


Review article

From lithium to sodium: critical metals for next-generation energy storage

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ABSTRACT

The global transition to renewable energy and electrified transport depends on scalable, affordable, and secure battery storage technologies. Lithium-ion batteries (LIBs) currently dominate this sector due to their high energy density, long cycle life, and mature manufacturing infrastructure. However, increasing demand for lithium, cobalt, and nickel has exposed major supply chain vulnerabilities, including geographic concentration, refining bottlenecks, price volatility, environmental impacts, and social concerns associated with critical metal extraction. This study aims to critically compare lithium- and sodium-based battery technologies by examining their electrochemical fundamentals, critical material requirements, supply chain risks, environmental footprints, technical limitations, commercial readiness, and application-specific suitability. The study finds that sodium-ion batteries (SIBs) offer important strategic advantages due to the abundance and wide distribution of sodium, reduced dependence on cobalt and nickel, compatibility with aluminium current collectors on both electrodes, and potential cost and sustainability benefits in stationary and low-cost mobility applications. Key technical findings show that SIBs still face lower gravimetric and volumetric energy density, slower ion transport, hard carbon initial Coulombic efficiency losses, cathode phase instability, and electrolyte/interface challenges. Nevertheless, recent advances in hard carbon anodes, layered oxide cathodes, polyanionic frameworks, Prussian blue analogues, and electrolyte engineering are narrowing the performance gap. All in all, LIBs and SIBs are best understood as complementary technologies: LIBs will remain dominant in high-energy mobile applications, while SIBs are strategically positioned for grid storage, backup power, and micromobility, supporting a more resilient and diversified energy storage future.

1. Introduction

The global ambition for a decarbonised energy system is driving the rapid growth of renewable energy sources, such as wind and solar, which are inherently variable and weather-dependent. To ensure a stable and reliable energy supply, these resources must be paired with

efficient and scalable storage technologies. Batteries, in particular, have emerged as the cornerstone of this transition, acting as buffers that smooth out fluctuations, enable load shifting, and integrate renewables into power grids at scale. Beyond grid applications, batteries are also driving the electrification of transport, portable electronics, and emerging sectors like aviation and shipping. Their pivotal role in

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bridging the gap between intermittent renewable generation and consistent energy demand underscores that the future of clean energy is inseparable from advancements in battery technology (Armand and Tarascon, 2008; Sheth et al., 2023; Nykvist and Nilsson, 2015; Abdulsalam et al., 2024).

Lithium-ion batteries (LIBs) have so far dominated the global market owing to their high energy density, long cycle life, and mature manufacturing base. However, lithium resources are geographically concentrated in only a few regions, primarily the ‘Lithium Triangle’ of Chile, Argentina, and Bolivia, along with Australia and China, making global supply chains vulnerable to market fluctuations and geopolitical constraints. The extraction and refining of lithium, cobalt, and nickel, critical metals in most LIB chemistries, pose significant environmental and social concerns, including water scarcity in arid regions, high carbon emissions, and adverse community impacts near mining sites (International Energy Agency IEA, 2024; Olivetti et al., 2017; Harper et al., 2019). These limitations highlight that while LIBs have been transformative, their sustainability and scalability are increasingly questioned as global electrification accelerates. This aligns with broader evidence that critical mineral supply chains are structurally shaped by geopolitical competition, uneven development, and resource nationalism dynamics (Fernández et al., 2026; Ackah-Baidoo, 2025). Fig. 1 illustrates the geographically concentrated nature of lithium resources and the global flow of materials to battery manufacturing hubs and highlights key environmental and social risks associated with extraction, including water scarcity and emissions.

The energy storage market is projected to increase fourfold by 2030 from a 2018 baseline, primarily driven by the adoption of electric vehicles (EVs) and renewable energy penetration (U.S. Department of Energy, 2020). Fig. 2 shows the projected trend of the global energy storage market from 2018 to 2030. The proliferation of electric vehicles and a growing demand for electricity storage are connected to rising shares of variable renewables in the electricity supply mix. The integration of these rising volumes of variable electricity requires key enabling technologies, such as battery storage, to grow as well. The projected global demand for energy storage is expected to place significant pressure on existing battery supply chains, which are dominated by LIBs. Specifically, the reliance of LIB technologies on certain critical minerals has strained their supply chains, and recent studies have questioned their availability to meet rising demand (IEA, 2025). There are global strategic concerns and power imbalances in critical mineral supply chains, driven by increasing supply chain vulnerabilities and potential disruptions. This has raised concerns about energy security, especially as it relates to the supply chains of critical minerals (Kalantzakos, 2020; Abdulsalam et al., 2024). Recent work in critical minerals further highlights that mineral “criticality” is not purely geological but is actively produced through policy, market narratives, and geopolitical structuring of supply networks (Runganga et al., 2025; Vivoda et al., 2026). These concerns have introduced the need for diversification of energy storage technologies and securing complementary solutions to emerging technologies, and their associated critical mineral demands (Boafo et al., 2024; Shen et al., 2018).

In response to concerns about the sustainability and scalability of

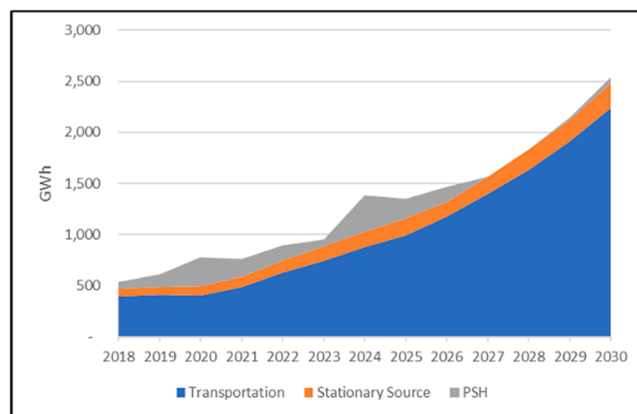


Fig. 2. Global energy storage market (Source: U.S. Department of Energy, 2020).

LIBs, sodium-ion batteries (SIBs) have re-emerged as a compelling alternative. Sodium, the sixth most abundant element in the Earth’s crust, is widely distributed in both seawater and mineral deposits, eliminating the risk of geographic concentration and ensuring long-term availability (Yabuuchi et al., 2014; Slater et al., 2013). The primary limitation of Sodium is its larger ionic radius and lower electrochemical potential, which result in a lower energy density than lithium. However, advances in electrode design, electrolyte optimisation, and interface engineering have significantly narrowed this performance gap (Hwang et al., 2017; Pan et al., 2013). Critically, SIBs do not rely on scarce or costly metals such as cobalt and nickel, and in many designs can employ aluminium current collectors for both cathodes and anodes, further reducing cost and material dependence (Salam et al., 2026;). These advantages make sodium-based technologies desirable for stationary grid storage, backup power, and other applications where cost, safety, and sustainability outweigh energy density requirements.

The study is positioned at the intersection of electrochemical performance, critical mineral security, environmental sustainability, and commercial deployment of next-generation battery technologies. Its scope extends beyond a conventional materials analysis by comparing lithium-ion and sodium-ion batteries across the full technology chain: critical metals, electrode and electrolyte design, life cycle impacts, supply chain vulnerability, application suitability, recycling, and policy support. The paper treats lithium and sodium not merely as electrochemical charge carriers but as strategic materials whose availability, processing routes, geopolitical exposure, and end-of-life pathways will shape the scalability of future energy storage systems. This framing is important because the study argues that lithium-ion batteries currently dominate high-energy applications, while sodium-ion batteries are increasingly relevant for stationary storage, micro-mobility, backup power, and cost- and sustainability-sensitive sectors.

The central objective is to clarify whether SIBs should be understood as direct replacements for LIBs or as complementary technologies within a diversified storage portfolio. Current literature often examines either

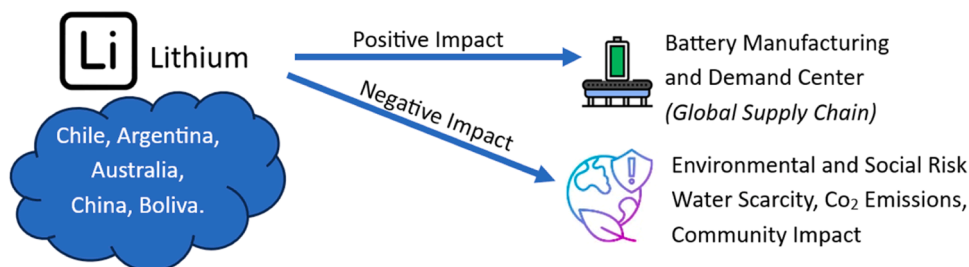


Fig. 1. Global LiB supply risk and environmental impact.

lithium-ion supply risks or sodium-ion electrochemistry in isolation, leaving a gap in integrated assessments that connect materials chemistry with market segmentation, resource security, manufacturing compatibility, environmental impact, and real-world deployment. This study addresses that gap by examining and bringing together technical and strategic evidence into a comparative framework that explains where each chemistry is most reliable. It highlights that lithium-ion technologies remain superior where gravimetric and volumetric energy density are dominant, particularly in long-range electric mobility, whereas sodium-ion technologies offer advantages where cost stability, material abundance, safety, and supply chain resilience are more decisive.

The novelty of the paper lies in its integrated systems-level contribution. Rather than presenting SIBs only as an emerging laboratory chemistry, the study links their electrochemical constraints (larger Na⁺ ionic radius, lower operating voltage, hard carbon inefficiencies, cathode phase instability, and electrolyte/interface challenges) to broader questions of industrialisation, policy, recycling, and sustainability. This enables a balanced conclusion: SIBs do not eliminate the need for LIBs, but they reduce dependence on critical lithium, cobalt, and nickel supply chains and can strengthen the resilience of global energy storage deployment. The study, therefore, contributes a technically grounded roadmap for battery diversification in the clean energy transition.

However, despite recent advances in SIBs highlighting their unique electrochemical properties (Deshmukh et al., 2025) and in LIBs focusing on energy density (Cao et al., 2020), there remains a paucity of studies that provide an integrated framework for comparing both battery storage systems. This review presents a comparative analysis of lithium and sodium as critical metals for next-generation energy storage. It explores their electrochemical fundamentals, innovations in electrode and electrolyte materials, environmental and supply chain implications, and real-world case studies of emerging commercial applications. It further considers the future outlook for lithium- and sodium-based batteries, emphasising the potential for coexistence, the role of computational materials design, and the importance of aligning battery innovation with global energy transition goals. The first section of this paper provides an evaluation of the critical metals required for LIB technologies, followed by an examination of the drivers of transition to sodium. This is followed by a deep dive into SIB Technology and the critical minerals required for this technology. The paper then considers case studies and industry development initiatives on battery storage systems and examines the success, challenges, and lessons learned in each case. Fig. 3 presents a structured comparison between lithium- and sodium-based batteries across key dimensions and integrates electrochemistry, materials, environmental performance, and supply chain considerations. The framework highlights the potential for complementary roles in future energy storage systems. SIB development continues to gain traction in the body of literature (Masemola and Dorrell, 2025; Deshmukh et al., 2025; Song et al., 2025; Cui et al., 2025).

