI stability remains a major obstacle. Similarly, the long-term stability of layered oxides or Prussian blue cathodes is still debated, with conflicting data on structural ro-

bustness. These discrepancies highlight the immaturity of the field and the need for systematic benchmarking.

2.5. Other Emerging Technologies

Beyond the systems discussed above, several emerging battery technologies are attracting growing interest due to their potential in terms of cost reduction, enhanced safety, and/or higher energy density. These include zinc-Air, lithium-Air, magnesium-ion and aluminum-ion batteries, to name but a few. They offer promising prospects, although major limitations are blocking their commercial adoption.

2.5.1. Zinc-Air Batteries

Zn-air batteries use a negative zinc metal electrode and a positive electrode where oxygen from the air is reduced. During discharge, oxygen reacts with electrons and hydroxide ions (OH^-) at the positive electrode to form water, while the zinc negative electrode is oxidized to Zn^{2+} , generating an electron flow. Rechargeable versions present challenges such as the formation of zinc dendrites and parasitic reactions at the negative electrode. Their lifetime and efficiency are therefore limited [63].

2.5.2. Lithium-Air (Li-Air) Batteries

Lithium-air (Li-air) batteries consist of a lithium metal negative electrode and a porous positive electrode that facilitates the reduction of oxygen during discharge, forming lithium peroxide (Li_2O_2). Theoretical energy density is very high, but the technology faces several obstacles: formation of reactive species degrading electrolytes and electrodes; limited coulombic efficiency; poor cyclability due to solid lithium peroxide deposits [63]. These challenges are still holding back the development of this technology.

2.5.3. Magnesium-Ion Batteries

Magnesium-ion (Mg-ion) batteries use Mg^{2+} ions as charge carriers, with a metallic magnesium negative electrode and a metal oxide-based positive electrode. Magnesium offers several advantages over lithium, including higher volumetric capacity, reduced dendrite formation risk, and greater earth abundance. However, these batteries have major kinetic problems, as diffusion of Mg^{2+} ions into the electrode materials is slow. Moreover, compatibility with liquid electrolytes is limited. Specific formulations must therefore be developed to avoid passivation of the negative electrode [64].

2.5.4. Aluminum-Ion (Al-Ion) Batteries

Aluminum-ion (Al-ion) batteries store energy using Al^{3+} ions, typically involving an aluminum metal negative electrode and a carbon-based positive electrode. Aluminum is abundant, low-cost, and theoretically capable of high charge storage, making it attractive for next-generation batteries. However, as with Mg-ion batteries, there is a kinetic problem. Al^{3+} ions have a high charge, which limits kinetics. There are also problems with the stability of electrolytes, which are often corrosive [65].

2.5.5. Potassium-Ion (K-Ion) Batteries

Potassium batteries also appear to be a promising alternative due to the abundance and low cost of potassium. The electrochemical principle is similar to lithium-ion, but as with sodium-ion systems, the size of the potassium ion is larger, which poses many challenges. The theoretical energy potential is high with a density around 300 Wh/kg. Graphite can also be used as a reversible anode, which allows the use of existing knowledge. On the other hand, the diffusion kinetics is slow, particularly due to the size of the K^+ ion, and the SEI layer is more unstable on graphite than for lithium-ion batteries. Several

perspectives attempt to overcome these obstacles by developing, for example, innovative electrolytes, such as polymer-gels or co-solvent organic electrolytes stable at high voltage, or by designing nano-structured architectures for the electrodes [66–68].

2.5.6. Some Promising Cathodes

In addition to traditional layered oxides, a number of other cathode families are being actively studied. Each has unique benefits but also significant drawbacks that prevent widespread use. Theoretical capacities above 300 mAh/g are made possible by vanadium-based oxides, such as V_2O_5 , which have high operating voltages and multielectron redox capacity. Severe structural instabilities, such as layer collapse and amorphization during repeated intercalation and vanadium dissolving into the electrolyte, counteract these advantages, though, and result in short cycle life and quick capacity fading. High-rate performance is further limited by their intrinsically low electronic and ionic conductivity, unless it is counteracted by carbon coating or nanostructuring techniques [69,70].

Recently, iron halides and $FeCl_3$ in particular, have drawn attention due to their abundance of constituent elements and low cost. The halide framework gives strong electronic conductivity, and the Fe^{3+}/Fe^{2+} redox pair offers a promising energy density in both liquid and solid-state geometries. However, halide ion migration and electrolyte reactivity are the primary causes of the severe reversibility and corrosion issues that $FeCl_3$ cathodes encounter. Unless interfacial engineering or protective coatings are used, these problems lead to unstable surfaces and low cycling stability [71].

The final cathode family discussed is a revolutionary class of recently emerged low-cobalt or cobalt-free cathodes: disordered rock-salt (DRX) oxides. With capacities surpassing 250 mAh/g, its cation-disordered structure permits large lithium excess and makes it easier to access both cationic and anionic redox processes. However, slow Li^+ diffusion and voltage hysteresis are caused by this compositional and structural instability, which restricts rate capability and energy efficiency. Furthermore, stability and scalability are severely hampered by the complicated synthesis conditions, possible oxygen loss, and local migration of transition metals during cycle [72].

All these technologies therefore have great potential, whether in terms of energy density, cost or sustainability. At present, most of these alternative chemistries remain confined to laboratory-scale demonstrations, with widely varying performance metrics reported. The lack of reproducibility and the absence of long-term cycling data make it difficult to assess their true potential. In particular, discrepancies between optimistic theoretical energy densities and modest practical values suggest that industrial relevance is still distant for these systems. Current research is focused on developing advanced materials and new electrochemical concepts to increase commercial viability. In the medium to long term, some of these alternatives may provide viable solutions for stationary storage, high-power applications, or portable electronic devices, and could complement or even replace lithium-ion technologies in specific markets.

3. Degradation Mechanisms for Each Technology

3.1. Degradation of Advanced Lithium-Ion Batteries (NMC, NCA, Enhanced LFP, Si/C, LNMO)

Lithium-ion batteries undergo various degradation mechanisms during their life cycle, which affect their capacity, internal resistance, and safety. These phenomena result mainly from chemical and physical changes in the electrodes and electrolyte, as well as the electrode/electrolyte interface.

3.1.1. Degradation of the Negative Electrode (Graphite and Si/C)

The SEI is a passivating layer that forms on the negative electrode (graphite or Si/C) during the first few cycles. It can become unstable over the course of cycles. When the potential of the negative electrode is less than about 1 V with respect to Li⁺/Li, decomposition of the organic electrolyte on the electrode surface is thermodynamically favorable. The decomposition products then form a layer on the surface of the electrode material, known as the solid electrolyte interphase [24,73,74]. This variation is illustrated in Figure 3, which compares SEI formation on graphite and Si-based negative electrodes.

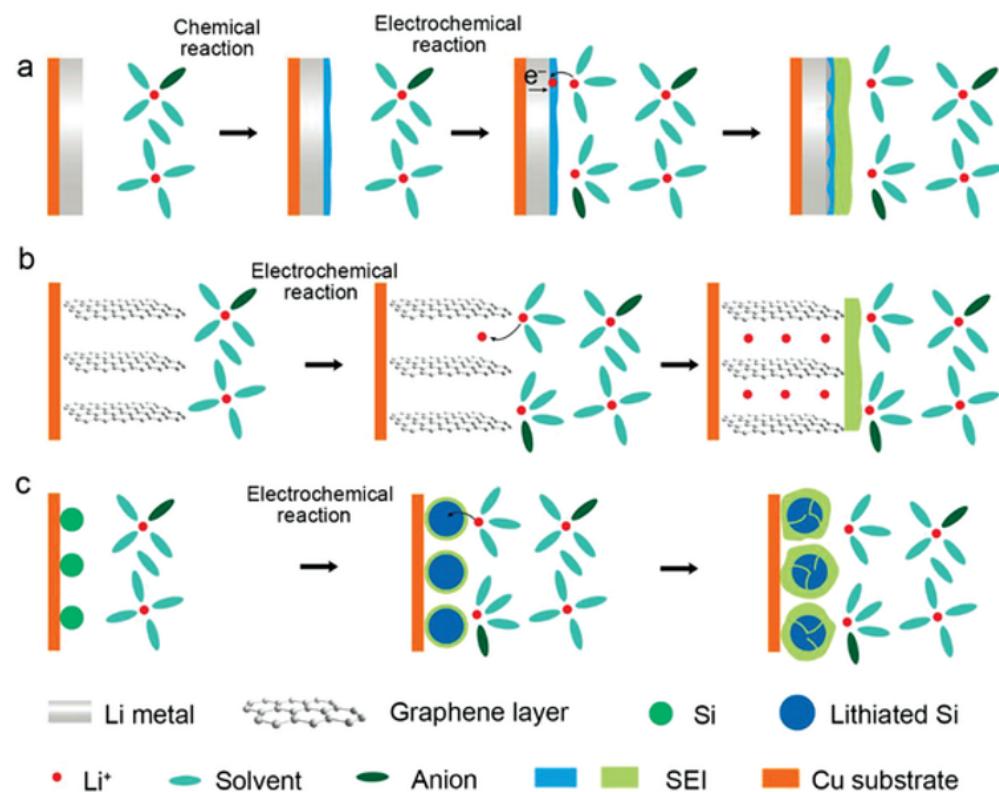


Figure 3. Schematic illustration of SEI layer formation on (a) Li metal, (b) graphite, and (c) silicon negative electrode and evolution on graphite and Si/C negative electrodes. Reproduced with permission [75]. Copyright 2020, Wiley-VCH.

