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COMPARATIVE REVIEW OF LITHIUM-ION AND SODIUM-ION BATTERIES FOR FUTURE ENERGY STORAGE APPLICATIONS

Jawed Ali Thaheem[*1], Shafique Ahmed Soomro[2], Dr. Ahmed Muddassir Khan[3], Muhammad Raza Punjwari[4], Ali Zain Ul Abden[5], Ateeq Ur Rehman[6]

[*1,2,34,6]*Faculty of Engineering Science and Technology, Department of Electrical Engineering, Indus University, Karachi, 75850, Pakistan.*
[5]*Manager Campus France Karachi Organization: Campus France, Karachi, 75850, Pakistan.*

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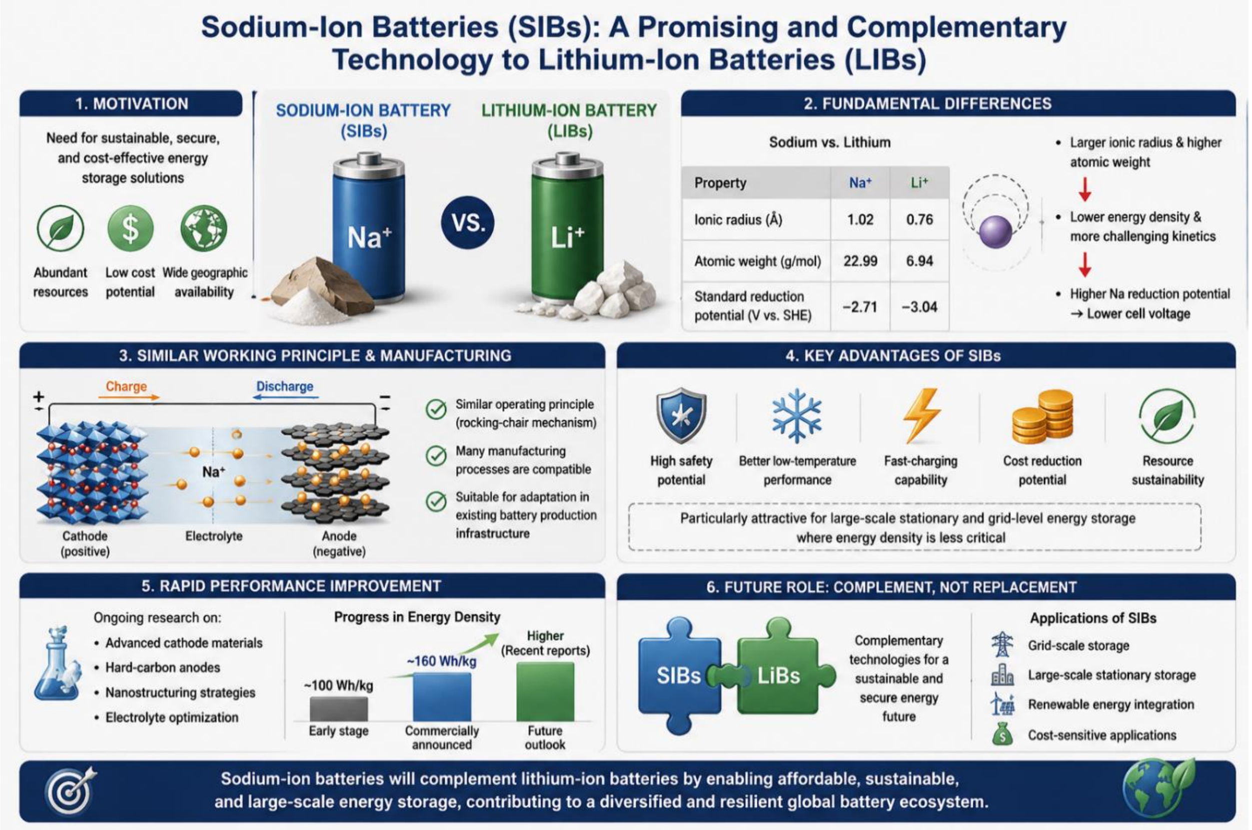
Corresponding Author: * Jawed Ali Thaheem