2. Critical metals in lithium - ion batteries

The global transition to electromobility has driven exponential

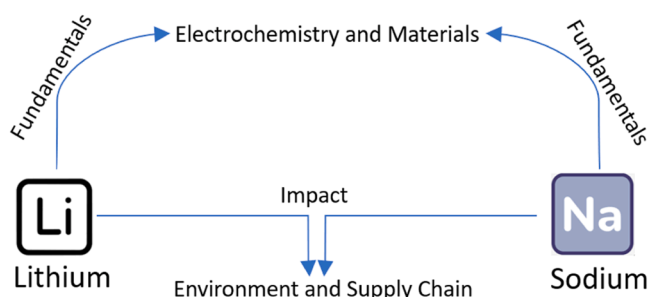


Fig. 3. Comparative framework: lithium vs batteries.

growth in the demand for LIBs. This has raised questions about the sustainability of critical metals required for this expansion. Different LIB battery chemistries require distinct combinations of Lithium, Cobalt, Nickel, Manganese and Iron, which create unique supply chain profiles. Lithium and cobalt, in particular, face acute supply chain risks due to geographically concentrated production and China's control over midstream and downstream refining (Tan and Keiding, 2023). This section explains the significance of these critical elements and explores their underlying supply risks and environmental challenges, setting the stage for alternative chemistries that reduce these critical material dependencies.

Supply chain vulnerability in batteries is rarely determined by geological scarcity alone; rather, it is shaped by bottlenecks that emerge when extraction, refining, chemical conversion, and cell manufacturing are concentrated geographically or corporately. A useful way to formalise this is to distinguish a) upstream risk (resource access, permitting timelines, grade decline, water and energy intensity), b) midstream risk (chemical conversion and refining capacity, process know-how, environmental compliance, and trade restrictions), and c) downstream risk (cell manufacturing concentration, equipment supply, and intellectual property constraints). In practice, lithium, cobalt, and nickel illustrate how midstream concentration can dominate overall risk even when multiple producing countries exist. A diversified mining base, for example, may not translate into resilience if conversion into battery-grade salts is constrained by a small number of refineries, specialised reagent supply, or high-temperature processing equipment. This bottleneck logic is central to comparing lithium-ion and sodium-ion pathways because sodium-ion reduces reliance on cobalt and nickel in many designs, but still depends on industrial chemical supply chains for salts, solvents, binders, and high-purity precursors. Following this train of thought, resilience should be interpreted as the robustness of the full chain rather than the availability of raw ore or brine alone.

2.1. Lithium

Lithium remains indispensable in all LIBs, serving as the primary charge carrier in both the cathode and the electrolyte (Koech et al., 2024). The concentration of global production and growing demand remain constraints on its availability. With an extremely low standard reduction potential of -3.05 V at 298 K, lithium offers a high capacity of about 3860 mAh/g which is crucial for achieving high density and voltage in lithium-ion cells (Varzi et al., 2020). Yet, supply issues persist; while vital to LIBs, lithium is primarily concentrated in Chile, Australia, and Argentina, which hold 74% of the world's lithium reserves (Rapier, 2024). Meanwhile, as mentioned earlier, China dominates the downstream lithium trade, accounting for 66.01% of the market (Alessia et al., 2021; Wang et al., 2023). This creates geopolitical vulnerabilities and supply risks, as evidenced during the COVID-19 pandemic, when China's production fell below 50%, disrupting global trade flows (Althaf and Babbitt, 2021). The extraction of lithium from hard rock (spodumene) or brine has significant environmental impacts, including substantial water use, carbon emissions, and land degradation (Das et al., 2025; Wu et al., 2025). These environmental impacts are even more pronounced when critical minerals are sourced from artisanal and small-scale operations (Eniowo, 2025; Eniowo et al., 2024; Owolabi et al., 2024; Zvarivadza, 2018; Zvarivadza and Nhleko, 2018). Although extraction from brine generates fewer greenhouse gas emissions (2.7–3.1 tonnes CO₂/tonne Li₂CO₃), the process is susceptible to climatic conditions due to low recovery efficiency and the significant water resources required (Kelly et al., 2021). In addition to extraction, lithium supply is strongly shaped by chemical conversion routes that determine cost, emissions, and the feasibility of rapid scaling. Hardrock spodumene typically requires comminution, concentration, high-temperature conversion (often through calcination), and leaching before precipitation to lithium carbonate or conversion to lithium hydroxide, which introduces energy intensity and process emissions that

depend on the electricity and heat source used in the region of refining. Brine routes rely on concentration and precipitation steps whose timelines and yields depend on climate, impurity chemistry, and evaporation management, which can extend working capital cycles. These conversion characteristics matter because battery cathode supply increasingly requires consistent high purity lithium salts with tight impurity specifications (for example, trace metals, moisture) that can affect cathode synthesis, cycle life, and safety. Emerging direct lithium extraction (DLE) concepts aim to shorten brine processing time and reduce land footprint; however, their large-scale environmental advantage depends on sorbent selectivity, regeneration chemistry, and brine reinjection strategy, as well as local water governance. It can be noted that the sustainability and resilience of lithium are shaped not only by where lithium occurs, but by the industrial maturity and environmental performance of the conversion pathway to battery-grade salts. To mitigate these environmental impacts, recycling has emerged as a safer option for lithium recovery. However, it faces technical challenges; the makeup of LIBs plays a critical role in defining which recovery method is most suitable. The most common approaches (hydrometallurgical and pyrometallurgical) can be energy-intensive and reagent-intensive, posing challenges for achieving large-scale circularity (Báña and Kazda, 2025). Given the geopolitical supply risks and environmental concerns associated with lithium, there is growing interest in more abundant alternatives, such as sodium and calcium.

2.2. Cobalt

Cobalt plays a crucial role in lithium-ion batteries by enhancing energy density and cycle life, thereby improving overall cathode performance. In layered cathode chemistries like NCA/NMC, Cobalt prevents cation mixing disorder and restrains phase change, thereby improving the overall structural stability of the LIB (Hussain and Bang, 2024). At the materials level, cobalt plays multiple stabilising roles in layered oxide cathodes beyond a simple contribution to capacity. It can influence cation ordering, reduce the tendency for transition metals to migrate into lithium layers during deep delithiation, and improve structural reversibility under high voltage operation. When cobalt content is reduced, Ni-rich layered oxides can become more susceptible to surface reconstruction (formation of rock-salt-like phases), micro-cracking driven by anisotropic lattice strain, and accelerated parasitic reactions with the electrolyte at a high state of charge. These degradation mechanisms manifest as impedance growth, oxygen release risk at elevated temperature, and capacity fade over repeated cycling, particularly under fast charging or high-temperature storage. As a result, the transition to low cobalt or cobalt-free cathodes is not solely a compositional substitution exercise; it is a coupled design problem involving particle morphology (single crystal vs polycrystalline), surface coatings, electrolyte additives, and charging protocols that constrain high voltage exposure. This complexity helps explain why cobalt remains difficult to eliminate entirely in certain high-energy cathode families, even as the industry seeks to reduce its use for ethical and geopolitical reasons. Innovations in cobalt-free cathodes have emerged through the use of Co-free single crystals, core-shell structures, and substitution with other metals, as well as ongoing research to improve their electrochemical stability. However, it still faces economic viability barriers (El Kouihien et al., 2025). Cobalt use is constrained sustainably by ethical and geopolitical issues. For example, more than half of the world's cobalt is mined in the Democratic Republic of Congo (DRC), where supply chains are often linked to child labour, hazardous working conditions, and exploitation in artisanal mines (Niri et al., 2024; Farjana et al., 2019). Also, China controls the Cobalt refining sector, leaving the rest of the world vulnerable to supply. The influence of corporate control on supply risk is low at the mine stage but high at the refining stage, due to China's strong control over its domestic production (Ericsson et al., 2024). These issues are now driving innovation into chemistries that reduce reliance on cobalt. The general demand for cobalt is forecast to grow by

200–500% over the next three decades, underscoring the strategic importance even as the world pursues alternatives (Alves Dias et al., 2018). Recycling is seen as a strategic alternative; reported that by 2050, recycling would provide 25% of cobalt demand, alleviating water and energy needs, and reducing carbon emissions (Golroudbary et al., 2022). While the supply risks of cobalt remain evident and demand is forecast to keep growing, a sustainable approach is to focus more research on recycling and promote innovation in cobalt-free alternatives.

2.3. Nickel

Nickel plays a critical role in the cathodes of LIBs by enhancing both their capacity and energy density. Nickel is predominantly utilised in layered-chemistry cathodes, such as nickel-manganese-cobalt (NMC) and nickel-cobalt-aluminium (NCA). Due to its high density and relatively low cost, the use of nickel in NMC cathodes has surged, rising dramatically from 33% to 90% to achieve greater performance (Koech et al., 2024; Purwanto et al., 2022). Nonetheless, at elevated temperatures, structural degradation can occur, primarily driven by the formation of rock salt layers, which hinder lithium-ion diffusion between the anode and cathode, ultimately leading to capacity fading (Ahangari et al., 2024). Moreover, the increasing dependence on nickel and the dominance of its refining processes introduce significant technical and supply challenges. To address these issues, innovations in materials and recycling methods have been proposed as effective solutions.

A more complete assessment of nickel criticality should account for how nickel-rich cathodes shift the dominant failure modes of lithium-ion cells. Increasing nickel content typically raises capacity but also increases the chemical reactivity of the charged cathode surface, which can accelerate electrolyte oxidation and gas generation. The resulting interfacial instability promotes cathode-electrolyte interphase (CEI) growth and impedance rise, reducing power capability and increasing thermal management demands. In addition, Ni-rich cathodes can experience greater oxygen activity at a high state of charge, which can amplify exothermic reactions during abuse conditions. These considerations imply that nickel dependence is linked not only to supply and sustainability, but also to safety engineering burdens and lifetime uncertainty when cells are operated aggressively. From a systems perspective, if higher nickel content requires more conservative operating windows or more complex thermal control to achieve acceptable durability and safety, then part of the 'energy density advantage' is converted into system-level cost and complexity. This reinforces the broader thesis that material selection and criticality must be evaluated alongside real operating constraints, not only theoretical energy performance.

2.4. Manganese

Manganese is a critical, less toxic, and cost-effective element primarily used in NMC and Lithium Manganese Spinel chemistries. It provides both chemical and structural stability to LIB cathodes, offering good rate capability. This capability helps stabilise the cathode by enabling rapid, efficient charging and discharging while maintaining capacity and temperature (Koech et al., 2024). However, the instability of the electrochemically active Mn^{3+} ion makes the battery susceptible to structural damage and capacity loss under high temperatures and frequent cycling. This degradation is associated with the destructive Jahn-Teller distortion and manganese dissolution. Researchers have noted that these issues can be mitigated through doping with specific metal ions, dual-doping, and the application of acid-resistant coatings (Koech et al., 2024). Manganese serves as a more environmentally friendly cathode material for LIBs due to its high abundance, lower production impact, and efficient recovery. As the 12th most abundant element in the world, with an approximate world reserve of 18 million tonnes, manganese helps alleviate ethical and geopolitical concerns

(Rajagopalan et al., 2022). In terms of environmental footprint, manganese has a relatively low global warming potential of 4–6 kg CO₂, compared to nickel's 7.64 kg CO₂ and cobalt's 11.73 kg CO₂. Furthermore, manganese is highly recoverable, achieving 98% recovery with the hydrometallurgical approach, though it is water-intensive. This makes manganese an attractive option with significant recovery potential (Zhang et al., 2018).