During expansion/contraction of the negative electrode due to intercalation or extraction, significant changes in electrode volume are observed, particularly when using a silicon-based negative electrode. The SEI formed then cracks and re-forms continuously, consuming cyclable lithium and electrolyte. The SEI is therefore dynamic and not stable [73]. In graphite in particular, SEI growth is the main mechanism in capacity loss at room temperature and standard cycling. The high reactivity of silicon and its wide variation in volume are the cause of the instability. This generates a thick, non-uniform layer due to excessive electrolyte reduction. This thick layer has low electrical and ionic conductivity and high Li⁺ ion transport resistance [76]. However, it is possible to mitigate the formation of an unstable SEI by using Si-based composite electrodes or with a nanostructured design [73]. Researchers have also succeeded in controlling SEI growth on silicon nanotubes with a rigid carbon outer shell [77]. In addition, SEI instability is less pronounced when the negative electrode is graphite-based, as volume expansion is lower and electrolyte decomposition products are relatively stable once the layer is formed [78]. However, despite extensive research, there is still no consensus on the “ideal” electrolyte formulation or additive package to stabilize the SEI, particularly when moving from graphite to high-capacity

Si/C anodes. Some studies report beneficial effects of FEC or VC additives, while others highlight accelerated cathode dissolution or impedance growth. This inconsistency points to a lack of standardized testing conditions, which makes it difficult to isolate the dominant factors governing long-term SEI stability.

Lithium metal deposition, or “plating”, is another degradation phenomenon where lithium metal is deposited directly on the electrode surface instead of intercalating into a site. This phenomenon is aggravated mainly by overcharging, low temperatures [79,80] or high C-rates but remains secondary at higher temperatures. It becomes significant only below 10 °C approximately. Lithium forms a metallic plate on the graphite negative electrode [81,82]. The plating is not necessarily uniform, which can gradually create dendrites that can pierce the separator and reach the positive electrode, creating a short-circuit and the risk of thermal runaway. This phenomenon is triggered by the exothermic decomposition of the electrolyte and positive electrode materials. It is also accelerated by low temperatures and the presence of nickel (for enriched electrodes) [81,82]. Graphite appears to be the least sensitive material to plating, ahead of silicon-based and lithium metal electrodes.

Materials are often added to electrodes to improve their performance. Silicon is mainly used for its high gravimetric capacity. However, its expansion by almost 300% during alloying with lithium is a real problem [83,84]. This expansion creates microcracks, degrades electrode cohesion, accelerates capacity loss and promotes the rupture of the SEI [83]. This loss of mechanical integrity leads to particle fragmentation and loss of electrical contact with the collector, accelerating capacity loss [32]. These phenomena tend to appear quickly, much more so than lithium plating. Si/C composites are used to mitigate this expansion. However, the problem persists at high silicon content [85].

3.1.2. Degradation of the Positive Electrode (NMC, NCA, LFP, LNMO)

In NMCs and NCAs, manganese, nickel or cobalt can dissolve in the electrolyte, particularly at high voltage or high SoC (State of Health). These species then tend to migrate to the negative electrode and act as catalysts for SEI [86,87]. In the case of layered positive electrodes, metal dissolution tends to accelerate the surface passivation mechanism (rock-salt), which inhibits Li⁺ ion transport, blocks access to electrochemical sites and increases interfacial resistance [87,88]. In nickel-rich layered materials such as NMC811, expansion (charge) and contraction (discharge) cycles induce a progressive evolution of the lattice parameter. The repetition of these variations generates an accumulation of mechanical stresses, causing intergranular cracking, loss of interparticle contact and an increase in internal resistance [89]. However, there is still no clear consensus on the relative contribution of transition-metal dissolution versus mechanical cracking to long-term capacity fade. Some studies emphasize dissolution-driven surface reconstruction as dominant, while others identify microcracking as the primary limitation, particularly in Ni-rich NMCs. This divergence underscores the complexity of degradation processes and the need for combined operando and post-mortem analyses to disentangle these effects.

The surface can also become unstable, particularly at high voltages. The $LiMO_2$ family of lithiated transition metal oxides, where M can be nickel, cobalt, manganese or aluminum in different proportions, constitutes a wide range of materials offering high capacity, good stability and high power. They are intended for use as positive electrode materials for Li-ion batteries [82]. Positive electrodes rich in nickel or other transition metals, particularly at high voltages such as 4.7 V LNMOs, promote electrolyte oxidation and the formation of a CEI (Cathode Electrolyte Interphase). This layer is generally thick and resistive [82,90]. This interface limits the diffusion kinetics of Li⁺ ions and increases the cell's internal resistance.

Thus, failure to control the thickness of this layer, either dilution or formation, leads to a reduction in battery life [82,91].

The LiFePO₄ (LFP) electrode is considered to be more stable than NMC and NCA electrodes. However, specific degradation mechanisms occur even if the degradation is rather slow. Iron dissolves in ionic form, aggravated by the presence of HF (resulting from the decomposition of LiPF₆). This iron migrates to the anode, where it can form a metallic deposit and thus increase impedance. In addition, it can act as a catalyst for the reduction in electrolyte components, forming a new SEI and resulting in lithium loss [92–94]. LFP also undergoes a volume change during cycling of around 6% to 7%. This volume change is greater during rapid charging, which can lead to particle cracking or even loss of contact between the grains and the collector [93,94]. However, the degradation is more related to the dissolution of iron than to cracks. Although iron dissolution is the most important process in cell degradation, metal dissolution remains less degrading than for NMC and NCA cells. Finally, it should be noted that LFP operates via a two-phase mechanism ($\text{LiFePO}_4 \leftrightarrow \text{FePO}_4$). During lithiation/delithiation, the interface between the two phases generates mechanical stresses. With cycling, these stresses cause the formation of pores, cracks, and loss of electrode/collector contact, leading to a decrease in capacity [93,94].

3.1.3. Degradation of the Organic Electrolyte

The electrolyte plays a central role in the performance and durability of Li-ion batteries. Its aging directly influences the formation and evolution of the electrode/electrolyte interface (SEI/CEI), safety, and chemical stability. The electrolyte is generally divided into three parts: the conductive salt, the solvent, and the additives. The choice of these three components is important for improving system stability, security, and performance, and limiting degradation. For conductive salts, LiPF₆ is the most common due to its good ionic conductivity in carbonates ($\sim 10^{-2}$ S/cm) and its compatibility with graphite. However, above 60 °C, its thermal stability is greatly reduced [95]. LiFSI is also used for greater thermal and chemical stability. It remains stable up to 180 °C, has good ionic conductivity, and the LiFSI-based electrolyte allows the formation of a protective surface on the negative graphite electrode. However, its ability to passivate aluminum remains insufficient at potentials above 4.0 V. LiFSI-based electrolytes are only suitable for cathodes such as LiFePO₄, as the potential reduces the tendency to oxidize [96]. There are several categories of solvents, including carbonates, esters, ethers, etc. Carbonates are the basis of commercial electrolytes in lithium-ion batteries. One example is ethylene carbonate (EC), which is essential for the formation of a stable SEI on graphite. It has a high dielectric constant (~90), which promotes the dissociation of lithium salt. However, its melting point is 36 °C, which is high, and its viscosity is high, making it less usable on its own. It is therefore often mixed with other solvents. Other solvents include DMC (dimethyl carbonate), EMC (ethyl methyl carbonate), and DEC (diethyl carbonate), which are linear solvents with low viscosity and low dielectric constant, making them good candidates for mixing [97]. The balance that allows for good performance at low temperatures and better thermal stability seems to depend on the ratio between EC and linear carboxylates, with 20% of each plus an acyclic carbonate offering the best compromise [96]. Finally, additives are used to improve the properties of the electrolyte or to reduce certain degradation mechanisms. FEC (fluoroethylene carbonate) improves cyclability, reduces lithium consumption, and promotes the formation of an effective SEI that is conductive to Li^{+} ions and electronically insulating, but accelerates the dissolution of the positive electrode by producing large quantities of HF [96,97]. VC (vinylene carbonate) is another widely used additive that improves the stability of SEI on graphite, limits the decomposition of carbonate solvents, and slows down the loss of cyclable lithium [96]. So, electrolyte plays a critical role in lithium-ion batteries.

by facilitating lithium-ion transport between electrodes. However, under high-voltage and elevated-temperature conditions, the electrolyte undergoes substantial degradation, posing significant challenges to cell performance, longevity, and safety.

At operating voltages exceeding approximately 4.5 V vs. Li⁺/Li, commonly encountered in high-energy positive electrode chemistries such as LiNi_{0.8}Mn_{0.1}Co_{0.1}O₂ (NMC811) and LiNi_{0.5}Mn_{1.5}O₄ (LNMO), electrolyte components such as LiPF₆ become thermodynamically unstable. Oxidation reactions at the positive electrode-electrolyte interface generate gaseous by-products including carbon monoxide (CO) and carbon dioxide (CO₂) [82,89]. The accumulation of these gases can lead to cell swelling, especially in pouch and cylindrical cell formats, and induces mechanical stress and electrochemical instability at the interface [98]. The use of more stable salts such as LiFSI or LiTFSI is limited by the corrosion of high-potential aluminum, which restricts their compatibility to high-voltage electrodes. Specific additives such as LiBOB can be used to form a stable SEI and reduce the dissolution of transition metals [99].

Furthermore, at elevated temperatures (typically above 60–70 °C) the degradation of the electrolyte accelerates markedly. A variety of volatile and acidic species are formed, such as: hydrogen fluoride (HF), arising from the decomposition of LiPF₆ and reactions with trace water; hydrocarbons such as methane (CH₄); oxidized carbon compounds, including CO and CO₂.