Abstract

Sodium-ion batteries (SIBs) are emerging as a promising alternative and complementary technology to lithium-ion batteries (LIBs) due to the abundance, low cost, and wide geographical availability of sodium resources. Although LIBs currently dominate high-energy-density applications, fundamental physical and electrochemical differences between sodium and lithium ions, including the larger ionic radius and higher atomic weight of sodium, generally result in lower energy density and more challenging electrode kinetics in SIBs. In addition, the higher standard reduction potential of sodium compared with lithium contributes to a lower cell voltage, which further limits the achievable energy density. Despite these limitations, sodium-ion batteries share similar working principles and many manufacturing processes with lithium-ion systems, making them suitable for adaptation within existing battery production infrastructure. SIBs also demonstrate important advantages in terms of resource sustainability, safety potential, low-temperature performance, fast-charging capability, and cost reduction, particularly for large-scale stationary and grid-level energy storage applications where energy density is less critical. Ongoing research on advanced cathode materials, hard-carbon anodes, Nano structuring strategies, and electrolyte optimization is rapidly improving the electrochemical performance and cycle life of SIBs. Commercially announced sodium-ion cells have already reached energy densities of around 160 Wh/kg, with more recent reports indicating further improvement. Therefore, sodium-ion technology is not expected to fully replace lithium-ion batteries in all applications. Instead, it is likely to complement LIBs by serving cost-sensitive, large-scale, and sustainability-focused energy storage sectors, contributing to a more secure and diversified global battery supply chain.



Sodium-Ion Batteries (SIBs): A Promising and Complementary Technology to Lithium-Ion Batteries (LIBs)

1. MOTIVATION

Need for sustainable, secure, and cost-effective energy storage solutions

2. FUNDAMENTAL DIFFERENCES

Sodium vs. Lithium

Property	Na^+	Li^+
Ionic radius (Å)	1.02	0.76
Atomic weight (g/mol)	22.99	6.94
Standard reduction potential (V vs. SHE)	−2.71	−3.04

- Larger ionic radius & higher atomic weight
- Lower energy density & more challenging kinetics
- Higher Na reduction potential → Lower cell voltage

3. SIMILAR WORKING PRINCIPLE & MANUFACTURING

- Similar operating principle (rocking-chair mechanism)
- Many manufacturing processes are compatible
- Suitable for adaptation in existing battery production infrastructure

4. KEY ADVANTAGES OF SIBs

Particularly attractive for large-scale stationary and grid-level energy storage where energy density is less critical

5. RAPID PERFORMANCE IMPROVEMENT

Ongoing research on:

- Advanced cathode materials
- Hard-carbon anodes
- Nanostructuring strategies
- Electrolyte optimization

6. FUTURE ROLE: COMPLEMENT, NOT REPLACEMENT

Complementary technologies for a sustainable and secure energy future

Applications of SIBs

- Grid-scale storage
- Large-scale stationary storage
- Renewable energy integration
- Cost-sensitive applications

Sodium-ion batteries will complement lithium-ion batteries by enabling affordable, sustainable, and large-scale energy storage, contributing to a diversified and resilient global battery ecosystem.

1. Introduction

Nowadays, Sodium ion batteries are developing as a promising alternative to lithium ion batteries due to sodium's abundance and lower cost, though lithium ion batteries currently offer better energy density and performance. Both technologies are advancing rapidly with difference strengths for various applications. Fundamental Properties and Differences. key differences between sodium and lithium ions stem from their physical and electrochemical properties-sodium ions are larger, heavier, and have higher electrochemical potential, resulting in low energy density and slower kinetics for sodium ion batteries, though technologies share similar operating principles. Conversely, sodium (Na) is 1,180 times more abundant than lithium, the second smallest and lightest alkali element, making it the fourth most prevalent element on Earth. Shows existence of Na Figure 1 (a) and (b).A cathode, an anode, an electrolyte, a diaphragm (also known as a separator), and a metallic collector make up an example SIB design. The fundamental electrochemical and physical differences between sodium and lithium ions create distinct performance characteristics for their respective battery technologies[1]–[4].