2.5. Iron and phosphate

Iron and phosphate are more abundant, safer, and sustainable alternatives used in LFP cathode chemistries (Abubaker et al., 2024; Balakrishnan et al., 2021). LIBs with LFP cathode chemistries are stable and environmentally friendly, which allows their usage in a wide range of temperatures between –20 and 150°C (Yang et al., 2002). However, they have lower energy density due to their low electronic conductivity (Balakrishnan et al., 2021). This has led to exploration into modifications of the LFP; the two most effective methods to improve electrochemical performance are carbon coating and doping (Yang et al., 2015). LFP chemistries have lower supply risk, which makes them increasingly attractive for Battery Energy Storage Systems (BESS) and EV applications (Cheng et al., 2024). Recycling of iron and phosphate is not economically attractive because of the low metal value (Zhang et al., 2025). Iron-phosphate chemistries (including LFP and emerging manganese-enhanced variants such as LMFP) demonstrate how abundant elements can support commercially successful batteries when safety and durability are prioritised over maximum energy density. The strong P-O bonding in phosphate frameworks improves thermal stability and suppresses oxygen release, which contributes to a wider safety margin under abuse conditions. At the same time, the lower operating voltage and lower electronic conductivity impose an engineering requirement for conductive networks, carbon coatings, and optimised electrode architecture to maintain power capability at practical loadings. This trade space is relevant to sodium-ion development because many sodium cathode families also emphasise structural stability, safer redox chemistry, and reduced reliance on scarce metals. In other words, the success of LFP provides a precedent: a battery chemistry can dominate large markets when it aligns with manufacturing scale, cost stability, and safety requirements, even if it is not the highest-energy option. This precedent supports the view that sodium-ion batteries can scale rapidly in segments where energy density is a secondary constraint and where cost and critical-material resilience are valued. Table 1 provides a quick reference for the critical metals in LIB, their key Roles, Supply Chains, and Sustainability Challenges.

3. Drivers for transition to sodium

A technically grounded discussion of SIBs should explicitly separate intrinsic thermodynamic limits from engineering and materials gaps that can be narrowed through innovation. At the cell level, stored energy is the integral of voltage over delivered capacity, commonly expressed as $\int V(Q) dQ$. Since sodium has a less negative standard reduction

potential than lithium, sodium-based cells typically operate at a lower average voltage when analogous cathode structures are used. The heavier atomic mass of sodium and the larger ionic radius of Na⁺ impose penalties on gravimetric and volumetric energy density because more host structure mass and volume are often required to accommodate reversible Na⁺ insertion. It is important to note that these intrinsic factors do not imply poor suitability for all markets. In stationary storage and micro-mobility applications, the decisive variables often shift from maximum energy density to cost stability, safety margin, fast charge acceptance at low temperatures, and long service life. It follows that the relevant technical question is not whether sodium-ion can universally replace lithium-ion, but whether sodium-ion can meet application-specific targets at lower critical material exposure while leveraging manufacturing compatibility with established lithium-ion production lines.

3.1. Resource abundance and geopolitical diversification

Researchers and energy institutions have shown interest in sodium-ion batteries as a backup to lithium batteries. This interest has been supported by the fact that sodium is very abundant in the Earth's crust; about 2.6%, making it the 6th most abundant element, which is more than lithium (about 0.002%) (Bukowski et al., 2020). This implies sodium is a comparatively more readily available resource and most commercial sodium deposits are in the form of the rock salt (halite), which can be found in brines, salt domes, salt lakes and uncommonly in sodium sulphate minerals like trona Na₃(CO₃)(HCO₃)·2H₂O Na₃(CO₃)(HCO₃)·2H₂O (sodium carbonate) and mirabite (Na₂SO₄·10H₂O Na₂SO₄·10H₂O). Sodium sulphate is found in non-marine alkaline environments (Haynes, 2015). These salt formations are distributed worldwide. Conversely, lithium is found in salt brines and, more rarely, in hard rocks in selected geographic locations. The South American brines include the lithium triangle and in the Tibetan plateau, and hard rock mostly in Australia, Brazil, Canada and China. This distribution poses significant geopolitical, market, and monopoly risks (International Energy Agency IEA, 2023). Fig. 4 presents a side-by-side comparison of sodium and lithium in terms of crustal abundance, resource types, and global distribution and highlights sodium's widespread availability from diverse sources versus lithium's geographically concentrated deposits. The illustration emphasises the strategic advantage of sodium as a more accessible and sustainable alternative for future energy storage systems.

New studies and reviews have therefore been implemented to establish sodium as a more readily available long-term energy storage strategy, particularly when it comes to grid expansion and increased power supply (Phogat et al., 2025b). Additional reviews have also revealed sodium as a more stable supply chain commodity for countries without primary sources of lithium (Hwang et al., 2017; Adebisi and Ndjuluwa, 2024).

3.2. Cost advantages at cell and pack level

When considering the cost of development for the two cases. The SIB

Table 1
Critical metals in LIB: role, chemistry and sustainability challenges.

Metal/mineral	Role in battery	Key chemistries	Supply chain risks	Environmental impact	Recycling status
Lithium	Charge carrier (electrolyte/cathode)	All Li-ion chemistries	High (Chile, Argentina, Australia)	Water use, brine depletion	Moderate, improving
Cobalt	Cathode stability, energy density.	NMC, NCA	Very high (DRC, China refining)	Toxicity, human rights.	High value, focus of recycling
Nickel	Cathode capacity, energy density	NMC, NCA	High (Indonesia, Russia, China)	GHG emissions, mining waste	High value, focus of recycling.
Manganese	Cathode stability, voltage	NMC, LMFP	Moderate (South Africa, Gabon)	Lower toxicity	Good recovery rates
Iron and phosphate	Cathode	LFP, LMFP	Low	Lower impacts	Less recycling focus

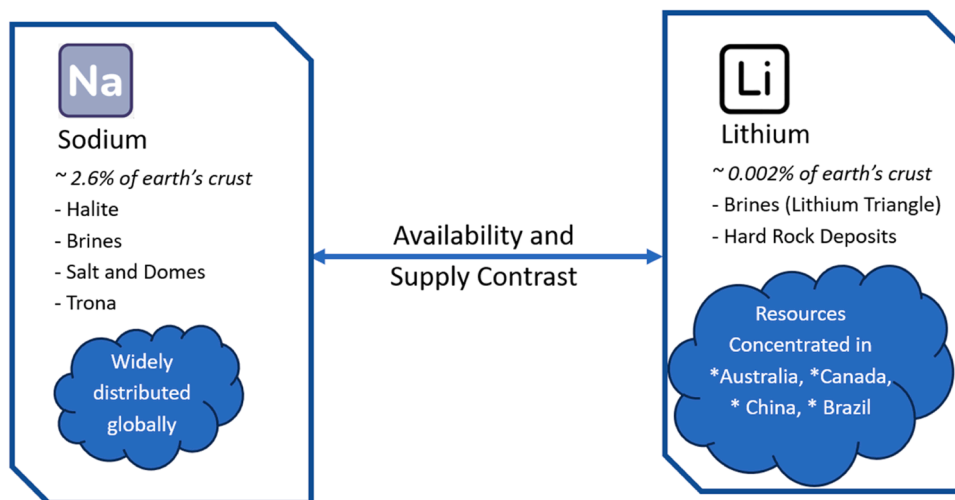


Fig. 4. Abundance of geopolitical distribution of sodium and lithium resources.

has had the upper hand, as sodium prices have been comparatively stable. Sodium prices have been around (USD 300–400), while for the counterpart, lithium prices have greatly fluctuated between the year 2021 and 2024, signalling high instability in commodity prices, thus affecting the production costs for Li-on batteries and investment planning for lithium-based systems. Recent techno-economic modelling demonstrates that sodium-ion batteries benefit from lower raw-material costs, driven by cobalt- and nickel-free cathodes and the use of aluminium current collectors on both electrodes. Pack-level optimisation studies show that sodium-ion systems can achieve 20–40% lower material costs per kWh than LFP systems in stationary applications, despite lower energy density (Castro et al., 2024). Fig. 5 compares sodium-ion and lithium-ion batteries at the cell and pack level in terms of cost stability, material composition, and economic performance and highlights the stable and lower sodium prices alongside cobalt- and nickel-free chemistry, contrasted with the volatility of lithium prices and reliance on critical materials.

3.3. Environmental footprint and life-cycle considerations

Environmental performance across the full life cycle is increasingly shaping battery technology choices. Studies assessing the environmental

footprints of sodium batteries found lower environmental impacts for SIBs than for LIBs. This can be attributed to lithium extraction from brines, which are associated with higher water consumption and greenhouse gas emissions, resulting in a comparatively higher footprint for lithium batteries. In contrast, sodium extraction pathways generally exhibit lower environmental impact intensity (Phogat et al., 2025a). This is because of the lower impact of extraction and processing, for instance, sodium batteries using lower-cost feed material like sodium carbonate and readily available metals like iron and manganese, unlike LiBs, which require critical metals like cobalt and nickel (Melchor-Martínez et al., 2021). The materials for SiB are less scarce and have lower environmental and social risk profiles, reducing cumulative life-cycle impact categories such as resource depletion and toxicity (Phogat et al., 2025a).