The exact nature and proportion of decomposition products are influenced by the electrolyte formulation, salt concentration, and temperature profile [82]. The formation of acidic by-products, particularly HF, initiates parasitic reactions that compromise both electrodes. On the positive electrode, HF promotes transition metal dissolution (e.g., Mn²⁺, Ni²⁺), which contributes to surface reconstruction and increased impedance. On the negative electrode, these species destabilize the solid electrolyte interphase (SEI), leading to further electrolyte decomposition, loss of lithium inventory, and increased interfacial resistance. While additives such as FEC and VC are widely employed to stabilize interfaces, their dual role (improving SEI formation while accelerating cathode degradation) remains a subject of debate. Contradictory results across studies suggest that additive efficiency is strongly dependent on electrode chemistry and testing conditions. This variability highlights the lack of universal electrolyte formulations capable of simultaneously stabilizing both anode and cathode interfaces under high-voltage operation. In general, electrolyte additions and composition are crucial for reducing deterioration. While new localized high-concentration electrolytes and salts like LiFSI and LiTFSI have demonstrated increased stability, sophisticated additives like FEC, VC, LiBOB, DTD, and others can control the development of SEI/CEI and reduce gas production. The necessity for comprehensive research linking electrolyte design with long-term degradation kinetics is highlighted by the fact that their effects are frequently chemistry-dependent and occasionally antagonistic.

The cumulative effects of these degradation pathways result in: accelerated capacity fade; impedance growth; loss of active material; thermal instability. It is important to note that many degradation mechanisms in LIBs do not occur in isolation but rather act synergistically. For instance, transition-metal dissolution from Ni-rich cathodes not only depletes the cathode active material but also deposits on the anode, where it catalyzes continuous electrolyte decomposition and destabilizes the SEI. Similarly, gas generation from LiPF₆ decomposition accelerates impedance rise while also exacerbating electrode particle cracking. Such coupled processes complicate the attribution of capacity fade to a single mechanism, underscoring the need for integrated studies that capture their interplay.

Gas evolution is often a precursor to thermal runaway, particularly in cells subjected to mechanical abuse or prolonged high-temperature operation. Thus, monitoring gas

generation and electrolyte decomposition is essential for early failure detection and safety diagnostics [82,100]. Figure 4 below summarizes the main mechanisms identified.

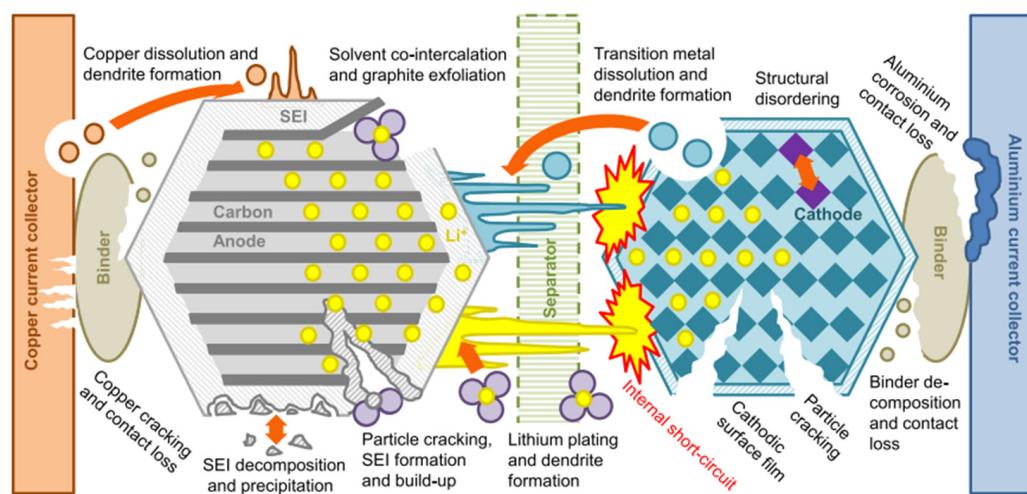


Figure 4. Main degradation mechanisms in lithium-ion batteries. Reproduced under terms of the CC-BY license [101]. Copyright 2016, Elsevier.

3.2. Degradation of Solid-State Batteries (SSB)

The transition to all-solid technology is accompanied by new difficulties in obtaining a stable system. A great deal of work is being done to reduce the degradation observed in this system, in order to make it viable for industry.

3.2.1. Degradation at Electrode/Solid Electrolyte Interfaces

One of the most critical challenges in all-solid-state battery (ASSB) development lies in the interfacial contact between the solid electrolyte and the electrodes. Unlike liquid electrolytes, which spontaneously wet the surfaces of the electrodes and fill interfacial voids, solid electrolytes lack this self-adjusting property. As a result, poor interfacial adhesion, void formation, and contact loss are common, especially during cycling.

In ASSBs, interfacial resistance is a major performance-limiting factor. Imperfect physical contact and heterogeneous ionic pathways reduce the efficiency of lithium-ion transport, leading to increased overpotentials and capacity loss [52,102]. The problem is exacerbated by repeated volume changes in the electrodes during lithiation and delithiation, which introduce mechanical stress and contribute to loss of interfacial integrity over time.

In addition to mechanical issues, chemical and electrochemical instabilities at the interface further compromise performance. Solid electrolytes, particularly sulfide- and oxide-based systems, can react with electrode materials, resulting in the formation of parasitic interphases. These interphases are often electrically insulating and ionically resistive, thus impeding lithium-ion mobility and contributing to irreversible capacity loss [103]. These reactions are responsible for the majority of capacity losses, particularly for sulfides.

Rigid electrolytes such as oxides or sulfides are subject to mechanical cracking. The positive electrode swells and deflates during cycling, as does the negative electrode. This is particularly true of LiM or silicon negative electrodes [17,104,105]. Another observable effect at these interfaces is electrode delamination due to the accumulation of mechanical stresses [52].

3.2.2. Degradation of the Negative Electrode

In addition to mechanical problems due to interfaces, the negative electrode can be subject to the growth of dendrites, which can even penetrate solid electrolyte in the case

of LiM. If they manage to penetrate the separator, they can cause a short-circuit and a loss of active lithium. In polymer electrolytes, this growth is accelerated at high current densities. They then take the form of filaments, which can themselves form branches. The phenomenon of lithium creep is observed [17,103,106].

When LiM is used as a negative electrode, the creation of pores and the loss of lithium are often observed during use. If this phenomenon increases during cycling, contact failure may occur. When the discharge current exceeds a certain threshold, lattice vacancies (in the sense of crystal structure) are injected into the metal at a higher rate than diffusion and creep allow. The resulting accumulation of lacunae leads to the formation of pores and resistance to lithium transfer at the interface [107].

3.2.3. Degradation of the Positive Electrode

As with the negative electrode, the main degradation of the electrodes comes from interactions with the electrolyte. We observe the loss of interfacial contact and an increase in interfacial resistance. However, positive active material can be lost in the form of by-products. With sulfide electrolytes, this loss is accentuated by cracking of the solid sulfide electrolyte [108], particularly at high temperature.

3.2.4. Degradation of the Solid Electrolyte

Solid electrolytes are not inherently stable under all operating conditions. For instance, LLZO can undergo chemical degradation upon exposure to moisture, forming insulating surface layers that impede ion transport [52]. Unlike sulfide-based electrolytes, cross-resistance and microcracks are responsible for the greatest capacity loss. Like liquid electrolytes, some solid electrolytes can release toxic gases during decomposition. In particular, sulfide-based electrolytes have been shown to generate H₂S and SO₂, especially under humid conditions or high voltage [109]. These gaseous by-products are corrosive and may react with other cell components, contributing to performance degradation and safety hazards. The combination of gas generation and electrochemical reactivity makes the stabilization of solid electrolytes a key challenge. Experimental studies have shown that emissions of these gases vary considerably depending on humidity and temperature [110]. For industrial design, it is therefore necessary to develop materials and protective engineering strategies to mitigate these effects and ensure long-term stability. There is also a need to work in a controlled atmosphere on the production, assembly, and storage lines in order to regulate H₂S production as much as possible. A protective coating on the electrodes is also possible to limit these reactions. Oxide electrolytes appear to be more chemically stable than their counterparts but have poor mechanical contact. Sulfides are good ionic conductors but chemically unstable with problematic gas production. Finally, polymers are flexible and allow good contact with electrodes. However, electrochemical stability is not the best and dendrite growth is a problem. Importantly, comparisons across studies remain difficult, as LLZO, sulfide, and polymer electrolytes are often tested under very different operating conditions (temperature, pressure, current density). This makes it unclear whether the apparent superiority of one class over another reflects intrinsic material properties or simply testing methodology. A systematic benchmarking under standardized protocols is therefore urgently needed to guide industrial choices.

In solid-state batteries, degradation processes are often strongly interconnected. Figure 5 illustrates the main degradation mechanisms in all-solid lithium metal batteries. Mechanical stresses induced by lithium plating can crack the solid electrolyte, which in turn increases local current density and promotes further dendrite growth. Likewise, chemical side reactions at unstable interfaces may reduce ionic conductivity, causing local hot spots that intensify mechanical failure. These feedback loops explain why degradation in SSBs

can sometimes appear abrupt or catastrophic, and they highlight the need to investigate multiphysics couplings rather than isolated failure modes.

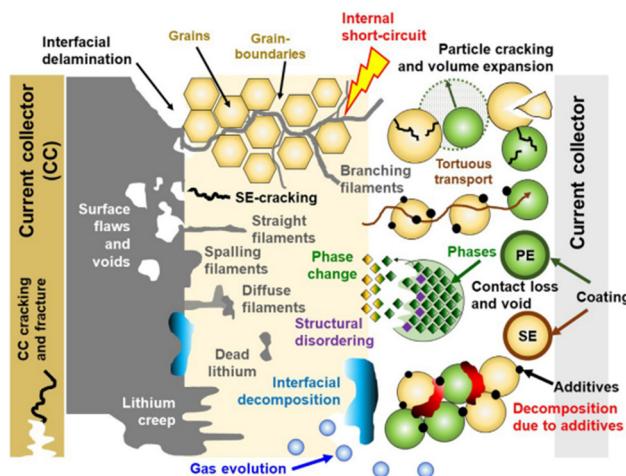


Figure 5. Summary of degradation mechanisms in an all-solid lithium metal cell. Reproduced with permission [52]. Copyright 2021. Elsevier Ltd.