Sodium ions are significantly larger than lithium ions, with an ionic radius of 1.02 Å compared to lithium's 0.76 Å This size difference has profound implications for ion intercalation kinetics and structural stability during battery operation. The larger sodium ions induce multiple structural evolutions during insertion and extraction processes, resulting in deteriorating host crystal cycling stability [2,3]From an electrochemical perspective, sodium has a higher standard reduction potential of -2.71 V compared to lithium's -3.04 V versus the standard hydrogen electrode [4]This approximately 0.33 V difference means that sodium-based electrode materials will generally operate at higher potentials than their lithium counterparts, directly impacting the overall cell voltage and energy density.[5]. The atomic weight difference further compounds these challenges, with sodium weighing 23 g/mole compared to lithium's 6.9 g/mole. Despite these challenges, the similar chemical properties between sodium and lithium as alkali metals enable sodium ion batteries to function as a "drop-in" technology, using the same cell design and manufacturing lines as lithium ion batteries. However, notable structural compatibility issues exist - for example, due to the energetic instability of sodium-graphite composites, the graphite used as anodes in commercial lithium ion batteries cannot be directly used in sodium ion batteries, The resent developments in battery technology, particularly the creation of inexpensive sodium-ion battery (SIB) electrode materials. The application of graphene-based nanocomposites is highlighted, and production techniques such surface modification, three-dimensional structures, and coatings on active materials are described. The structural characteristics of electrodes, production methods, and the impact of graphene on performance are the main topics of discussion in this assessment of the state of the art. Important mechanisms under investigation include the interaction of graphene with active chemicals, sodium ion insertion processes, and electrochemical reactions in energy storage. Lastly, it outlines the challenges faced by graphene-based nanocomposites and suggests directions for further research [6-7]. Interestingly, sodium ions have approximately 30% lower desolation energy than lithium, which can result in smaller charge transfer resistance for sodium ion batteries [8]. The main purpose of comparing lithium-ion batteries (LIBs) and sodium-ion batteries (SIBs) is to support better choices about which battery should be used in which job. LIBs remain the benchmark for many products, but rising demand for cheaper, safer, and more scalable storage means alternatives must be judged against them in a structured way rather than in isolation. Several reviews make this explicit: comparison is used to present performance and economic targets side by side, relate academic progress to commercial needs, and test whether newer chemistries are viable for near-term deployment [9]. A second purpose is to identify application fit. Because sodium is abundant and low cost, and because weight matters less in some sectors, comparing SIBs with LIBs helps show why sodium-ion may be attractive for stationary storage, smart grids, backup power, and some low-cost vehicles, even if it does not match LIBs in energy density. In other words, the comparison helps separate markets where LIB performance is essential from markets where lower cost, broader material availability, or sustainability may matter more. A third purpose is to make the trade-offs clearer for research and engineering. Since LIBs and SIBs share the same basic rocking-chair mechanism and similar cell architecture, LIB knowledge can serve as a useful baseline for evaluating sodium systems. At the same time, direct comparison reveals where sodium behaves differently enough that it needs its own materials, interphases, and full-cell design rules. This is useful both for guiding R&D and for avoiding the mistake of assuming sodium-ion is just lithium-ion with a different ions [10]. Finally, the comparison has a planning purpose. Reviews frame battery comparisons as tools for scientists, engineers, industry, and policymakers to make informed decisions about technology selection, industrial adoption, sustainability goals, and future investment. This matters because the key question is no longer only whether sodium-ion works, but whether it is ready enough, cheap enough, and useful enough to complement or replace lithium-ion in specific cases during the broader energy transition.