Life cycle assessment (LCA) comparisons between lithium-ion and sodium-ion systems are highly sensitive to methodological choices, and the interpretation should explicitly state key boundary conditions. A robust LCA should define the functional unit (for example, 1 kWh of delivered electricity over the battery lifetime), the system boundary (cradle to gate vs cradle to grave), the assumed cycle life and depth of discharge, and the electricity mix used for materials processing and cell manufacturing. For the reason that stationary storage applications can

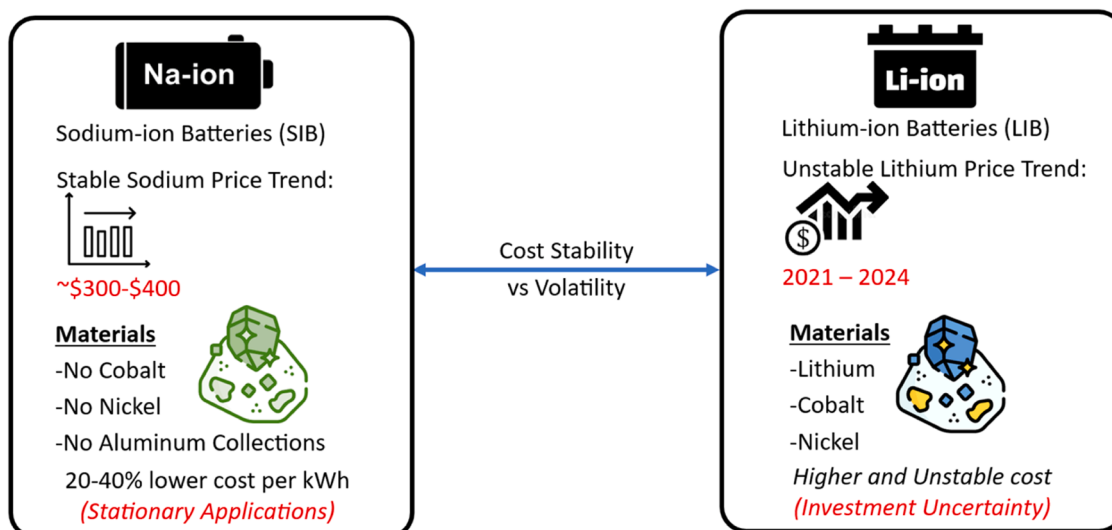


Fig. 5. Cost advantages of sodium-ion vs lithium-ion batteries.

differ substantially in duty cycle and lifetime from mobility applications, comparing batteries on a per kWh produced basis (lifetime throughput) is often more meaningful than per kWh of nameplate capacity. Allocation choices for byproducts in mining and refining (especially for nickel, cobalt, and manganese) can shift results across impact categories such as climate change, water use, and toxicity. For sodium-ion batteries, uncertainties also remain in scaling hard carbon production, establishing dedicated recycling pathways, and controlling moisture-sensitive cathodes during manufacturing. When LCA studies report advantages for sodium-ion in resource depletion and criticality metrics, the most defensible conclusion is that sodium-ion has a strong potential to reduce critical-material pressure, while the net climate benefit depends on manufacturing energy sources, cycle life achieved in real deployments, and whether recycling and clean electricity are integrated early in the value chain.

The extraction of sodium carbonate is 1.3 kg CO₂ compared to 7.7 kg CO₂ for lithium carbonate. In addition, sodium batteries use hard carbon anodes, which produce less CO₂ than the synthetic graphite anodes for lithium batteries (3.2 kg CO₂ for hard carbon vs 25 kg CO₂ for graphite (Voß et al., 2025)). However, while SIBs can outperform LIBs on resource-scarcity metrics, their greenhouse gas impacts may be similar under some scenarios, especially when comparing cells of equivalent energy capacity. This underscores that sodium's environmental benefit stems primarily from resource intensity and supply chain impacts rather than intrinsic lower emissions in all categories (Wickerts et al., 2023). Prospective life-cycle assessments indicate that sodium-ion batteries can achieve up to 30–40% lower climate change impacts per kWh stored in stationary applications, assuming comparable cycle life. Fig. 6 presents a life-cycle environmental comparison between sodium-ion and lithium-ion batteries, highlighting differences in emissions, water use, and material intensity. It shows that sodium-ion systems have lower CO₂ emissions and reduced reliance on scarce and high-impact materials compared to lithium-ion batteries. The illustration emphasises that sodium-ion batteries can achieve significantly lower overall environmental footprints, particularly in stationary energy storage applications.

3.4. Application fit and market segmentation

Recent studies on the energy storage market have revealed the parameters driving the demand for LIBs and SIBs. The market is currently segmented based on the application fit of each battery storage type. For example, Bhanu et al. (2024) analysed the interrelationships among battery capacity (Battery OEMs), battery electrode composition, range anxiety (EV owners), subsidy (Government), and their effects on LIB cost (per kWh) and market demand. It was found that battery capacity and LIB electrode composition drive higher LIB demand. Generally, LIBs dominate high-energy-density applications. Although state-of-the-art SIBs have energy densities in the lower range of LIBs, improvements can be expected with new discoveries of anode and cathode materials, as LIB technology has evolved (Chayambuka et al., 2020). Abdolrasol et al. (2025) noted that recent efforts to advance Na-ion batteries focus on improving cathode/anode materials, developing solvent-free electrolytes, and enhancing fast-charging and low-temperature performance, aiming to offer alternatives to Li-ion batteries for electronics and EVs.

Nevertheless, SIBs also currently dominate some market segments, especially in cost-sensitive and stationary applications. A recent study by Keiner et al. (2026) shows that SIB potentially outperforms LIB in the medium term, with greater cost sensitivity and lower risk of price spikes and supply shortages. Consequently, it has been argued that, given recent cost developments and learning curves, batteries are no longer a cost-critical component in the energy system. A comparative assessment of the suitability of lithium-ion and sodium-ion batteries based on dominant system-level performance requirements is shown in Table 2.

3.5. Other lingering challenges and integration constraints

Despite accelerating progress, sodium-ion batteries still face technical and systemic limitations that constrain broader deployment. Long term reliability in sodium-ion batteries is governed by coupled degradation processes at both electrodes and their interfaces, many of which are strongly dependent on temperature, voltage window, and electrolyte composition. On the anode side, unstable solid electrolyte interphase (SEI) growth can consume sodium inventory and increase impedance,

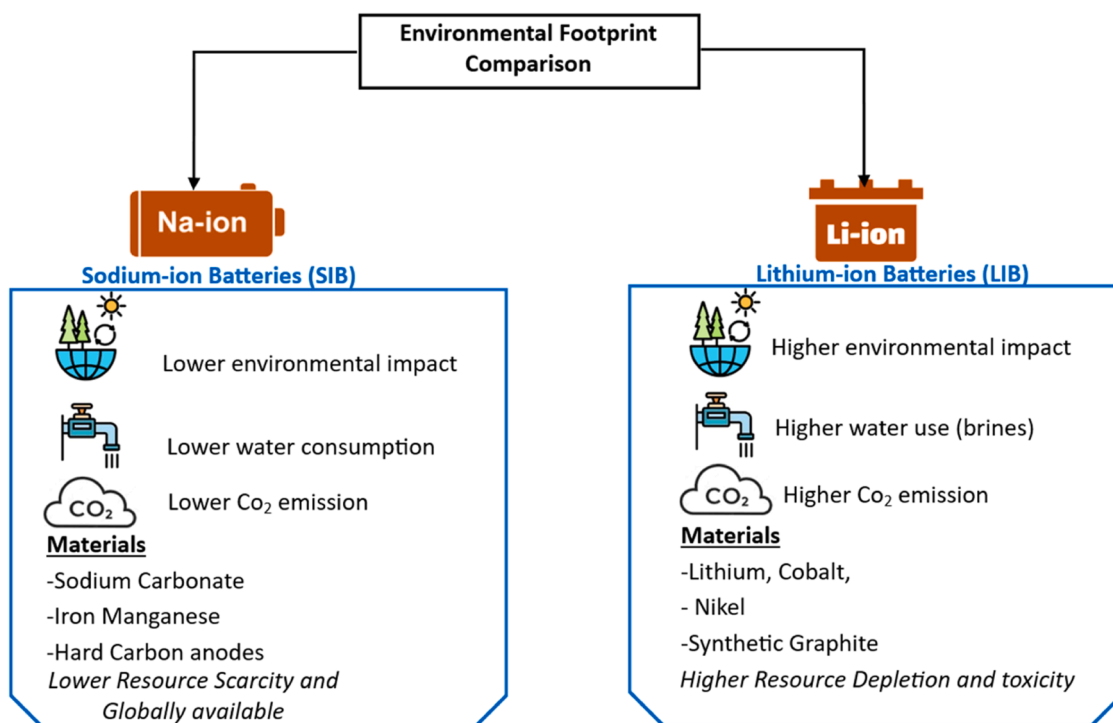


Fig. 6. Life-cycle environmental performance: sodium-ion and lithium-ion batteries.

Table 2
Comparative application suitability of lithium-ion and sodium-ion batteries based on dominant system-level performance requirements.

Application category	Key performance requirement	LIB suitability	SIB suitability	Rationale
Grid-scale storage	Low cost, long cycle life, safety	High	Very High	Energy density less critical; SIB cost and safety advantages dominate
Renewable integration (PV/Wind)	High cycle stability, fast response	High	High	Comparable performance at lower material risk
Telecom & UPS	Reliability, thermal stability	High	Very High	SIBs show wider thermal operating windows
Low-speed EVs (e-bikes, forklifts)	Moderate energy density, low cost	Medium	High	Weight constraints relaxed; cost decisive
Passenger EVs	High gravimetric energy density	Very High	Low	Sodium energy density remains limiting

while repeated volume changes can degrade conductive networks and promote electrode swelling that increases cell resistance. On the cathode side, layered oxides may experience irreversible phase transitions, transition metal migration, and surface reconstruction under deep desodiation, while Prussian blue analogues can be sensitive to structural water, vacancy disorder, and side reactions triggered by residual moisture. Electrolyte oxidation at high cathode potentials produces a cathode-electrolyte interphase (CEI) that can stabilise the surface if well formed, but can also become resistive if uncontrolled. These phenomena interact: for example, gas generation from electrolyte decomposition can increase internal pressure and worsen interfacial contact, while sodium inventory loss at the anode forces higher cathode potentials at the end of charge, accelerating cathode-side reactions. As a result, demonstrating durable sodium-ion performance requires not only improved active materials but also balanced full cell design, realistic electrode loadings, and protocols that reflect duty cycles in target applications (grid cycling, micromobility commuting, or low temperature operation).

Lower volumetric energy density, moisture sensitivity in certain cathode chemistries (notably Prussian blue analogues), and incomplete understanding of long-term degradation mechanisms under real-world duty cycles remain key challenges (Luo et al., 2016; Wang et al., 2015). Table 3 outlines the summarised limitations, their impacts, and the adopted mitigation measures, based on Phogat et al. (2025a) and

Table 3
Principal limitations affecting large-scale integration of sodium-ion batteries and corresponding mitigation strategies.

Challenge area	Current status	Impact on deployment	Mitigation pathways
Volumetric energy density	Lower than LIBs	Limits use in compact systems	Electrode densification, cathode design
Cathode moisture sensitivity	Moderate (PBAs)	Manufacturing complexity	Controlled synthesis, coatings
Long-term degradation	Partially understood	Lifetime uncertainty	SEI optimisation, advanced electrolytes
Manufacturing scale-up	Early commercialisation	Cost and yield risk	Adapted LIB production lines
Recycling infrastructure	Emerging	Sustainability uncertainty	Simplified hydrometallurgical routes

Slater et al. (2013). In addition, large-scale manufacturing optimisation and end-of-life recycling pathways for sodium-ion batteries are still under development. Recent reviews emphasise that while the absence of critical metals simplifies recycling, dedicated collection, separation, and recovery processes must be established in parallel with commercialisation to ensure that projected sustainability benefits are fully realised (Hwang et al., 2017; Bommier and Ji, 2015; Slater et al., 2013).

The integration pathway in Fig. 7 illustrates the end-to-end lifecycle development of SIB systems from materials sourcing through manufacturing, deployment, and end-of-life recycling. It emphasises the sequential and interconnected nature of each stage, highlighting how advances in materials design and production processes must align with scalable manufacturing and application requirements.