3.3. Degradation of Lithium-Sulfur Batteries

Li-S technology is attracting growing interest due to its high theoretical energy density and the abundance of sulfur. However, large-scale commercialization is largely hampered by sustainability challenges.

3.3.1. Degradation of the Negative Electrode

As with other systems using LiM as a negative electrode, dendrite growth is observed in Li-S systems. The same effects are also observed, namely lithium loss, the possibility of short-circuiting and flammability [60,111,112].

The formation of a brittle SEI is also observed. It is described as “mossy” or even dendritic, notably due to the instability of lithium in the face of polysulfides [112,113]. As a result, this layer is constantly being rebuilt and dissolved. Deposition is then inhomogeneous, with the formation of micro-dendrites leading to significant mechanical stress [113,114]. Continuous dissolution and reformation of the SEI as well as dendrite growth are the main limiting factors of lifetime. Dendrite growth is particularly accelerated for higher current densities.

The use of lithium metal as a negative electrode in Li-S batteries therefore presents a number of challenges, as shown in Figure 6.

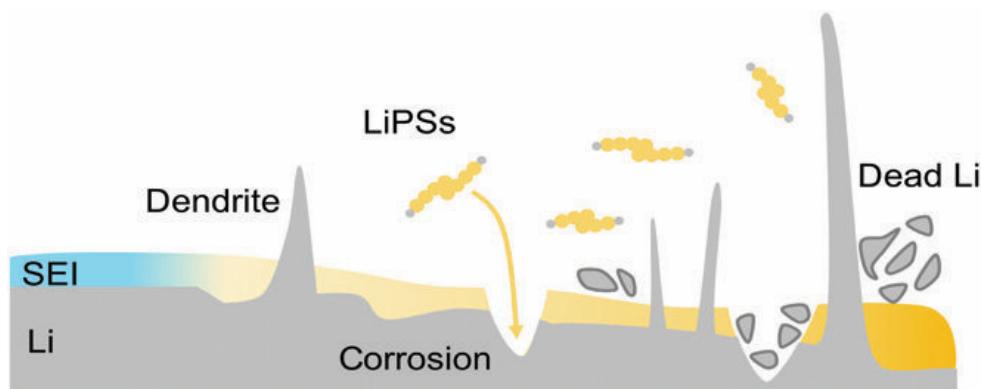


Figure 6. Challenges of using a lithium metal negative electrode in Li-S systems. Reproduced under the terms of the CC-BY license [115]. Copyright 2023. Chen-Xi Bi et al.

3.3.2. Degradation of the Positive Electrode

During the operation of these systems, insoluble and especially insulating products such as Li_2S_2 and Li_2S are formed. The main factor in the formation of these species is the shuttle effect, but this can also be due to local saturation or spontaneous precipitation. In this way, the reversibility of sulfur reactions into polysulfides is gradually reduced, leading to a loss of active sulfur [60,116,117]. This mechanism consumes a lot of active sulfur and is the most critical for cyclic capacity. Moreover, the sulfur electrode can expand by up to 80% during lithiation, leading to mechanical rupture of Li_2S layers and loss of electrical contact with the current collector [118–120]. As more sulfur becomes inactive, cycling induces rapid capacity decline. In solid-state Li-S systems, this expansion disrupts solid–solid interfaces, limiting both ionic and electronic transport [112]. The combination of chemical by-product formation and mechanical stress degrades electrode integrity. Moreover, while most studies agree on the detrimental impact of insoluble Li_2S deposition, reports diverge on whether electrode expansion or polysulfide loss is the dominant contributor to capacity fade. This uncertainty partly stems from the lack of operando mechanical characterization during cycling, which remains an underexplored field for Li-S research. In Li-S systems, the interplay between the shuttle effect and electrode mechanics is particularly critical. Dissolved polysulfides not only cause loss of active material but also react with the lithium anode, thickening the SEI and altering its morphology. At the same time, the large volume expansion of sulfur during lithiation increases porosity and electrolyte consumption, which further facilitates polysulfide dissolution. This coupling creates a self-reinforcing cycle that accelerates degradation, yet only a few studies have explicitly examined these interactions in detail. Nonetheless, ongoing work is paving the way toward improved cyclability and safety in Li-S technology.

3.3.3. Degradation of the Electrolyte

The shuttle effect is a degradation mechanism observed in lithium-sulfur systems where polysulfide ions migrate between electrodes in a cyclic fashion leading to a loss of active sulfur. Under the effect of the electric field and concentration gradients, long-chain lithium polysulfides (Li_2S_6 to Li_2S_8) diffuse through the separator and migrate to the negative electrode. They then react with the lithium metal to form shorter polysulfides (Li_2S_2 to Li_2S_6) and insoluble $\text{Li}_2\text{S}_2/\text{Li}_2\text{S}$. This mechanism is specific to this technology, which differentiates Li-S systems from other chemistries. This clearly undesirable phenomenon has two major consequences: the passivation of the lithium negative electrode by the formation of an insulating layer of $\text{Li}_2\text{S}_2/\text{Li}_2\text{S}$, thus reducing access to active sites for electrochemical reactions; and the accumulation of short-chain polysulfides near the passivated negative electrode [111,117]. These species can then diffuse back to the positive electrode and react with long-chain polysulfides, fueling a redundant cycle known as the shuttle effect, illustrated in Figure 7. This mechanism subsequently leads to rapid loss of capacity and low coulombic efficiency.

This effect insulates the surface of the negative electrode with sulfides and progressively delays rapid lithium access. This progressively leads to low flow capacity [60]. Temperature is an aggravating factor in the shuttle effect, as the reaction is accelerated like all other secondary reactions [118]. Despite numerous proposed strategies including conductive hosts, catalytic interlayers, or functional separators (see the Section 5.2 “Necessary Innovation”), none has yet provided a complete solution to the shuttle effect. For instance, while interlayers can efficiently trap polysulfides, they often penalize volumetric energy density, a trade-off that remains underexplored in the literature. Moreover, reports on the long-term chemical stability of polysulfide-adsorbing materials are sometimes conflicting,

suggesting that durability at scale is still uncertain. Finally, Figure 8 summarizes the main aging mechanisms in these systems.

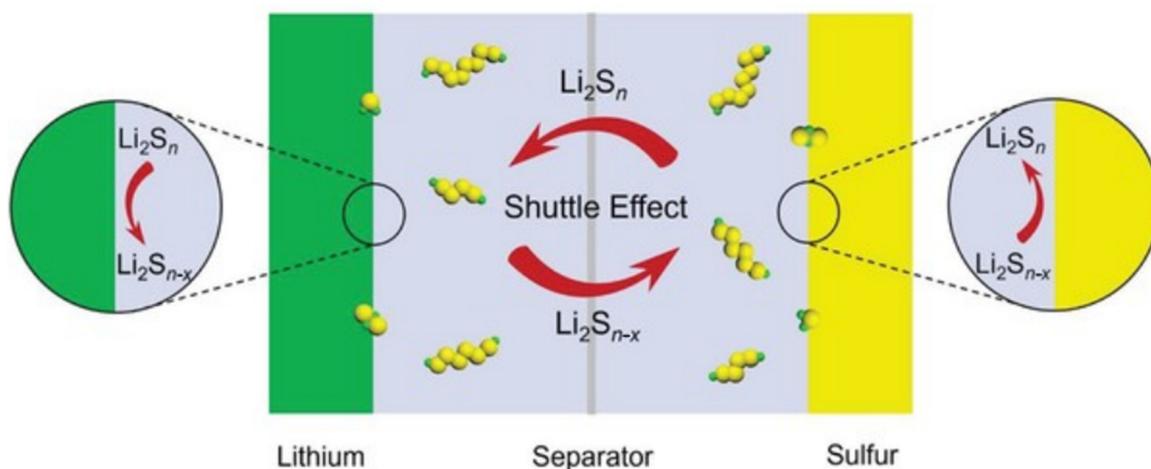


Figure 7. Schematic representation of the shuttle effect in Li-S batteries. Reproduced and adapted under the terms of the CC-BY license [116]. Copyright 2022. Wiley-VCH.

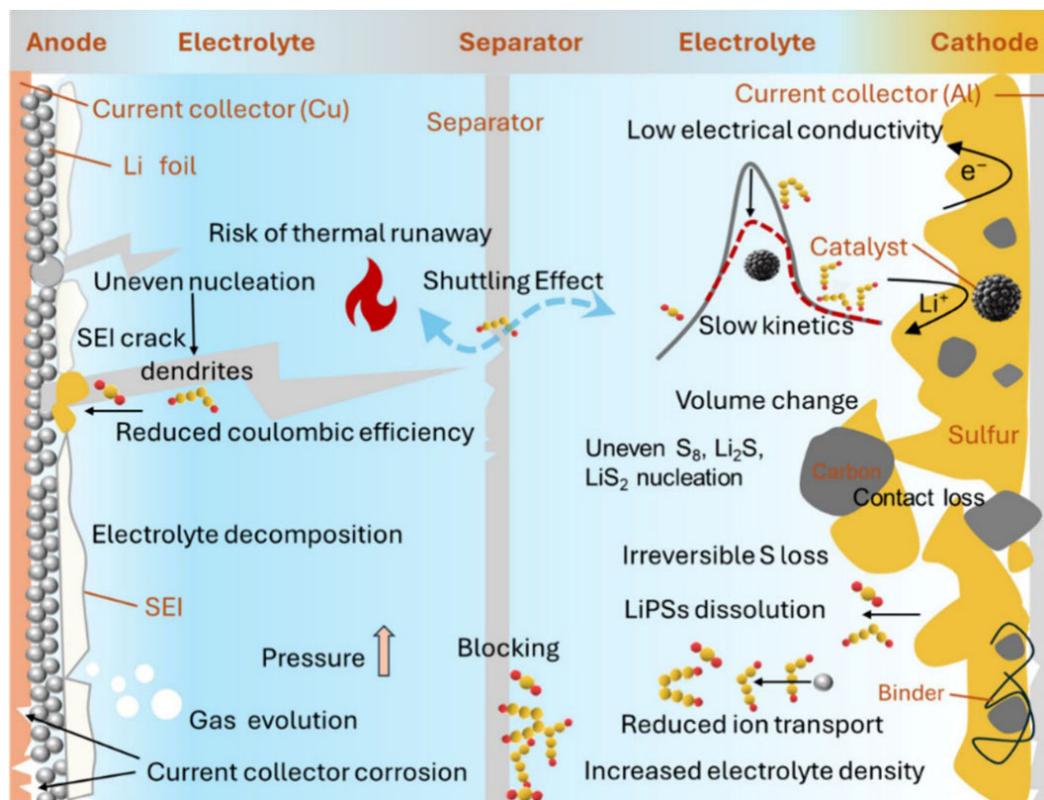


Figure 8. Main challenges and degradation mechanisms in Li-S batteries. Reproduced under terms of the CC-BY license [121]. Copyright 2024, American Chemical Society.