The main purpose of this review paper is to provide a comprehensive comparative analysis of lithium-ion batteries and sodium-ion batteries for future energy storage applications. This review examines the fundamental working mechanisms, electrode materials, electrolyte systems, electrochemical performance, cycle stability, safety behavior, cost factors, environmental impact, and commercial potential of both battery technologies. By comparing their strengths and limitations, this paper aims to identify which battery system is more suitable for different applications, including electric vehicles, portable electronic devices, renewable energy storage, and grid-scale stationary storage systems. In addition, this review highlights the major scientific and technical challenges that must be addressed to improve the long-term performance, safety, and sustainability of next-generation rechargeable batteries. The novelty of this review paper lies in its integrated comparison of lithium-ion and sodium-ion batteries from both technological and sustainability perspectives. Many previous studies mainly focus on the electrochemical performance of a single battery system; however, this review compares both technologies by considering energy density, material abundance, and cost, safety, recycling potential, environmental impact, scalability, and future commercial application. This broader approach provides a clearer understanding of the practical role of both battery systems in the future energy-storage market. The review also emphasizes that sodium-ion batteries should not simply be considered a direct replacement for lithium-ion batteries, but rather as a complementary technology for low-cost, safe, and large-scale energy storage. Therefore, this paper contributes by presenting a balanced and application-oriented discussion that can help researchers, engineers, and policymakers understand the future direction of sustainable battery development.

2. Performance Parameters Comparisons

Sodium ion batteries typically achieve 20% lower energy density and shorter cycle life compared to lithium ion batteries, but offer superior safety, better low temperature performance, faster charging rates, and lower internal resistance. Current sodium ion prototypes reach 75-200 Wh/kg while lithium ion batteries achieve higher densities. Direct performance comparisons reveal significant trade-offs between sodium and lithium ion technologies across multiple parameters. Energy density represents the most substantial difference, with sodium ion batteries achieving approximately 20% lower energy density than lithium ion systems. Current practical sodium ion prototypes demonstrate energy densities of 75-200 Wh/kg compared to lithium ion equivalents, though theoretical sodium ion energy densities can reach up to 290 Wh/kg for active materials. This gap stems fundamentally from sodium being three times heavier than lithium and having lower standard electrochemical potential, making it difficult for sodium ion batteries to outperform lithium ion systems in energy density, specific capacity, or rate capability.

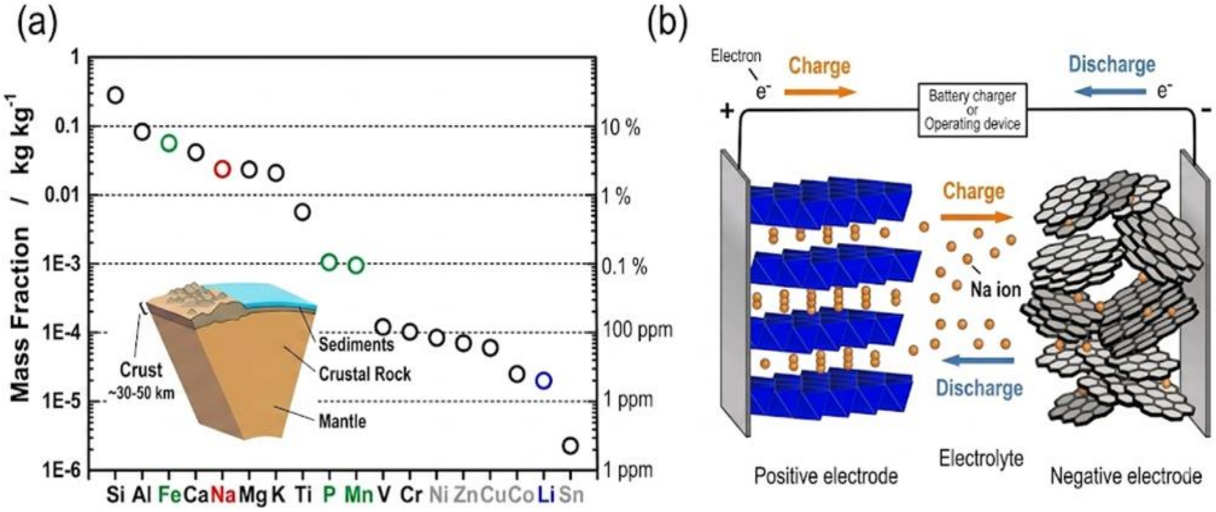


Figure 1. The abundance of major elements in globe (b) Schematic diagram of a sodium-ion battery Pianta, N. et al [2].