4. Sodium-ion battery technology

4.1. The working principle

The SIB operates based on the ‘rocking chair’ mechanism, which is inherited from the lithium-ion technology (Joy et al., 2024). In this architecture, sodium ions (Na^+) act as the charge carriers, shuttling between the host structures of the positive electrode (cathode) and the negative electrode (anode) (Joy et al., 2024). During charging, an external power source extracts sodium ions from the cathode material, which then migrate through the ionically conductive electrolyte and cross the separator to intercalate into or be adsorbed onto the anode. In the discharging process, the flow reverses with sodium ions moving from the higher energy state in the anode back to the cathode, while electrons flow through the external circuit to provide power (Lin et al., 2025). At a fundamental level, sodium-ion cells operate through coupled ionic and electronic transport driven by gradients in chemical potential. During charge, Na^+ is extracted from the cathode host structure and inserted into the anode host, while electrons move through the external circuit to maintain electroneutrality. The open circuit voltage can be expressed as $V = (\mu_{\text{cathode}} - \mu_{\text{anode}})/(F)$, where μ represents the sodium chemical potential in each electrode and F is Faraday’s constant. In practical porous electrodes, rate capability is governed by a combination of electrolyte transport (ionic conductivity and concentration polarisation), solid-state diffusion in active particles, and interfacial charge transfer kinetics. A useful scaling relationship is that diffusion-limited characteristic time increases approximately with $t = L^2/D$, where L is the characteristic diffusion length and D is the sodium diffusion coefficient in the host structure; thus, particle size, morphology, and diffusion pathways strongly influence fast charge behaviour. This transport framing clarifies why nanostructuring, conductive architectures, and electrolyte engineering are repeatedly emphasised across sodium-ion research: they reduce effective diffusion lengths, stabilise interfaces, and mitigate polarisation that otherwise limits capacity utilisation at higher current densities. Although the mechanical principle remains identical to LIBs, the differences lie in the specific physical and chemical attributes of sodium, which are driven mainly by these two factors: the standard redox potential and the ionic radius (Hussain and Bang, 2024). Sodium ions possess an ionic radius of 1.02 Å, larger than that of the lithium ion with an ionic radius of 0.76 Å (Lin et al., 2025). This difference has a significant effect on the battery engineering, one of which is the volumetric strain; can cause pulverisation of the electrode particles during long-term cycling (Lin et al., 2025).

4.2. Cathode and anode materials

4.2.1. Anode materials

Graphite is the common anode material for LIBs, but fundamentally unsuitable for SIBs, particularly when used with conventional carbonate electrolytes. This is because the energy required to expand the graphite layers to accommodate the larger Na^+ ion is not offset by the weak

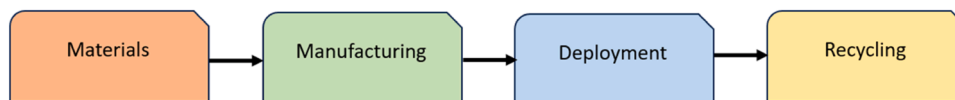


Fig. 7. End-to-end value chain integration pathway for sodium-ion battery deployment.

binding energy between sodium and the graphene sheets (Lin et al., 2025). Certain ether-based electrolytes could be used with SIB, but the process increases the volume expansion and consumes a large amount of electrolytes, which is unsuitable for commercial use (Park et al., 2020). Hard carbon is the preferred anode for SIB due to its disordered microstructures, designed to accommodate larger ions like sodium (Nikgoftar et al., 2025). They consist of small, randomly oriented graphene nanosheets that are highly cross-linked, preventing them from aligning into a graphitic structure even at extreme temperatures (Nikgoftar et al., 2025). The interlayer spacing provides a lower energy barrier for the intercalation of sodium ions; the nanopore architecture allows it to store sodium through a pore-filling mechanism, which yields high reversible capacities (Zhou and Shen, 2025). Recent studies indicate that sodium intercalation in hard carbon is less sensitive to temperature and faster than lithium insertion in graphite, offering the benefit of being weather-independent (Foley, 2025).

One critical design constraint in sodium batteries for hard-carbon systems is managing sodium inventory. From a design perspective, the challenge in SIBs is to ensure sufficient cyclable sodium without compromising safety, scalability, or process integration. This issue is particularly critical when transitioning from laboratory-scale half-cell testing to practical full-cell development, as the use of sodium metal counter electrodes in half-cells can obscure true sodium losses and lead to overestimation of achievable performance in commercial systems (Yuan et al., 2025). In recent years, the development of SIBs' anodes has branched into two main categories: plain carbonaceous materials, which offer stability and longevity, and alloying materials for higher energy density. Table 4 presents the anode material - hard carbon and carbonaceous anodes. Their performance is highly dependent on the precursor material (e.g., biomass, lignin, coal) and the carbonisation temperature (Kumari et al., 2025).

To complement the energy density of hard carbon, Research on alloying elements such as Tin, Antimony, and Phosphorus with theoretical capacities exceeding those of hard carbon has emerged (Rehman et al., 2024). These alloying elements, despite their high theoretical capacities, face a major technical challenge: volume expansion. A primary approach to stabilise these alloying anodes involves fabricating nanocomposites of these metals with a carbon framework, which accommodates volume strain and provides a continuous pathway for sodium-ion transport (Rehman et al., 2024).

4.2.2. Cathode materials

The three primary families of SIB cathode materials based on their structure and performance are Layered Transition Metal Oxides, Polyanionic Compounds and Prussian Blue Analogues (PBAs) (Joy et al., 2024). These cathode materials primarily determine the operating voltage and energy density of the SIB cell (Joy et al., 2024). The three dominant sodium cathode families can be differentiated not only by capacity and voltage, but also by their structural degrees of freedom and the failure modes that appear under practical cycling. In layered transition-metal oxides, sodium resides in well-defined interlayer sites and diffuses along two-dimensional pathways, but deep desodiation can trigger stacking changes (e.g., O3 ↔ P3 ↔ O1) and transition-metal migration that degrade reversibility. Layered transition oxides for SIBs are synonymous with the NMC chemistries in LIBs; they offer high operating voltages and specific capacities (Rehman et al., 2024). The O3-type Oxides of cathode chemistry have high sodium content (approx. 1.0) but suffer from complex phase transitions at high voltage (Hirsh et al., 2020b). The P2-type oxides with a lower sodium content of 0,

Table 4

Hard carbon and carbonaceous anodes, electrochemical parameters and their performance.

Anode material	Specific capacity (mAh/g)	Average operating voltage (V)	Cycle life (Cycles)	Technical implications
Hard Carbon (HC)	250 – 400	0.1 – 0.3	2000 – 6000	The primary industrial choice offers a 'sloping' region for adsorption and a 'plateau' for pore filling. SIB-specific energy is currently bottlenecked by HC's lower tap density (Zhou and Shen, 2025).
Lignin-derived HC	300 – 325	0.1 – 0.2	> 200 (1Ah cell)	Sustainable byproduct of the wood industry; demonstrates excellent reversible storage potential and low carbon footprint (Hirsh et al., 2020b).
Soft Carbon (SC)	150 – 250	> 0.5	1000 – 2000	Easier to synthesise than HC but suffers from higher operating voltages, which reduces the overall cell energy density (Lin et al., 2025)
N-doped Carbon	350 – 450	0.2 – 0.5	1000 – 3000	Nitrogen doping introduces defects that serve as additional active sites for Na ⁺ adsorption, though this can lower the initial Coulombic efficiency (ICE) (Hirsh et al., 2020b)

67 offers better structural stability during high-rate cycling (Joy et al., 2024). Na-rich Oxides reach even higher capacities (130–180 mAh/g) by using both metal and oxygen reactions, though they often suffer from 'voltage decay' over time (Zeng et al., 2025).

The polyanionic frameworks are known for being the safest and most rugged options due to their strong internal chemical bonds (Zeng et al., 2025). Cathode chemistry includes: The NVP (Na₃ V₂(PO₄)₃), which is exceptionally stable with a very long cycle life, but the vanadium in its composition makes it more expensive (Joy et al., 2024). Fluorophosphates offer higher specific capacity, 120–130 mAh/g, placing them amongst the best-performing Polyanionic compounds (Voß et al., 2025). As for the sulphates, it uses widely available, low-cost materials like iron to provide high voltage, but moisture sensitivity remains a concern. The Prussian Blue Analogues (PBAs) have a unique open '3D framework' that allows ions to move in and out very easily (Chen et al., 2020). The two main cathode chemistries are Fe-based PBAs and Prussian White. Fe-based PBAs have a key advantage of low cost and easy manufacturing. The Prussian white is a sodium-rich version that allows the advantage of higher specific capacities (Chen et al., 2020). A major technical challenge for both chemistries is removing 'zeolitic water' (trapped water molecules) from the structure, which can ruin battery performance if not handled correctly (Chen et al., 2020).

4.3. Electrolytes

The electrolyte system is paramount to the kinetic stability of the SIB because the electrodes commonly operate at potentials exceeding the thermodynamic stability limits of the solvents (Liu et al., 2023). Solvents employed in SIB electrolytes in recent literature are those with a high dielectric constant to ensure high salt dissociation, but they must also have low viscosity to allow for fast ion diffusion. Particularly important are electrolyte systems using carbonates, ethers, phosphate esters, or ionic liquids as solvents, which account for the vast majority of reports on electrolyte optimisation for non-aqueous Na-ion batteries (Darjazi et al., 2024). The most successful demonstrations of Na-ion batteries use non-aqueous electrolytes based on organic solvents. The addition of Fluoroethylene carbonate (FEC) in carbonate SIB systems facilitates the formation of a robust, NaF-rich SEI that suppresses continuous electrolyte decomposition (Hirsh et al., 2020a). Ether-based electrolytes have gained prominence for their superior compatibility with hard carbon and sodium metal anodes (Liu et al., 2023). In some ether systems, sodium ions can intercalate into the carbon or alloy hosts as solvated ions, thereby bypassing the high-energy desolvation step at the interface. This enhances the rate capabilities (Park et al., 2020). Another key advantage is that the SEI layers formed from ethers are thinner and more flexible compared to the carbonate electrolytes, which improves the battery cycle life, performs great in cold temperatures, but the major drawback is incompatibility with high voltage cathodes like NVPF due to its low oxidative stability (Liu et al., 2023). Research is trending towards Localised High-Concentration Electrolytes (LHCEs) and Solid-State Electrolytes. LHCEs stabilise the high-voltage cathodes in ether-based systems, while Solid-state sodium batteries, utilising ceramic separators, offer the potential for intrinsic safety and energy densities up to 239 Wh/l at the cell level, though they currently face challenges with interfacial resistance at room temperature.