3.4. Degradation of Sodium-Ion Batteries

Na-ion batteries are emerging as a promising alternative to lithium-ion batteries in certain applications. The abundant availability and low cost of sodium are the strong points of this technology. Often compared with LIBs for their similar operating principle, NIBs exhibit quite distinct electrochemical behaviors, notably in terms of insertion kinetics, but also material stability, which influences aging mechanisms. Understanding these

differences is essential to improving the lifetime of these systems and ensuring their competitiveness in the marketplace.

3.4.1. Degradation at the Negative Electrode/Electrolyte Interface

In sodium-ion batteries, the negative electrode most commonly used to date is hard carbon. However, the SEI that forms on its surface is unstable due to the larger size of Na^+ ions and its reactivity with certain solvents. This results in irreversible loss of cycling sodium, thus capacity degradation and SEI growth becomes very unstable. Electrolyte salts (NaPF_6 , NaClO_4 , NaTFSI , etc.) strongly influence the nature of the products making up the SEI (NaF , Na_2CO_3 , Na_2O , various organics) [62,122–124]. For example, NaPF_6 is often preferred for its better thermal stability and lower tendency to form undesirable side products such as NaF . However, the use of NaPF_6 in electrolytes can lead to the formation of a less stable SEI, which can limit long-term performance [125]. The choice of solvents (often multiple to ensure good conductivity) is therefore important to find the right compromise. SEI instability is the major mechanism that limits the cyclability of hard carbon negative electrodes; it is currently one of the main obstacles to commercialization. Although several studies have attempted to engineer a more stable SEI on hard carbon through electrolyte design, results remain highly variable. In particular, the choice of salt (NaPF_6 vs. NaClO_4 vs. NaTFSI) appears to drastically change SEI composition and stability, but no consensus has emerged. Moreover, contradictory findings exist regarding whether fluorinated solvents or additives actually improve or destabilize the SEI. This highlights a critical research gap in achieving reproducible, durable SEI formation for Na-ion cells.

As with LIBs, sodium-ion technology is subject to sodium plating, particularly at low temperatures [123,126]. This plating can lead to the formation of dendrites, stripping and the formation of “dead” sodium, that is unusable because the link with the electrode is broken, as shown in Figure 9. In the long term, this cycle leads to ever larger dendrites and ever greater loss of active material, culminating in a short-circuit [124,127]. Finally, at the interface, cracks in the SEI are observed due to volume contraction during sodium extraction. This then opens up more avenues for dendrite growth during subsequent plating. Repeated plating/stripping of Na^+ ions lead to the accumulation of “dead” sodium, the formation of additional SEI, increased porosity of the sodium negative electrode and electrolyte depletion. All this causes poor cycling stability [127]. As stated previously, low temperatures tend to aggravate sodium plating, as with lithium-ion batteries. High current density, on the other hand, creates heterogeneity in the deposit, which promotes the creation of dendrites.

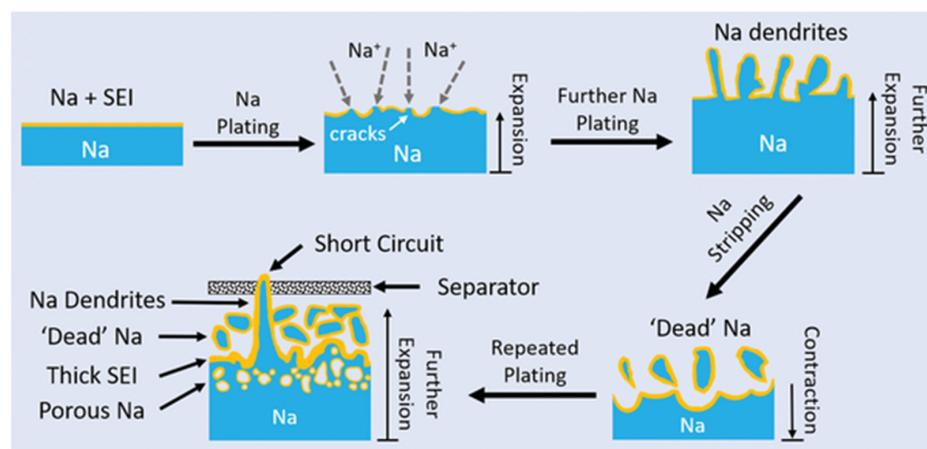


Figure 9. Diagram of stripping/plating/dendrite formation phenomena. Reproduced under the terms of the CC-BY license [127]. Copyright 2019. Wiley-VCH.

Interestingly, while lithium plating is a well-recognized degradation pathway in LIBs (especially at low temperature) its equivalent in Na-ion systems appears even more detrimental. Due to the larger ionic radius and lower diffusion kinetics of Na^+ , sodium plating leads more readily to dendrite formation and loss of active material. Yet, systematic comparative studies under identical conditions are lacking, leaving uncertainty about whether mitigation strategies developed for LIBs (such as electrolyte optimization or current density control) can be directly transposed to NIBs.

3.4.2. Degradation of the Negative Electrode

Negative electrodes based on Na-Sn or Na-Sb alloys are being explored for sodium-ion systems. However, they are subject to very large volume expansions of over 200%, or smaller variations during high-potential phase transitions in the case of layered oxides. Intra-particle cracks are then created [125,128,129]. Extreme volume expansion is the main cause of premature mechanical failure, which is significantly more critical than in the case of lithium-ion batteries.

Mechanical sputtering is accelerated when alloys are used under cyclic conditions. This phenomenon is mainly found in certain alloy-based negative electrodes such as antimony, tin, phosphorus or Na_3Sb , $\text{Na}_{15}\text{Sn}_4$, Na_3P (alloyed phases) [130,131].

3.4.3. Degradation of the Positive Electrode

Positive electrodes for sodium-ion batteries include different types of materials, whether layered oxides, polyanion-type compounds, Prussian Blue analogues, olivine/phosphates, etc. Each type has its own specific aging mechanisms. These electrodes are often subjected to mechanical stresses that accumulate due to volume variations during the insertion/extraction of Na^+ ions. As a result, cracks form in the active particles, leading to loss of electrical contact. The crystalline structure is also destabilized by the phase transitions that occur during operation, leading to irreversible loss of capacity and affecting sodium diffusion kinetics [132].

In the case of NVP ($\text{Na}_3\text{V}_2(\text{PO}_4)_3$), sodiation/desodiation leads to the opening and closing of microcracks, which can subsequently propagate and destabilize the structure [132]. Partial dissolution of sodium or transition metals (TM) is also observed in NVP or oxide-based positive electrodes. Vanadium dissolution, for example, is observed when using NVPF ($\text{Na}_3\text{V}_2(\text{PO}_4)_2\text{F}_3$) as a positive electrode [123,124,131]. This causes a loss of active material and a decrease in electronic conductivity. The dissolution of transition metals (V, Mn, Fe, etc.) in electrolytes is often more destabilizing than mechanical cracking alone. In Na-ion batteries, degradation pathways also tend to reinforce each other. For example, transition-metal dissolution from layered cathodes can migrate to the anode and catalyze electrolyte decomposition, which destabilizes the already fragile SEI on hard carbon. Likewise, electrolyte breakdown products can trigger gas evolution, which in turn accelerates electrode cracking and loss of contact. These coupled effects partly explain why NIBs often show sudden impedance growth after moderate cycling, a behavior still insufficiently characterized in the literature.

Concerning layered oxides, particle cracking is observed due to structural expansions/contractions during intercalation/de-intercalation. This leads to loss of electrical contact and increased exposure to electrolyte, further degrading the system. electrochemical stability problems of electrolytes (particularly for the high potentials of layered positive electrodes rich in Ni/Mn) are today a major limitation for reaching high voltages.

Conflicting findings exist regarding the relative stability of different positive electrode families. For instance, while Prussian blue analogues are often described as more structurally robust, recent reports suggest that water content and defect chemistry critically

affect their long-term performance. Similarly, vanadium dissolution in NVP-based systems remains poorly quantified under realistic cycling conditions, limiting the ability to predict lifetime with confidence.

Thus, it is necessary that each type of electrode be carefully studied to identify the degradation phenomena specific to it.