Cycle life performance also favors lithium ion technology, with sodium ion batteries achieving approximately 65% of lithium ion battery cycle life . However, advanced sodium ion battery designs have demonstrated up to 4,000 cycles, approaching lithium ion performance levels.Manufacturing consistency shows sodium ion batteries with slightly elevated parameter variations compared to lithium ion systems - capacity variation of 0.53% (comparable to lithium ion) but AC resistance variation of 2.22%, moderately higher than lithium ion batteries due to the relatively nascent state of sodium ion manufacturing technology [11,12]. Despite these limitations, sodium ion batteries demonstrate superior performance in several critical areas. They exhibit better low-temperature performance, with normal working ranges of -40°C to 80°C and some products maintaining over 92% capacity retention at -20°C, significantly outperforming lithium iron phosphate batteries' 60-70% retention at similar temperatures . Safety performance strongly favors sodium ion technology, with stable chemical properties, higher internal resistance generating less instantaneous heat during safety tests, and the ability to discharge to 0V for safer transportation, Additionally, sodium ion batteries demonstrate faster charge-discharge rates and better peak-rate performance compared to lithium ion systems. Electrochemical characteristics also differ notably between the technologies. Many sodium ion electrode materials exhibit capacitor-like features with sloping plateaus in charging/discharging curves, unlike lithium ion materials which typically display fine plateaus. However, the higher half-cell potential of sodium ion batteries (0.3-0.4V higher than lithium ion) allows for wider electrolyte selection ranges and the use of solvents and salts with lower decomposition potentials [13].