4.4. Current limitations

With the rapid pace of scientific progress, SIBs still lag behind LIBs in energy density, at 250 Wh/kg compared to LIBs' 300 Wh/kg. This is due to three major technical barriers; Firstly, the inherent specific capacity of sodium ions is the most important hurdle. Sodium has a higher atomic mass (23.0 g/mol to 6.9 g/mol Li) and also a higher redox potential than Lithium. A SIB requires a greater quantity of active material than a LIB to store the same amount of energy. This inherent mass and potential penalty affect every part of the SIB. There exists a trade-off between capacity and stability for SIB cathodes. Layered oxides offer high capacities but are prone to structural damage when over 50% of sodium is extracted, causing rapid capacity fading (Hirsh et al., 2020b). In contrast, polyanionic materials, such as NVP, offer exceptional stability but suffer from reduced energy density. This reduction is due to the presence of large, heavy, non-charge-contributing molecular units (e.g., PO₄) that act as inert 'dead weight'. (International Renewable Energy Agency, 2025) while current commercial initiatives, like CATL's second-generation SIBs, aim for 200Wh/kg through framework optimisation, this performance still falls short of high-nickel LIBs. Thirdly, hard carbon, despite its stability, suffers from significant volumetric limitations. The very disordered structure that facilitates Na⁺ intercalation also contributes to a high surface area and a multitude of defects. These features lead to sodium consumption during the initial cycle as a Solid Electrolyte Interphase (SEI) is formed (Kumari et al., 2025). Consequently, the initial Coulombic efficiency (ICE) for hard carbon is typically 80–85%, significantly lower than the > 90% seen for graphite in LIBs (Nikgofar et al., 2025). This initial loss of active sodium necessitates that manufacturers 'over-provision' the cathode material. This over-provisioning increases both the weight and cost of the cell without providing any increase in its usable energy (International Renewable Energy Agency, 2025).

Table 5 summarises the comparative metrics of sodium-ion and

Table 5

Comparative metrics of Na-ion and Li-ion technologies at the commercial level.

Parameter	Sodium-ion battery (SIB)	Lithium-ion battery (LFP)	Lithium-ion battery (NMC)
Energy density (Wh/kg)	100 – 160	140 – 190	200 – 300
Volumetric density (Wh/L)	200 – 350	350 – 500	500 – 750
Cycle life (80% DoD)	2000 – 6000	3000 – 10,000	1000 – 2500
Operating temp (°C)	-40 to 60	-20 to 60	-20 to 55
Anode current collector	Aluminum	Copper	Copper
Sustainability rating	High (Co-free, Ni-free)	Moderate (Li, P)	Low (Co, Ni, Li)

lithium-ion technologies at the commercial cell level. Some unique advantages of sodium-ion batteries (SIBs) include their widespread availability and relatively low cost. Additionally, SIBs do not alloy with aluminium at low potentials, unlike lithium-ion batteries (LIBs), which require heavy and costly copper anode collectors. This feature typically reduces the overall cost of the cell by 5–8% and helps to offset the energy density penalty by decreasing the 'inactive' mass of the battery (Farhan et al., 2025). The technical evolution of SIBs shows they are a robust and sustainable alternative to LIBS. While The fundamental ion physics of sodium creates a major hurdle with respect to the energy density, the abundance of sodium, the structural flexibility of disordered carbons and polyanionic frameworks creates a high-performance, low-cost storage solution Also, the move towards aluminum current collectors, biomass-derived hard carbons, and ether-based electrolytes has created a distinct electrochemical identity for SIBs bridging the lithium challenge, so that global energy transition becomes economical and ecologically viable (Farhan et al., 2025).

Fig. 8 presents a comparative overview of the current technical limitations of sodium-ion batteries relative to lithium-ion batteries, highlighting key barriers such as lower energy density, intrinsic atomic and electrochemical constraints, cathode stability trade-offs, and hard carbon inefficiencies. It illustrates how these limitations arise from fundamental material and ion-transport characteristics, while also contrasting them with lithium-ion benchmarks in performance and maturity. Despite these challenges, the figure also emphasises that sodium-ion batteries retain significant advantages in cost, resource abundance, and materials engineering potential, supporting their continued development as a viable alternative energy storage technology.

4.5. Safety, abuse tolerance, and standards

Safety is a decisive differentiator in energy storage deployment because it influences permitting, insurance, transport classification, and public acceptance. For LIBs, thermal runaway risk is linked to the presence of flammable organic electrolytes, reactive charged cathode surfaces (especially at high state of charge), and failure mechanisms such as internal short circuits caused by manufacturing defects, mechanical damage, or lithium plating under fast charging at low temperatures. SIBs share many architectural similarities with lithium-ion cells and therefore are not inherently 'non-flammable'; however, they can offer safety advantages through chemistry choices that reduce oxygen release risk and through manufacturing features such as aluminium current collectors on the anode that avoid copper dissolution issues under deep discharge. From a practical safety engineering standpoint, the key questions are: a) how the cell behaves under abuse (overcharge, over-discharge, external short circuit, nail penetration, and thermal exposure), b) how fast heat is generated relative to heat dissipation at the module and pack level, and c) whether gas generation and pressure rise are controlled under realistic operating windows. For grid-scale

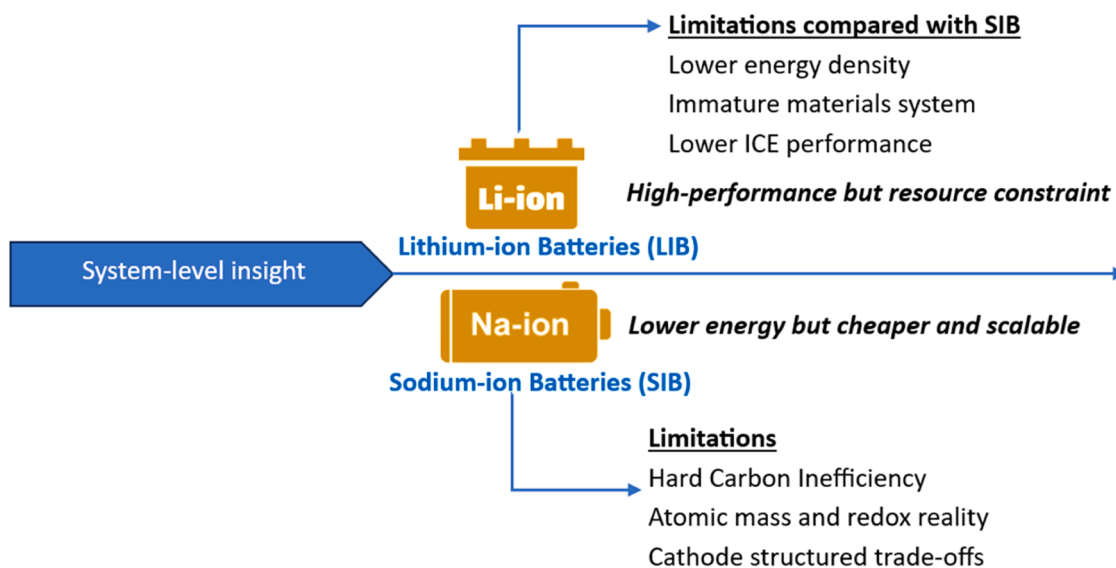


Fig. 8. Technical limitations and performance comparison of sodium-ion and lithium-ion batteries.

deployments, standards and certification regimes translate safety performance into bankability. It follows that as sodium-ion commercialisation accelerates, reporting should increasingly include safety-relevant metrics such as heat generation, thermal stability of charged electrodes, gas evolution tendencies, and performance retention under low-temperature fast-charge conditions, especially in the applications where sodium-ion is positioned to lead.

5. Critical materials for sodium-ion batteries

SIBs have garnered significant attention primarily due to the supply risks and price volatility of critical minerals such as Cobalt, Nickel, and Lithium, which are required for LIBs (Yao et al., 2025). This necessitates the shift towards more abundant and accessible materials and minerals. In the SIB, cathode material systems currently under extensive research include transition metal oxides, polyanionic compounds, and Prussian blue analogues (PBAs), each exhibiting distinct crystal structures and electrochemical performance (Yuanyuan et al., 2025). The anode materials include graphitic and hard carbon, alloy-type materials, and emerging materials like metal oxides, sulfides, and organics (Bogale et al., 2026). In addition to the cathode and anode materials, electrolyte salts, such as NASICON compounds, which have high ionic conductivity and are used as electrolytes in SIBs, require minerals such as rare-earth elements, phosphorus, and Silicon. Performance advantages of SIBs over LIBs are notable in the literature (Yu et al., 2023; Zhao et al., 2023; Nayak et al., 2018; Sawicki and Shaw, 2015). Overall, the key materials required in SIBs are shown in Table 6.

5.1. Global reserves and mining hotspots

The material landscape for SIBs is significantly different from that of LIBs in terms of resource distribution. Sodium, one of the most abundant elements on Earth (approximately 1000 times more abundant than lithium), is widely distributed, particularly in sources such as seawater and soda ash (Mashfy et al., 2026; Phogat et al., 2025a; Cai et al., 2024). The United States boasts the largest natural soda ash reserves, with other significant deposits located in Botswana, Ethiopia, Kenya, and Turkey; China also produces synthetic soda ash (Mashfy et al., 2026). In stark contrast, lithium resources are limited and geographically concentrated, with over 85% of global production originating from a few countries, primarily Australia, Chile, and China. China dominates the lithium refining capacity (Mashfy et al., 2026). The potential demand for lithium is highlighted by the fact that replacing all 800 million cars with electric

vehicles powered by 15-kWh lithium-ion batteries could deplete up to 30% of known lithium reserves (Armand and Tarascon, 2008). Cobalt mining is highly concentrated, with 50% of the world's supply coming from the Democratic Republic of Congo, rendering it a geopolitically sensitive feedstock and raising ethical concerns related to its extraction (Castro et al., 2024; More and Yadav, 2024; Armand and Tarascon, 2008). Manganese, Iron, and Aluminium: These elements are globally abundant, providing a stable supply for battery production without significant cost volatility (More and Yadav, 2024; Armand and Tarascon, 2008).

5.2. Potential supply chain vulnerabilities

Although SIBs inherently reduce some supply chain risks, several challenges remain. SIBs markedly reduce reliance on expensive, geopolitically sensitive materials such as lithium, cobalt, and nickel, which are critical for LIBs. This transition mitigates supply chain vulnerabilities and promotes the adoption of more sustainable battery chemistries (Mashfy et al., 2026; More and Yadav, 2024; Eniowo et al., 2026). Likewise, issues with lithium and cobalt supply risks continue to have a significant influence. Despite the benefits of SIBs, demand for LIBs continues to escalate, leading to projections that lithium supply may outstrip demand by 2028 unless significant advancements in recycling or the adoption of alternative materials occur (Mashfy et al., 2026). Additionally, the concentrated nature of cobalt mining presents ongoing supply risks (Armand and Tarascon, 2008; More and Yadav, 2024).

There are also concerns over manufacturing compatibility and costs. SIB manufacturing processes are largely compatible with existing LIB infrastructure, facilitating scale-up and reducing reinvestment costs (Cai et al., 2024; Mashfy et al., 2026). However, the lower material value of SIBs may limit the profitability of recycling initiatives relative to LIBs, hindering the establishment of a robust recycling infrastructure (Cai et al., 2024). Some SIB cathode materials are also moisture-sensitive, necessitating humidity-controlled manufacturing environments, which increase production costs (Cai et al., 2024). Furthermore, there are trade-offs between performance and cost. While SIB raw materials are generally cheaper, their lower energy density (90–150 Wh/kg compared to 130–285 Wh/kg for LIBs) often necessitates larger battery packs for equivalent energy output. This requirement can negate the cost advantage of raw materials when considering the total system cost (Mashfy et al., 2026). For instance, hard carbon, commonly used as an SIB anode, can be more expensive than graphite (Mashfy et al., 2026).