3.4.4. Electrolyte Degradation

The electrolyte in sodium-ion batteries is susceptible to multiple degradation mechanisms. Its electrochemical stability window defines its operational range, and exceeding this window induces oxidation or reduction reactions. At high potentials, electrolyte oxidation can degrade the cathode electrolyte interphase (CEI) and generate gaseous by-products, increasing internal pressure, flammability risks, and structural damage [123,124,131,133,134]. At low potentials, electrolyte reduction contributes to SEI formation but may also consume active components [124]. Additionally, decomposition of salts such as NaPF_6 forms catalytically active species like PF_5 , which act as Lewis acids, promoting parasitic reactions [131]. Despite these challenges, sodium-ion batteries hold strong promise for sustainable and low-cost energy storage. Improving the chemical stability of materials is key to enhancing durability, and significant efforts are already underway to mitigate ageing. The main aging mechanisms for sodium-ion batteries are presented in Figure 10. It is interesting to note the strong similarity of these mechanisms with those observed in Li-ion systems. These two technologies share many aging processes. The main differences lie mainly in the extent of these processes.

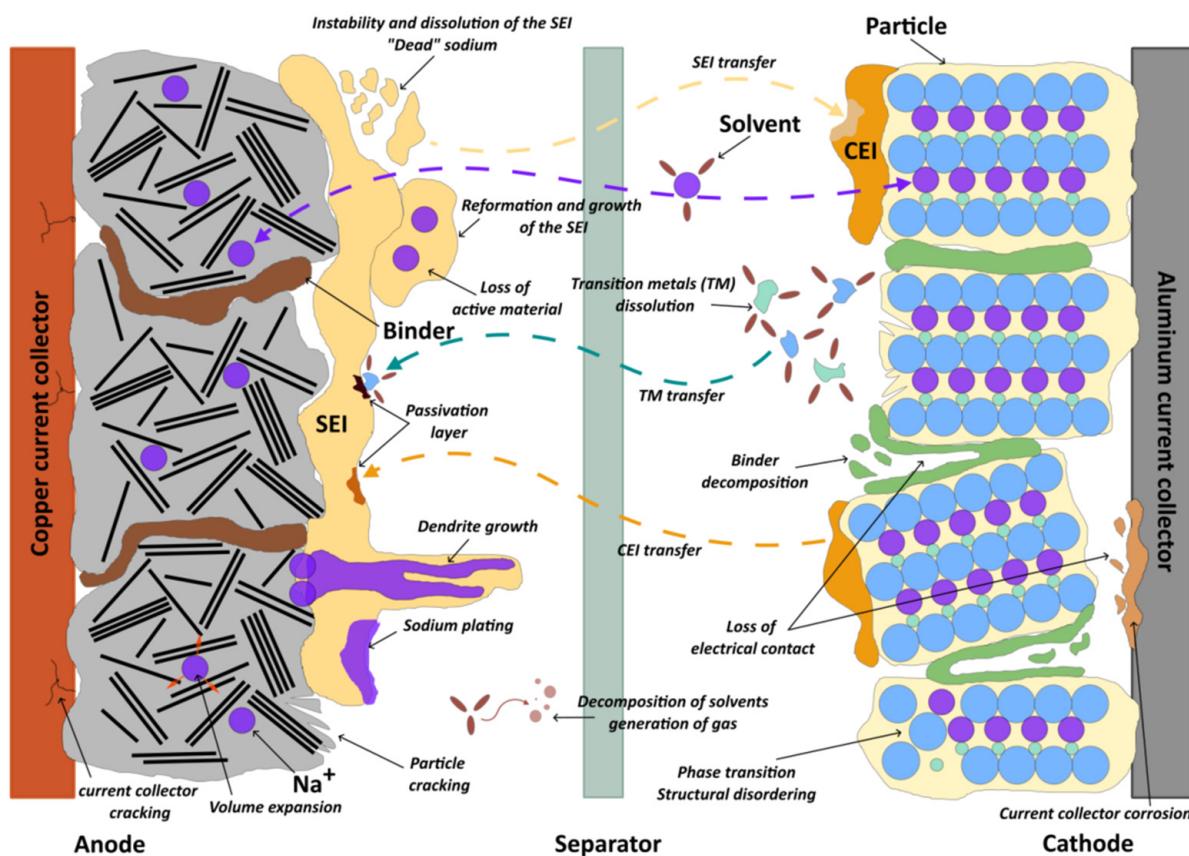


Figure 10. Main aging mechanisms for sodium-ion batteries. Original figure created by the authors, inspired by figures published for lithium-ion batteries in Refs. [135,136]).

A better understanding of these degradation pathways will accelerate the scaling and adoption of this technology. The next section will summarize key degradation mechanisms across technologies and highlight their unique features.

4. Comparison of Degradation Mechanisms Between Different Technologies

Table 2 shows that each technology has its own specific degradation mechanisms. These mechanisms are often linked to their constituent materials. The challenges are therefore not only related to the intrinsic chemistry of the active elements, but above all to the complete electrochemical environment. It is worth noting that for all technologies, mechanical and chemical stability are at the heart of cyclability problems. Problems such as extreme volume changes or the rigidity of solid electrolytes are key issues for the development of these technologies. So, with the main mechanisms at our disposal, it is possible to discuss strategies for material design, choice of additives or interface engineering to reduce their influence. The next section presents some challenges and prospects for these technologies.

Table 2. Summary of degradation mechanisms and specific technologies.

Technology	Main Aging Mechanisms	Features/Interest	Limits/Critical Points
Advanced Li-ion batteries	<ul style="list-style-type: none"> - SEI instability (cracking on Si/C) - Lithium plating (low temperature, overload, high C-rate) - Volume expansion of Si (nearly 300%) → cracks, loss of contact - Dissolution of metals (Mn, Ni, Co) - Resistive CEI on Ni-rich positive electrodes - Electrolyte decomposition at high voltage/temperature - Electrode cracking/delamination - High interfacial resistance (poor contacts) - Parasitic reactions at interfaces - Cracking of rigid electrolytes - Dendrite growth (LiM) - Delamination under mechanical stress - Chemical degradation (e.g., LLZO with humidity) - Possible gas generation (e.g., H₂S) - Shuttle effect of polysulfides - Formation of insulating Li₂S/Li₂S₂ - Lithium dendrites - SEI unstable on LiM - Volumetric expansion of sulfur-positive electrode (>80%) - SEI unstable (especially on hard carbon) → loss of active material - Sodium plating (low temperature) → short circuit - Electrolyte decomposition at high voltage - Irreversible electrode damage - Significant volume expansion - Dissolution of sodium in electrolyte 	<ul style="list-style-type: none"> - Mature, high-performance technology - High energy density - Compatibility with optimized electrolytes - Prospects for improvement with Si and nanomaterials 	<ul style="list-style-type: none"> - Volume expansion of the negative silicon electrode - high-voltage degradation - Unstable CEI (Ni-rich materials) - Cost and criticality of materials (Co, Ni)
Solid-State batteries	<ul style="list-style-type: none"> - Increased safety (no liquid electrolyte) - Potential for lithium metal (high energy density) - Reduced thermal risk 		<ul style="list-style-type: none"> - Unstable solid interfaces - Poor electrode/electrolyte adhesion - Dendrites despite solid electrolyte - Costly and complex to manufacture - Low industrial maturity
Li-S batteries	<ul style="list-style-type: none"> - Very high theoretical capacity - Inexpensive, abundant and non-toxic sulfur - Possibility of enhancement with conductive hosts (carbon, Metal–Organic Framework (MOF)) 		<ul style="list-style-type: none"> - Loss of active sulfur, self-discharge - Low intrinsic conductivity - High volume variation - Unstable SEI - Limited cyclability
Na-ion batteries	<ul style="list-style-type: none"> - Abundant and inexpensive sodium - Better environmental sustainability - Good power performance - Compatible with various electrodes - Greater safety at high temperatures 		<ul style="list-style-type: none"> - Energy density still lower than Li-ion - SEI rather unstable - Volume expansion for some negative electrode materials - Risk of plating

5. Challenges and Prospects

All-solid, lithium-sulfur and sodium-ion batteries represent promising alternatives to current technologies. They offer potential advantages in terms of safety, cost and performance. However, a number of challenges still limit their widespread deployment.

5.1. Current Challenges

Several key challenges continue to hinder the development of emerging battery technologies. Among them, the lack of long-term experimental correlation remains a major limitation. For systems such as solid-state batteries (SSBs), lithium–sulfur, and sodium-ion, there is insufficient cycling data under realistic conditions. This scarcity of feedback makes

it difficult to establish reliable correlations between degradation phenomena and practical durability, complicating the assessment of long-term stability.

In addition, the instability of solid interfaces and new chemistries (sodium and sulfur) pose certain limitations. In all-solid batteries, chemical and mechanical compatibility between electrolyte and electrodes is paramount: internal stresses due to volume variations or local reactions can lead to cracking, delamination or even complete failure of the interfacial contact. Similarly, Li-S and Na-ion batteries suffer from material instability, with polysulfide dissolution in Li-S due to the shuttle effect, and SEI instability in Na-ion. For this reason, further innovation is needed to overcome these limitations.

Beyond the physico-chemical aspects, other challenges limit the development of these technologies. As mentioned above, the lack of feedback from experience is an obstacle to the overall understanding of the new systems, and this lack of maturity makes it difficult to scale-up and industrialize these products. Some manufacturing processes are much more costly on a large scale than in the laboratory. In the case of solid electrolytes, for example, special conditions are required for their manufacture. These generally include high pressures, inert atmospheres and high temperatures [137]. Transposition to production lines is a challenge in itself. In addition, some high-performance materials, such as the lanthanum-based solid oxides used in advanced LIBs [138] or sulfur-based electrolytes, present high costs or critical resources.

The recyclability of these systems is a point of reluctance to accept them. Recycling for lithium-ion technologies is beginning to develop, and prototype production lines are emerging. On the other hand, very few studies exist for new technologies. The development of these new systems must be accompanied by research into recycling. The complex architectures of SSBs and the irreversible reactions in Li-S systems pose difficulties for end-of-life treatment.