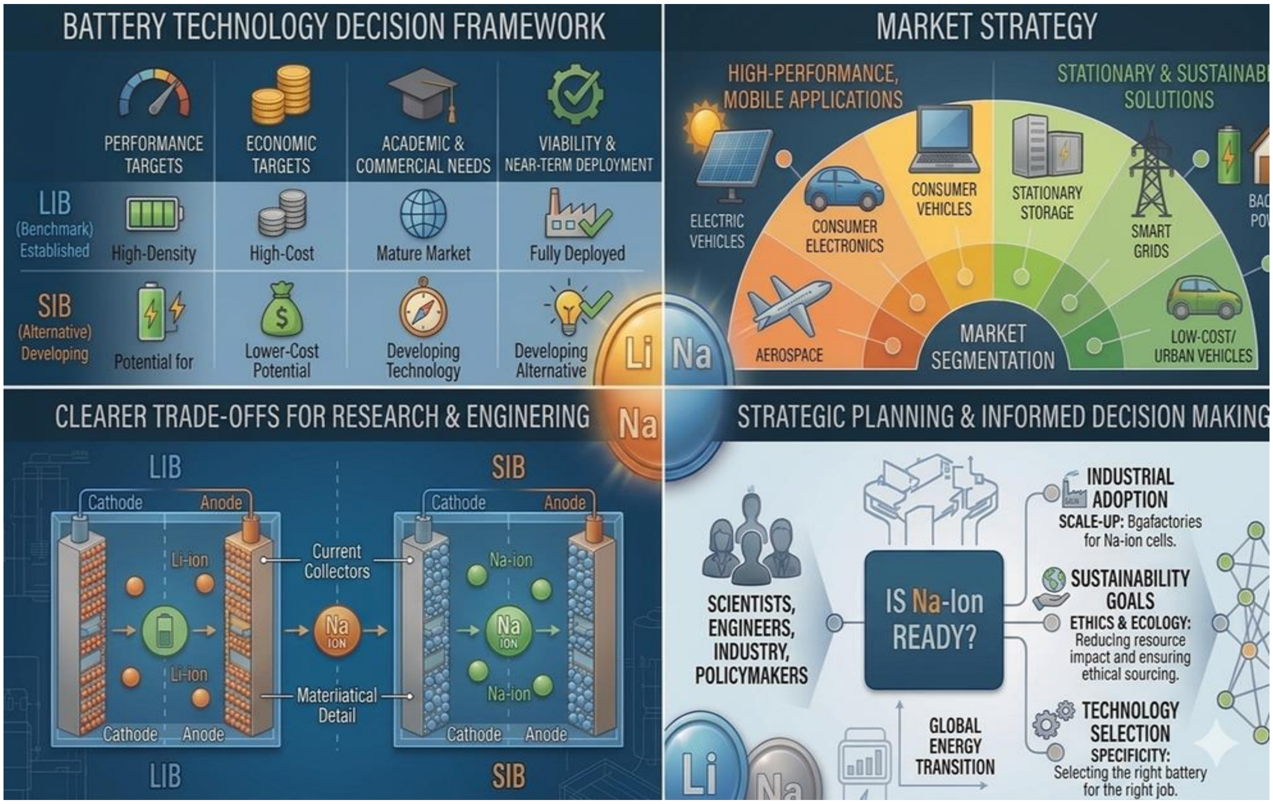


Figure 2. (a) Shows the comparative over of both batteries lithium-ion and sodium-ion and illustrating advantages as well as disadvantages and future energy system.

2.1. Comparing Lithium-Ion and Sodium-Ion Batteries: Advantages, Performance, and Applications.

Lithium-ion batteries (LIBs) are the current mainstream rechargeable batteries for portable electronics, electric vehicles, and many stationary systems because they combine high energy density with long cycle life and mature manufacturing. Interest in sodium-ion batteries (SIBs or NIBs) has grown because lithium resources are more limited, more unevenly distributed, and expected to become more costly as demand rises, while sodium is abundant, widely distributed, and inexpensive.[14]. A commonly cited resource advantage is that sodium makes up about 2.7-2.8 wt% of the Earth's crust, versus roughly 0.0065 wt% for lithium. At the cell level, LIBs and SIBs share the same basic "rocking-chair" working principle: during charge, alkali ions leave the positive electrode and insert into the negative electrode through the electrolyte, while electrons move through the external circuit; during discharge, the process reverses. In sodium-ion cells specifically, Na+ is de-inserted from the cathode and inserted into the anode during charging, then moves back to the cathode during discharge. Because sodium and lithium are both group-1 alkali metals with similar electrochemical behavior, many LIB ideas, synthesis routes, and cell formats can be adapted to SIBs, including cylindrical, prismatic, and pouch designs. Overall, the comparison starts from a shared operating concept but quickly becomes a materials problem: LIBs are more established and optimized, while SIBs aim to trade some of that maturity for lower raw-material cost, wider resource availability, and better long-term supply sustainability. The main strengths of lithium-ion batteries are well established: they offer high gravimetric and volumetric energy density, high charge-discharge efficiency, good power capability, long cycle life, low self-discharge, and a mature commercial base, which is why they remain the default choice for portable electronics and many electric vehicles.[15]. Their main drawbacks are cost, safety concerns tied to flammable electrolytes and thermal runaway, and dependence on less abundant or unevenly distributed raw materials, especially lithium and often cobalt and nickel. The price that is high price of lithium or sodium salts alone is usually not the main cost driver; transition metals such as cobalt and nickel can matter more for total cell cost and supply risk. Sodium-ion batteries have a different value case. Their clearest advantages are the abundance and broad geographic availability of sodium, lower precursor cost, and the possibility of reducing reliance on expensive or supply-constrained elements, which makes them appealing for sustainable and large-scale storage .Several papers also point to practical cost benefits from cell design, such as the use of aluminum instead of copper on the anode current collector, and to the fact that many SIBs can reuse much of the existing LIB manufacturing know-how and formats. SIBs also face materials-specific disadvantages: graphite is generally not a practical anode host for Na+, hard carbon usually gives lower capacity and higher voltage hysteresis, and alloy anodes are available from a smaller set of elements and can follow more complex reaction paths than in LIBs. On the cathode side, sodium layered oxides can provide good capacity and voltage but often suffer from poor cycling stability, while polynomic compounds tend to be more structurally stable and thermally robust but often have lower capacity and weaker rate capability.[15,16].