Table 6
Critical raw materials for sodium-ion batteries.

Critical raw materials	Uses	References
Iron and Manganese	These transition metals are frequently utilised in SIB cathodes, serving as cost-effective substitutes for cobalt and nickel. Notable examples include P2-type sodium manganese iron oxide and iron sulfide (FeS) for anodes, which are valued for their abundance and high theoretical capacities.	(He et al., 2025; Tian et al., 2021).
Aluminium	In SIBs, aluminium serves as the anode current collector, enabling the replacement of the more expensive copper. This shift offers both material and weight benefits and mitigates corrosion risks associated with sodium-based chemistries. Aluminium doping enhances the structural stability and electrochemical performance of the cathode.	(More and Yadav, 2024)
Titanium	Doping with titanium stabilises SIB cathodes, such as NaFe _{1/3} MnO ₂ , by suppressing the Jahn-Teller distortion. This improvement leads to enhanced cycling and rate performance, making titanium an important component in SIB development.	Qiu et al., 2025; Sharma et al., 2025)
Hard Carbon	A prevalent anode material for SIBs, hard carbon is favoured over graphite (commonly used in LIBs) due to its compatibility with sodium ion storage. Its diverse sources, coal, pitch, and biomass, contribute to its attractiveness as a sustainable material.	(Mashfy et al., 2026; Jia et al., 2025; Ren et al., 2023; Liu et al., 2022).
Organic Compounds	Emerging organic electrode materials offer structural flexibility, abundance, and environmental benefits. Often characterised by high gravimetric energy density and stable cycling performance, these organics are gaining traction in SIB research.	(Zhong et al., 2024; Hu et al., 2023)
Vanadium (V)	Compounds like NaV ₂ (PO) ₄ F are considered for use in polyanionic cathodes, providing competitive specific energy density, which is critical for enhancing the overall performance of SIBs.	(Liaqat et al., 2025; More and Yadav, 2024)

On interfacial stability, challenges such as electrolyte decomposition, interface side reactions, structural degradation, and electrode cracking contribute to interfacial failure, significantly impacting SIB performance and long-term reliability. Achieving a balance between battery safety and preventing circuit shortages demands advanced engineering solutions. Additionally, despite using more abundant elements, the extraction and processing of raw materials for SIBs can still have environmental consequences, including water pollution and greenhouse gas emissions (Phogat et al., 2025a). Therefore, designing green and sustainable battery systems requires careful consideration of life cycle assessments, raw material abundance, and the potential for electrode recycling (Armand and Tarascon, 2008). A typical green and sustainable battery system's life cycle assessment factors are indicated in Fig. 9.

Optimising battery performance while decarbonising manufacturing processes is crucial for mitigating the climate impact of SIBs (Zhang et al., 2024). While SIBs present a promising alternative to LIBs, their development involves navigating the complexities of material sourcing,

supply chain dynamics, performance optimisation, and environmental sustainability. The future of this technology will depend on continued research and innovation in these areas.

6. Case studies and industry developments

6.1. Tiamat energy 5 GWh gigafactory (France)

Tiamat Energy, a spin-off from the French National Centre for Scientific Research (CNRS), represents Europe's primary surviving hope for domestic sodium-ion production following the collapse of Northvolt in Sweden. Located in the 'Battery Valley' of Hauts-de-France, the project focuses on high-power applications rather than the high-energy EV autonomy targeted by CATL (Tiamat, 2026). Unlike the layered oxide chemistries favoured by CATL and Faradion, Tiamat specialises in fluorophosphate-based cathodes (NVPF). This polyanion chemistry is characterised by a robust crystal structure that allows for rapid ion insertion and extraction. Consequently, these cells offer exceptional power density and cycle life but suffer from lower energy density compared to layered oxides. This makes their cells ideal for hybrid electric vehicles (HEVs), which require rapid bursts of power for regenerative braking and acceleration, as well as power tools and frequency regulation services on the grid, rather than long-range EVs. While the roadmap targets 5 GWh by 2029, the commissioning of the initial 0.7 GWh phase has faced delays, slipping from late 2025 to 2026. The Tiamat project is a litmus test for whether a specialised, high-performance European battery chemistry can carve out a niche against Asian giants (Tiamat, 2026).

6.2. Natron energy Holland facility (United States)

In April 2024, Natron celebrated the opening of the first commercial-scale sodium-ion factory in the US in Holland, Michigan. However, by September 2025, the company had ceased operations, and its assets were being liquidated (Natron Energy, 2024). Natron employed a Prussian Blue analogue electrode chemistry. This distinct approach differs radically from the layered oxide and polyanion chemistries. Prussian Blue offers an open lattice structure that permits extremely fast ion movement and minimal structural degradation, resulting in extreme cycle life (tens of thousands of cycles) and ultra-high power. However, it suffers from very low volumetric energy density. This limitation restricted the addressable market to stationary applications where weight and size are secondary to power and longevity, such as data centre Uninterruptible Power Supply (UPS) systems and peak shaving for EV fast chargers (Natron Energy, 2024). The collapse was attributed to the 'capital intensity' of scaling manufacturing in the US and the inability to compete with the plummeting costs of LFP batteries. As LFP prices dropped below \$50/kWh, the specific value proposition of Natron's long-life but expensive-to-scale technology eroded. Table 7 presents a summary of commercial/ pilot projects for Na-ion batteries across different regions.

6.3. Performance metrics from trials

6.3.1. Cycle life: durability vs. chemistry

Cycle life data varies significantly depending on the chosen cathode chemistry, revealing a trade-off between energy density and longevity. For Layered Oxides (Faradion, 2021). The HiNa's 32140 cylindrical cells are projected to a standard life of 2000–4000 cycles for first-generation products (Wan, 2023). This is sufficient for passenger EVs (where calendar life often expires before cycle life), but is on the lower end for premium grid storage compared to LFP. CATL claims its newest generation achieves 10,000 cycles. This rivals high-end LFP. However, verifying these 10,000-cycle claims in real-world conditions remains an ongoing process for the industry.

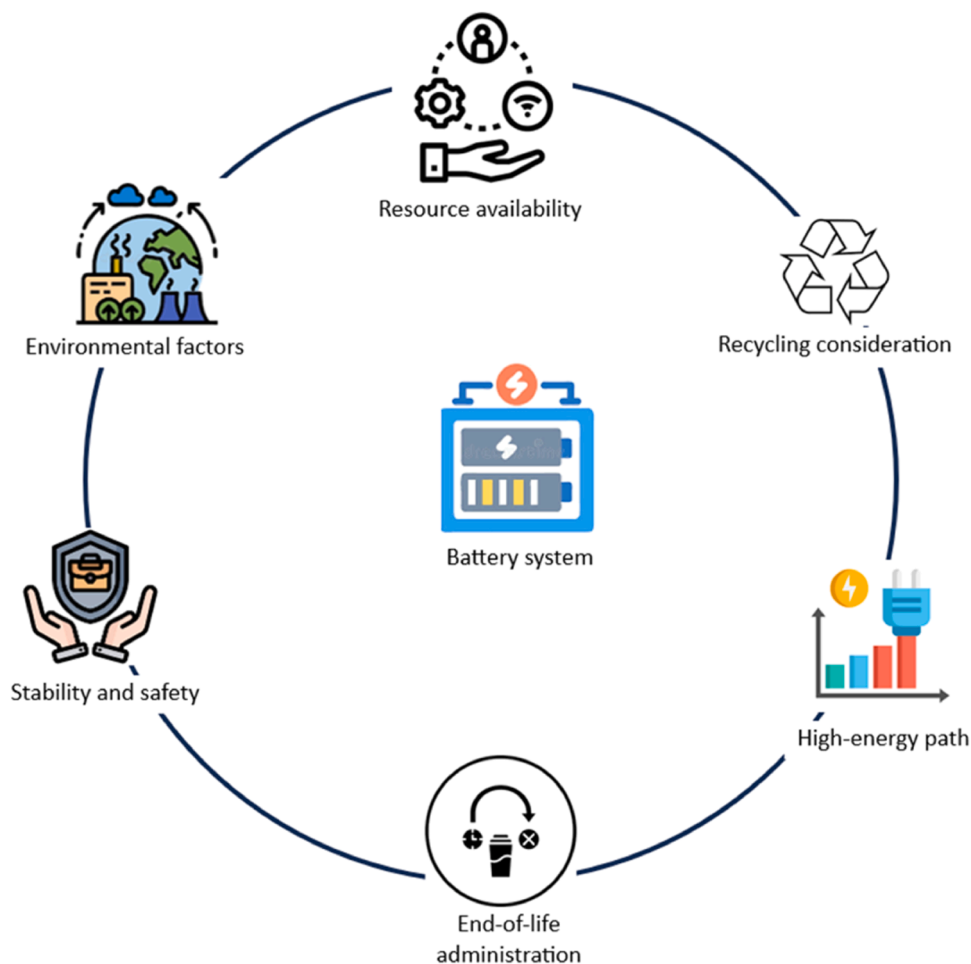


Fig. 9. Green and sustainable battery systems life cycle assessments.

Table 7
Commercial/ pilot projects for Na-ion batteries across different regions.

S/ N	Lead company	Application	Project scale	Status
1.	Contemporary Amperex Technology Co., Limited (CATL)	Passenger Electric Vehicles (EV) and Heavy-Duty Trucks	Mass Production (Multi-GWh capacity integrated into existing lines)	Active Mass Production (Commenced April 2025)
2.	HiNa Battery Technology Co., Ltd. (in partnership with Datang Group)	Grid-Scale Stationary Energy Storage (BESS)	100 MW / 200 MWh (Phase 1: 50 MW / 100 MWh operational)	Operational (Phase 1 connected June 2024)
3.	Reliance New Energy Solar Ltd (incorporating Faradion Ltd technology)	Grid Storage, Light Electric Vehicles (2-Wheelers/3-Wheelers)	Multi-GWh (Part of the Dhirubhai Ambani Green Energy Giga Complex)	Construction/Pre-Production (Production start slated for H2 2025)
4.	Tiamat Energy (Backed by Stellantis, Arkema, MBDA)	Power Tools, 48 V Hybrid Vehicles, Stationary Storage	5 GWh target (0.7 GWh Pilot Phase)	Development/ Delayed (Construction confirmed; Pilot commissioning pushed to 2026)
5.	Natron Energy	Data Centres, Industrial Power, EV Fast Charging Support	600 MW capacity (Holland, MI); Planned 24 GWh (NC)	Terminated (Operations ceased September 2025)

6.3.2. Safety and transport logistics

Unlike LIBs, which must be shipped at 30% SOC and are classified as dangerous goods due to the risk of thermal runaway, SIBs using aluminium current collectors on the anode allow them to be discharged to 0 Volts without chemical degradation (dissolution of the copper collector, which happens in Li-ion). This allows SIBs to be transported as general cargo rather than hazardous materials, significantly reducing logistics costs and insurance premiums. Faradion and Reliance have highlighted this as a key enabler for deployment in developing markets with less rigorous safety infrastructure (Faradion, 2021).