When temperature or electrical abuse occurs, batteries can experience catastrophic failure in addition to slow electrochemical degradation. Excessive heat generation or inadequate heat dissipation can cause thermal runaway, a self-accelerating exothermic process that causes fast temperature rise, electrolyte breakdown, and venting. The onset usually occurs in the following order: cathode decomposition ($>200\text{ }^{\circ}\text{C}$), which releases oxygen and intensifies the reaction kinetics, SEI breakdown ($\sim 80\text{--}120\text{ }^{\circ}\text{C}$), and the reaction of the lithiated anode with electrolyte ($\sim 120\text{--}180\text{ }^{\circ}\text{C}$) [139,140]. Although the lower thermal stability of organic electrolytes can cause these thresholds to shift downward, similar processes are seen in sodium-ion systems. Solvent oxidation/reduction and transition-metal-catalyzed breakdown processes produce gas during cycling or misuse. Cell swelling, an increase in impedance, and the accumulation of internal pressure are all caused by gases like CO_2 , CO , H_2 , and hydrocarbons. Na_2CO_3 breakdown in Na-ion cells can also produce volatile species, which further jeopardizes safety [141]. Localized heating and interfacial deterioration are accelerated by electrical abuse situations such internal dendritic bridging, external short circuit, and overcharge. While short circuits cause strong Joule heating that can ignite electrolyte vapors, overcharge causes transition-metal breakdown and oxygen release.

Thus, the long-term dependability and aging control of next-generation batteries depend heavily on safety-oriented techniques (shutdown separators, flame-retardant electrolytes, overcharge protection, and temperature management systems). It is crucial to incorporate these processes into aging studies because, while recurrent small thermal or electrical stressors might not cause failure right away, they can build up over time and encourage gas production, impedance increase, and the loss of active materials.

5.2. Necessary Innovations

With the development of electric mobility, and the need to store more and more energy, the popularity of batteries is growing rapidly. A joint study by the European Patent Office and the International Energy Agency showed that between 2005 and 2018, patent filings relating to batteries and storage technologies increased by almost 14% per year, compared with an average of 3.5% per year for other technological fields [142]. Numerous innovations are thus being proposed, but some appear to be a priority in order to industrialize these systems. Each technology has its own advances and research to mitigate degradation phenomena or overcome scientific barriers. Some innovations in this area will be presented in the following sections.

5.2.1. Advanced Lithium-Ion

As Li-ion technologies are the most widespread, it is essential to find a solution to the most compromising mechanisms. Several studies are attempting to eliminate lithium dendrites and stabilize the SEI. To do this, a study is working on the design of a new liquid electrolyte capable of inhibiting dendrite formation by ensuring uniform lithium deposition on the negative electrode [143,144]. This development represents a significant step forward for the use of lithium metal electrodes.

Silicon anodes offer very high capacity for lithium-ion batteries, but their significant expansion during lithiation/delithiation and the formation of an unstable SEI limit their practical application. To solve this problem, one study proposes coating the silicon anode with a protective layer composed of aluminum fluoride and polyacrylic acid, which promotes the formation of a stable LiF-rich SEI. This can mitigate volume changes during cycling. Thus, it has been demonstrated that these electrodes could be used for new-generation high-energy-density systems [145,146].

Finally, we can note the development of non-flammable electrolytes. For industrial development, the risk of ignition is a huge challenge. A study has therefore looked at non-flammable electrolyte formulations. The aim is to increase thermal stability and reduce the formation of gases such as CO₂ and CO, thereby reducing the risk of swelling and thermal runaway [147,148].

Yet, most of these strategies are demonstrated under controlled laboratory conditions, and their performance under realistic automotive or grid-storage environments remains largely unknown. The gap between laboratory results and industrial feasibility suggests that many of these approaches may still require years of development before large-scale implementation.

5.2.2. SSB

In all-solid-state batteries using a lithium metal or sodium metal electrode, one of the major problems is the formation of dendrites during cycling. Several studies are attempting to develop a solution to mitigate this phenomenon. One of these involves depositing a buffer layer composed of tin and carbon on the current collector. Tin promotes the uniform deposition of lithium (or sodium) metal, thereby reducing the sites of dendrite nucleation. Carbon acts as a physical barrier that prevents the growth of dendrites due to its lithiophobic nature [149,150].

The electrode/electrolyte interface is crucial to the performance of these systems. Poor adhesion at this interface can promote dendrite formation or cause layers to detach, leading to increased interfacial resistance. Studies propose electrolyte coatings to improve adhesion between the electrodes and the electrolyte. These coatings act as intermediate layers to promote contact. These materials are particularly suitable for LLZO-based and sulfide-based electrolyte systems [151,152].

We have seen previously that LLZO is a promising solid electrolyte for all-solid-state batteries, particularly due to its high ionic conductivity and thermal stability. However, it is highly sensitive to moisture and CO₂ in the air. Once exposed, chemical reactions occur and degrade the LLZO, which can compromise these systems. To improve the atmospheric stability of LLZO, doping with gallium and tantalum has been considered. The introduction of these elements has made it possible to modify the electronic density and chemical stability of the material. But also, to form more stable chemical bonds. These methods have shown a clear improvement in the stability of LLZO to moisture and CO₂ [153]. Another study shows similar effects with other doping elements [154].

Contradictory findings are reported regarding the efficiency of interlayers and coatings in suppressing dendrites. While some studies show nearly complete suppression under low current densities, others still observe dendrite penetration at higher cycling rates. This suggests that current solutions remain highly dependent on testing conditions, raising concerns about scalability.

5.2.3. Li-S

As with other technologies, several solutions are being developed to mitigate degradation phenomena. One strategy is to use highly conductive carbon hosts. The aim is to confine sulfur and polysulfides through physical adsorption and to provide greater electronic conductivity. This results in an improvement in usable capacity and cyclability. However, adsorption alone may not be sufficient to retain polysulfides over the long term [155,156].

Another interesting strategy is to modify the separator to mitigate the shuttle effect caused by polysulfides. Conventional separators are inert and only play a mechanical and electrical insulation role. For Li-S systems, it is possible to modify them and add a functional interlayer to trap, filter, or reconvert soluble polysulfides. These interlayers can be conductive, catalytic, or hybrid. This significantly improves coulombic efficiency and stabilizes cyclic capacity. However, there is a risk of increasing ionic resistance if the layer is too thick and not very permeable to Li⁺. The addition of these layers also has a negative impact on volume density [157,158].

New architectures are also proposed to limit phenomena such as dendrites or the shuttle effect using protective coatings or three-dimensional host materials for sulfur [159]. Researchers have developed a solid β-Li₃N electrolyte that offers high ionic conductivity and enhanced resistance to dendrite formation. This has enabled the production of high-performance prototypes with a lithium metal negative electrode for lithium-sulfur batteries [160,161].

Although these strategies improve cycling stability in small-scale cells, they often compromise volumetric energy density or add complexity to the system architecture. This trade-off is rarely addressed in the literature, leaving open the question of whether such solutions are viable for real-world applications.

5.2.4. Na-Ion

Sodium-ion batteries face numerous obstacles. One of these is the instability of the SEI, which has a significant impact on longevity. A poorly formed SEI leads to irreversible sodium loss, increased interfacial resistance, etc. One study proposes the formulation of a “tailor-made” electrolyte aimed at achieving an optimal organic/inorganic balance in the SEI. The main idea is not to eliminate NaF, which is useful for chemical stability, but to avoid excess NaF and combine it with a controlled organic fraction to form a thin, uniform SEI. As a result, the coulombic efficiency on the tested cells is greater than 99.9% after 500 cycles, indicating very low sodium loss. This process is therefore a remarkable solution

but needs to be tested over thousands of cycles and under different conditions for industrial feasibility [162,163].

During the operation of Na-ion systems, part of the cyclable sodium is consumed in the first cycles by the formation of the SEI. This results in a net loss of active sodium and an immediate reduction in the reversible capacity. A study proposes the introduction of an external reservoir to perform pre-sodiation to compensate for the irreversible loss of sodium. The consumed sodium then comes from an external source. This solution shows an improvement in energy density, increased cyclability and a coulombic efficiency greater than 95% [164,165].

Finally, we can discuss the limitations of liquid electrolytes in these systems. Indeed, the high mobility of organic solvents leads to migration of parasitic species and instability of the electrode/electrolyte interface. As with Li-ion batteries, the risk of flammability is a problem. Finally, the absence of a mechanical barrier does not allow to stem the growth of dendrites. Thus, several studies propose the use of solid or partially solid electrolytes for these systems [103,166,167]. Quasi-solid or gel electrolytes reduce the mobility of solvents and solid electrolytes offer ionic conductivity of the order of mS/cm but mechanically block the growth of dendrites. Thus, these electrolytes represent a promising solution to improve the safety of these systems. Their success, however, depends on the reduction in interfacial resistances [168,169].

Most reported improvements in SEI design or pre-sodiation are demonstrated over a few hundred cycles, while practical applications require several thousand. The absence of long-term data, particularly under variable temperatures, is a critical gap that must be addressed before industrial deployment.

5.2.5. Degradation Analysis and Performance in Emerging Batteries

It is also the use of accelerated aging protocols adapted to each technology that will allow an advanced understanding of what is happening in the system under conditions as close as possible to reality. Standardization is therefore a major advantage for making results more reliable. The idea would then be to base oneself on international standards such as norms and protocols. For example, there is the IEC 62660 standard [170] which defines the test methods for lithium-ion batteries used in electric vehicles. It also includes cycling and calendar aging protocols. This standard therefore makes it possible to define a framework for evaluating batteries.

The US Department of Energy has also published a set of experimental protocols under the name US DOE Battery Test Protocols aimed at standardizing tests for energy storage systems.