2.2. Cost and Resource Availability

Sodium's abundance (2.74% of Earth's crust vs 0.0065% for lithium) provides significant cost advantages, with sodium ion batteries potentially 30% cheaper than lithium system. While current sodium ion batteries cost $223/kWh compared to $168/KWh for high-density lithium systems, manufacturing compatibility and reduced raw material costs make promising for large-scale applications. The fundamental resource advantage of sodium over lithium creates compelling economic incentives for sodium ion battery development. Sodium is extraordinarily abundant, comprising approximately 2.74% of the Earth's crust compared to lithium's mere 0.0065%, making sodium over 420 times more abundant. This translates to sodium being the sixth most abundant element on Earth with content of about 23,000 ppm versus lithium's 17 ppm (,Critically, sodium resources are distributed worldwide and completely free from geographical constraints, unlike lithium deposits which are concentrated in specific regions and prone to supply chain vulnerabilities. Current cost analyses reveal mixed but promising economic prospects for sodium ion batteries. Direct manufacturing cost comparisons show sodium ion batteries achieving $223/kWh compared to $229/kWh for lithium iron phosphate and $168/kWh for high-energy nickel manganese cobalt lithium batteries (,However, theoretical cost projections suggest sodium ion batteries could achieve $40-77/kWh, representing approximately 30% cost reduction compared to lithium iron phosphate systems [.The cost advantages stem from multiple factors: abundant raw materials reducing material costs by approximately half when using iron-manganese-nickel cathodes, the ability to use aluminum current collectors on both electrodes (since sodium doesn't alloy with aluminum unlike lithium), and compatibility with lower concentration electrolytes [18].Manufacturing compatibility provides additional economic benefits through reduced infrastructure investment requirements. Sodium ion batteries function as "drop-in" technology that can utilize existing lithium ion battery production lines and equipment, 1minimizing capital expenditure for manufacturers transitioning between technologies. This manufacturing similarity extends to cell design and assembly processes, though some material substitutions are necessary - particularly graphite anodes which cannot be used in sodium systems due to poor sodium intercalation.The economic case for sodium ion batteries strengthens significantly for large-scale applications where the cost advantages of abundant raw materials become most pronounced [19-20] While lithium's limited availability and consequent price escalations create sustainability concerns for massive grid storage deployments, sodium's abundance positions sodium ion batteries as particularly attractive for stationary energy storage, grid applications, and large-scale renewable energy integration where cost per kWh matters more than energy density So in simple terms, LIBs are better when compact size, low weight, and maximum performance are the top priorities, while SIBs are better positioned where low cost, resource security, and scale matter more, even if the cell is larger or heavier for the same stored energy.[21-22].

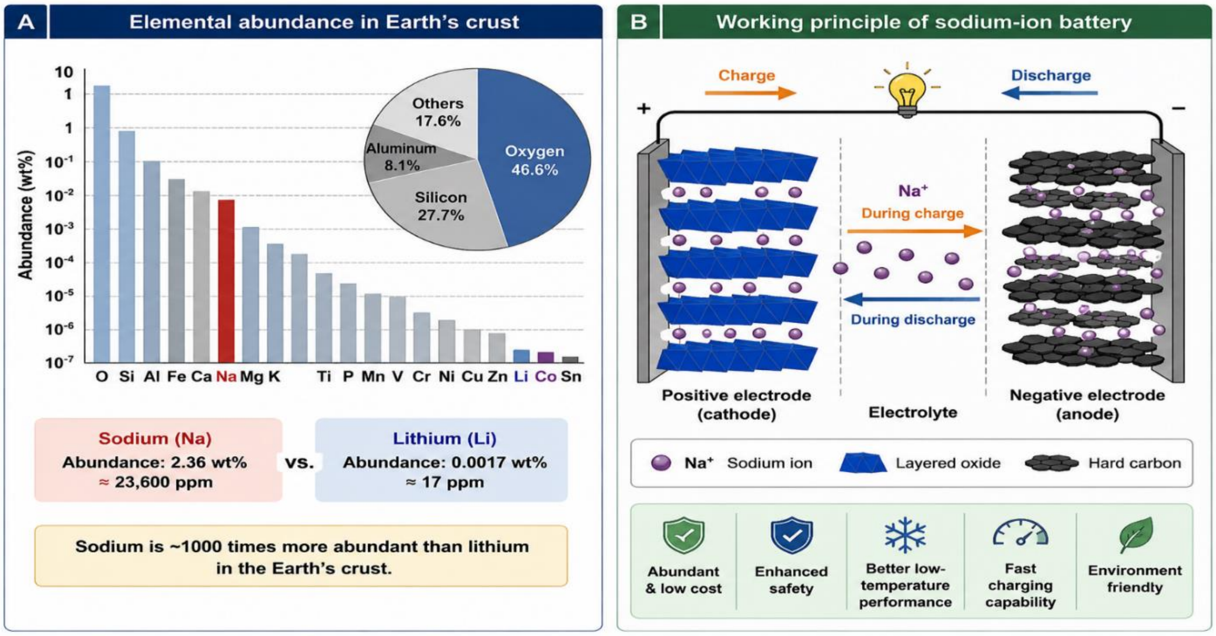


Figure 3. Production of sodium and lithium-ion battery.