6.4. Policy and funding support in various countries

6.4.1. China: vertical integration and standardisation

China employs supply chain control and standardisation to solidify its monopoly on the post-lithium future. In 2024/2025, China introduced the national standard GB/T 44265-2024 for SIBs in electric energy storage. Managed by the China Quality Certification Centre (CQC), this standard unifies safety and performance testing (Natron Energy, 2024). This forces global suppliers to design to Chinese specifications if they wish to compete in the world's largest battery market. China's late 2025 expansion of export restrictions on high-energy battery technologies and key materials, including SIB anode material graphite, creates a geopolitical hurdle. This necessitates Western development of domestic SIB supply chains, as US/EU firms face complications importing Chinese SIB cells due to required export licenses (Gabriel et al., 2025). Also, in the 'New Energy Storage Technologies' implementation plan by the National Development and Reform Commission. The mandate targets a

30% cost reduction in energy storage by 2025 to achieve unsubsidised commercial viability (Gabriel et al., 2025).

6.4.2. European Union: funding innovation amidst industrial crisis

Despite an ambitious policy, the EU's slow execution, worsened by Northvolt's collapse, hinders its SIB efforts. The EU has invested hundreds of millions in SIB R&D to stay relevant, exemplified by the 'Made-in-Europe' ATENA+ Horizon Europe project (Murray, 2022). In 2025, the Commission granted €852 million for battery projects (including Tiamat) to cover CAPEX and OPEX (Westerheide, 2025). While the 'Batteries Regulation' and the 'Net Zero Industry Act' set ambitious targets for domestic production capacity, Northvolt's 2025 bankruptcy starkly exposed the vulnerabilities of this strategy. Consequently, Tiamat Energy has emerged as the principal beneficiary of French and EU state aid, leveraging funds from Bpifrance to revitalise industrial activity in the Hauts-de-France region. This shift signals a change in focus towards backing specialised, smaller companies rather than concentrating resources on a single, pan-European industrial giant.

7. Challenges and opportunities

7.1. Technical hurdles and performance gaps

7.1.1. Gravimetric and volumetric energy density

The primary challenge for SIBs lies in the inherent physical and chemical differences of Sodium and Lithium. These differences are responsible for the limits of energy density, voltage stability, and power performance. To bridge this gap, there is a rise in scientific innovations focusing on the structural mechanics of host materials and the thermodynamics of ion transport. As of early 2025, the gravimetric energy density of SIB ranges from 100 to 160 Wh/kg with CATL's Naxtra range reaching 175 Wh/kg (International Renewable Energy Agency, 2025). This still falls below the 200–300 Wh/Kg benchmark of NMC and LFP chemistries (International Renewable Energy Agency, 2025). The volumetric energy density gap is more pronounced with SIBs exhibiting a deficit compared to LFP-based LIBs (Voß et al., 2025). Breakthrough research published in 2025 has identified organic cathode materials, such as bis-tetraaminobenzoquinone (TAQ), that utilise a four-electron redox process to achieve an electrode-level energy density of 606 Wh/kg. Despite demonstrated peak performance in the lab, commercial scaling is limited by the performance of hard carbon (HC) anodes and the need for layered oxide structural stabilisation (Voß et al., 2025).

7.1.2. Voltage decay and lower operating potentials

The operating voltage of SIBs is constrained by the inherent redox potential difference between sodium and lithium. This margin of 0.33 V lowers the energy density in the cells, especially when analogous cathode structures are employed. Layered oxide cathodes, such as O3 and P2-type materials, suffer from a phenomenon known as voltage decay, which is primarily driven by irreversible phase transitions and the migration of transition metal ions during high-voltage cycling. (Komenda and Piątek, 2025). Research has shown that through dual-doping strategies, incorporating Cu and Mg into the lattice can suppress phase transitions at high voltage, maintain a nominal voltage, resulting in a higher energy density at the material level.

7.1.3. Diffusion kinetics and the sluggish sodium ion

The larger ionic radius of sodium ions compared to lithium (1.02 Å vs. 0.76 Å for Li) causes mechanical stress, often called 'breathing' of the crystal lattice. This stress leads to a lower diffusion coefficient and limited rate performance (Abdulsalam et al., 2024; Salam et al., 2026). A primary pathway to overcome these barriers is nanostructuring of the electrode materials, particularly the use of hollow morphologies in PBAs and sulfur-doped hard carbons, which have been employed to minimise solid-state diffusion distances (Komenda and Piątek, 2025).

7.2. Recycling and end-of-life considerations

As SIBs move towards mass adoption, researchers are keen to study the sustainability of their life cycles. Unlike Lithium, SIBs offer a theoretically higher carbon footprint due to the abundance of sodium and the replacement of synthetic graphite with hard carbon (Voß et al., 2025). A robust end-of-life strategy for sodium-ion batteries should be built on design-for-recycling principles rather than treated as a downstream afterthought. Even when cathodes avoid high-value metals such as cobalt and nickel, recycling remains important to reduce waste, recover aluminium and transition metals, and prevent environmental leakage of electrolytes and fine particulate carbon. The economic challenge for sodium-ion recycling suggests that process simplicity, low energy input, and minimal reagent use will be more decisive than maximising recovery of a single high-value metal. Direct recycling concepts (where electrode materials are recovered and regenerated with limited structural destruction) are promising because they can reduce both energy use and chemical consumption compared with fully destructive routes. However, direct recycling viability depends on cathode stability (ability to restore stoichiometry and structure), contamination control, and the existence of standardised cell formats that facilitate disassembly. Building a circular sodium-ion ecosystem will therefore likely require early coordination between manufacturers, recyclers, and policymakers to establish collection systems, safe discharge/handling protocols, and material labelling that enables efficient sorting and process selection. In this sense, sodium-ion commercialisation offers an opportunity to integrate circularity earlier than was achieved for lithium-ion batteries, potentially reducing future waste burdens as stationary storage markets expand.

Traditional recycling methods like pyrometallurgical and hydrometallurgical have been criticised for high energy consumption and secondary pollution. Emerging Recycling methods like direct recycling, where cathode materials are regenerated with the crystal structure intact, are a preferred pathway for SIBs. A pioneering technique of direct recycling is known as Ice stripping, a low-scaled delamination method for hard carbon and Prussian White electrodes (Guzmán et al., 2025). It makes use of distilled water and freezing temperatures to delaminate the active materials (Guzmán et al., 2025). This method achieves a recovery efficiency of 98%, reducing costs by 70% compared to chemical washing methods or conventional ultrasound (Guzmán et al., 2025).

7.3. Potential for hybrid storage systems

Hybrid battery systems, also referred to as the 'AB battery' or 'Abacus' structure, integrate lithium and sodium cells into a single pack to create a superior performance profile. Commercialisation of these hybrid systems started in 2024, marking a strategic pivot in the SIB sector. A primary commercial example of this integration is CATL's Freevoy Super Hybrid battery, launched in late 2025 (CATL, 2024). The architecture leverages the high energy density of lithium and the low-temperature performance of sodium-ion to improve system reliability. The combination of these chemistries in a defined ratio and arrangement has increased the low-temperature range of hybrid vehicles by 5% (CATL, 2024) and supports 4C ultra-fast charging (280 km range in 10 min) (Miao, 2026). A significant technical hurdle in hybrid systems is accurately estimating state-of-charge (SoC) when two chemistries with different voltage behaviours are used in the same circuit. Manufacturers like CATL now use the stable voltage behaviour of the sodium-ion battery as a 'benchmark' to calibrate the (SoC for the lithium-ion portion of the pack, increasing control precision by 30% (Miao, 2026). Researchers have proposed using Nonlinear Autoregressive with Exogenous Inputs Neural Networks (NARXNN) to capture the complex nonlinear behaviours of the two chemistries during variable charging and discharging cycles (Udeogu, 2022). The SIB sector is at a critical juncture. Although technical challenges, such as voltage decay and poor kinetics, persist, advances in material science (doping layered

oxides and nano-structuring hard carbons) are rapidly closing the performance gap with lithium-ion technology. The move toward a circular economy is supported by sustainable, profitable direct recycling methods such as ice-stripping. Hybrid Li-Na packs offer an immediate integration route for SIBs into automotive applications, capitalising on their safety and superior cold-weather performance while maintaining necessary range.

8. Concluding remarks and recommendations

This review has demonstrated that lithium-ion and sodium-ion batteries possess distinct advantages, positioning them as complementary rather than competing technologies in the future energy storage landscape. Lithium-ion systems will continue to dominate applications requiring high energy density and compact form factors, such as electric mobility, whereas sodium-ion batteries offer a sustainable alternative characterised by abundant raw materials, lower costs, and reduced environmental impact for stationary grid storage. To maximise the strategic benefits of this complementary relationship, policymakers and industry stakeholders should prioritise diversifying supply chains and implementing targeted regulatory frameworks that support the development of sodium-ion technologies for grid-scale applications. In addition, investing in sodium-ion development roadmaps is crucial to maintain a competitive track with lithium-ion and mitigate risks associated with supply chain volatility. Continued research and development efforts must focus on overcoming the technical limitations of sodium-ion batteries, specifically regarding their lower energy density and long-term cycling stability, to ensure their commercial viability and widespread adoption in the energy sector. Establishing robust recycling infrastructure early in the deployment cycle will be crucial for minimising resource depletion and ensuring the circular economy of sodium-ion battery materials. By recovering critical components such as sodium, iron, and manganese, recycling processes can further reduce reliance on virgin material extraction and enhance the overall sustainability profile of these systems. Ultimately, the synergistic integration of lithium-ion and sodium-ion technologies will provide a more resilient, secure, and low-carbon energy storage infrastructure capable of meeting the diverse demands of the global community. This integrated approach will be vital for achieving carbon neutrality and securing a sustainable energy future.

From a research and development perspective, the most impactful agenda for sodium-ion batteries is increasingly clear and can be stated as a set of coupled priorities: stabilise high-capacity cathodes against phase transitions and voltage decay through compositional tuning, morphology control, and CEI engineering; improve hard-carbon anode ICE and volumetric performance through microtexture control, densification strategies that preserve transport, and scalable pre-sodiation methods; develop electrolyte systems that simultaneously support low temperature fast charge and high-voltage cathode stability, with explicit focus on SEI/CEI chemistry and gas suppression; and demonstrate long-duration reliability under realistic grid and mobility duty cycles, including calendar aging, thermal excursions, and high rate operation. Parallel to these technical priorities, commercialisation should prioritise early standardisation, safety testing, and recycling pathway development to ensure that the sustainability promise of sodium-ion is realised in practice. Achieving these goals will not eliminate lithium-ion batteries; instead, it will enable a complementary portfolio in which sodium-ion reduces critical material pressure and strengthen energy security while lithium-ion remains essential for high-energy mobility, where mass and volume are dominant constraints.

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– review & editing, Supervision, Resources, Project administration, Funding acquisition. **John Adebisi:** Writing – original draft, Validation, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Tawanda Zvarivadza:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Said Omar Khadija:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Moshood Onifade:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Manoj Khandelwal:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Conceptualization.

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