We are then seeing several attempts to standardize the methods. In addition to standardizing methods, one could very well imagine proposing a minimum dataset for the quality and comparability of experimental studies. The idea would then be to introduce parameters such as operating temperature, SoC window, C-rate, monitoring impedance by electrochemical spectroscopy, etc.

Another key limitation of current literature is the tendency to study degradation mechanisms in isolation. In practice, most aging pathways are coupled: cathode dissolution accelerates SEI breakdown, gas generation promotes particle cracking, and mechanical stresses exacerbate electrochemical instabilities. Such interdependent effects are rarely quantified systematically, yet they are crucial to build accurate predictive models. Future research should therefore focus on integrated, multiphysics approaches that capture these couplings rather than treating each degradation mode as an independent phenomenon.

The analysis of degradation mechanisms is primarily used to evaluate state of health (SoH), often supported by predictive modeling over time or using equivalent circuit

model [171–173]. However, current models rarely integrate the full coupling of thermal, mechanical, chemical, and electrical phenomena. The integration of artificial intelligence (AI) holds great promise to advance multiphysics models, enhancing degradation prediction and battery management system (BMS) optimization. Data-driven techniques have become increasingly effective in recent years for analyzing and forecasting battery deterioration. Through the direct extraction of degradation patterns from sizable datasets, these methods supplement experimental and mechanistic investigations. Techniques for machine learning (ML) and deep learning (DL) have been effectively used to forecast end-of-life behavior, estimate state-of-health (SoH), and find patterns in cycling data. Indirect insights into aging mechanisms can also be obtained by using data-driven models to help extract features from electrochemical impedance spectroscopy (EIS) or incremental capacity analysis (ICA). Recent developments create hybrid or “physics-informed” frameworks that connect empirical data to mechanistic insight by fusing physics-based and machine learning models. These methods preserve the interpretability of the underlying degradation phenomenon while increasing forecast accuracy. Despite their potential, there are still issues with data accessibility, uniformity, and transferability between various chemistries (LIBs, SSBs, Li-S, and Na-ion). By incorporating these techniques into degradation analysis, next-generation battery systems could be better understood and optimized more quickly.

Finally, limiting the dissolution of active species would increase the durability of these batteries. Encapsulation methods are being developed for sulfur in particular. Sulfur is trapped in carbon nanospheres to minimize the loss of active sulfur and thus increase cyclability [174]. A similar process is used for zinc-air batteries [175]. Figure 11 attempts to show the volumetric and gravimetric energy density for several battery cells.

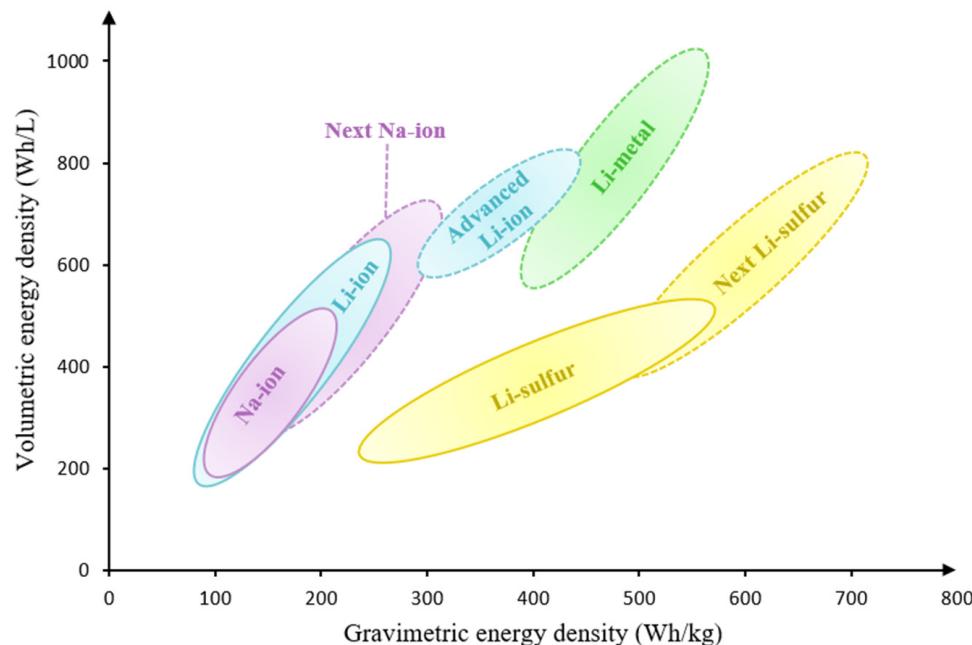


Figure 11. Comparison of volumetric and gravimetric energy for several battery cells and future battery cells. Original figure created by the authors using information from references [10,57,103,176–185].

There is therefore a great deal of innovation in the field of batteries, particularly in new technologies. The aim is to increase performance, reduce costs and improve durability. According to recent studies, advanced Li-ion batteries could achieve an energy density of over 350 Wh/kg [181]; sodium-ion batteries from 220 to over 250 Wh/kg [182,183]; lithium-sulfur batteries over 500 Wh/kg [184,185]; and finally, for all-solid batteries using a

lithium metal negative electrode, more than 400 Wh/kg [103]. Figure 12 shows the Ragone diagram based on several datasheet for emerging battery technologies.

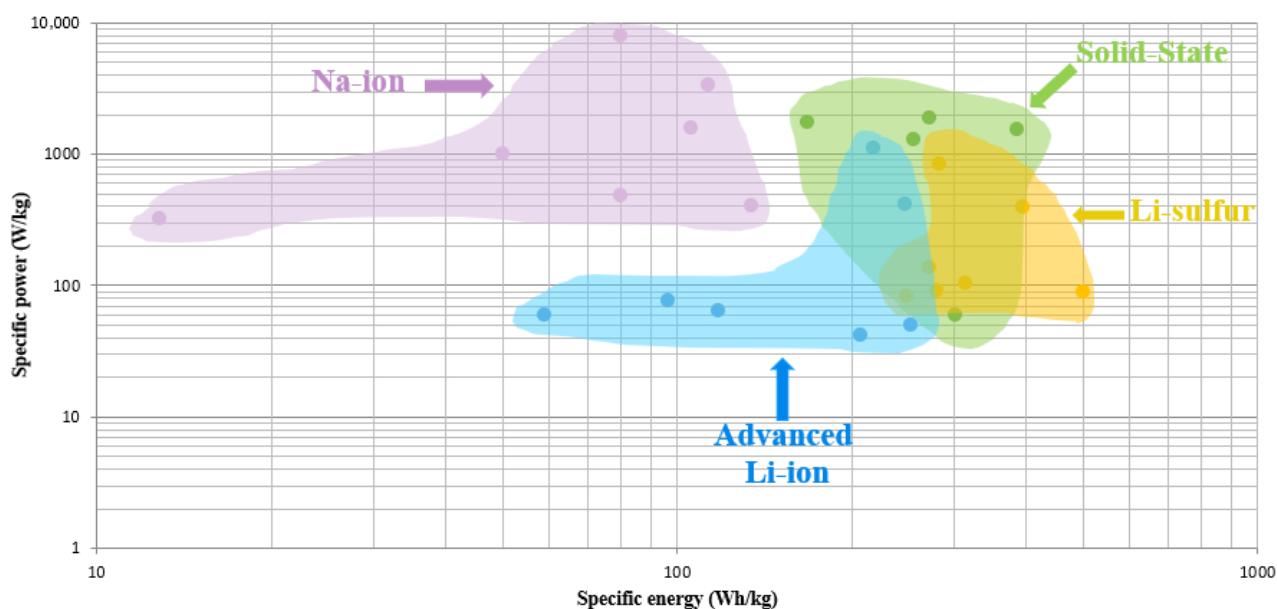


Figure 12. Ragone diagram for several emerging battery categories based on experimental data. Original figure created by the authors using information from references [186–207].

These prospects clearly illustrate the potential of these technologies to meet the needs of mobile and stationary applications.

6. Conclusions

New-generation batteries offer compelling prospects to meet increasing global demands for higher energy density, cost-effectiveness, enhanced safety, and longer durability. However, their industrial deployment remains significantly limited by an incomplete understanding of their ageing mechanisms, which vary considerably depending on the chemistry and architecture of the system.

This review has identified the dominant degradation pathways in several emerging technologies. These mechanisms, ranging from interfacial instabilities, irreversible parasitic reactions, mechanical stress, to active material loss, are numerous and interdependent. Despite differences in chemistry, several degradation phenomena appear common across technologies, including interfacial layer instability, accumulation of inactive species, increased internal resistance, and loss of cyclable lithium or sodium. Conversely, technology-specific degradation mechanisms persist, such as the shuttle effect in Li-S systems or sodium plating in Na-ion batteries.

Overall, one major limitation across emerging chemistries is the lack of standardized aging protocols. Reported degradation rates often vary not only with chemistry but also with testing methodology, making it difficult to compare results across studies. Similarly, most reports focus on short-term cycling, while systematic long-term data under realistic conditions remain scarce. Finally, recycling strategies for SSBs, Li-S, and NIBs are still largely unexplored, representing an underdeveloped but critical research direction for sustainability.

Future advances will require integrated strategies combining accelerated testing, multi-scale modelling, operando characterization, and post-mortem analysis, ideally within standardized frameworks to facilitate cross-study comparisons. The convergence of these approaches, possibly enhanced by artificial intelligence, could yield predictive models

capable of optimizing battery design and battery management systems. It is clear that mastering degradation mechanisms represents a strategic lever for turning emerging battery chemistries into reliable, sustainable, and scalable technologies for future energy systems. Finally, it is worth stressing that many of the most publicized announcements on next-generation batteries often extrapolate short-term laboratory data to long-term industrial projections. Bridging this gap will require not only materials innovation but also rigorous protocol standardization, transparent reporting, and independent benchmarking, without which performance claims remain difficult to validate.

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