2.3. Manufacturing and Compatibility

All the headings in the main body of your paper are Sodium ion batteries are considered "drop-in" technology that can use existing lithium ion battery manufacturing lines and equipment, reducing infrastructure costs. Key difference includes the need for alternative anode materials since graphite doesn't work sodium, and the advantages of using aluminum current collectors on both electrodes. The manufacturing compatibility between sodium and lithium ion batteries represents one of the most significant advantages for sodium ion technology adoption. Due to the similar chemical properties of sodium and lithium as alkali metals, sodium ion batteries can use the same cell design and manufacturing lines as lithium ion batteries [23] This compatibility makes sodium ion batteries a "drop-in" technology that can be produced using existing infrastructure for lithium ion batteries, eliminating the need for new production facilities and significantly reducing capital investment requirements. The shared manufacturing processes extend beyond basic assembly to include similar recyclability and working principles. Both battery types follow comparable production methodologies, materials processing, and equipment requirements, though some notable material substitutions are necessary [24]. Figure(2): Comparison of sodium-ion batteries (SIBs) and lithium-ion batteries (LIBs) in terms of ionic size, electrochemical potential, energy density, safety, temperature performance, and application domains, adapted from published literature

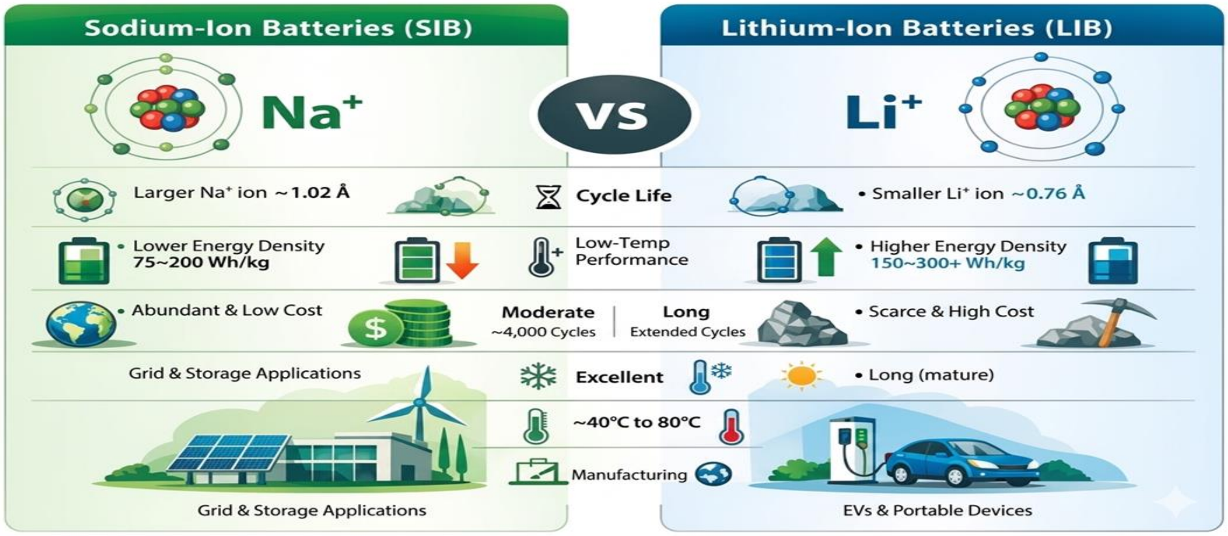


Figure 4. (a) Comparison of sodium-ion batteries (SIBs) and lithium-ion batteries (LIBs) . Hounjet, L. J et al.[23].

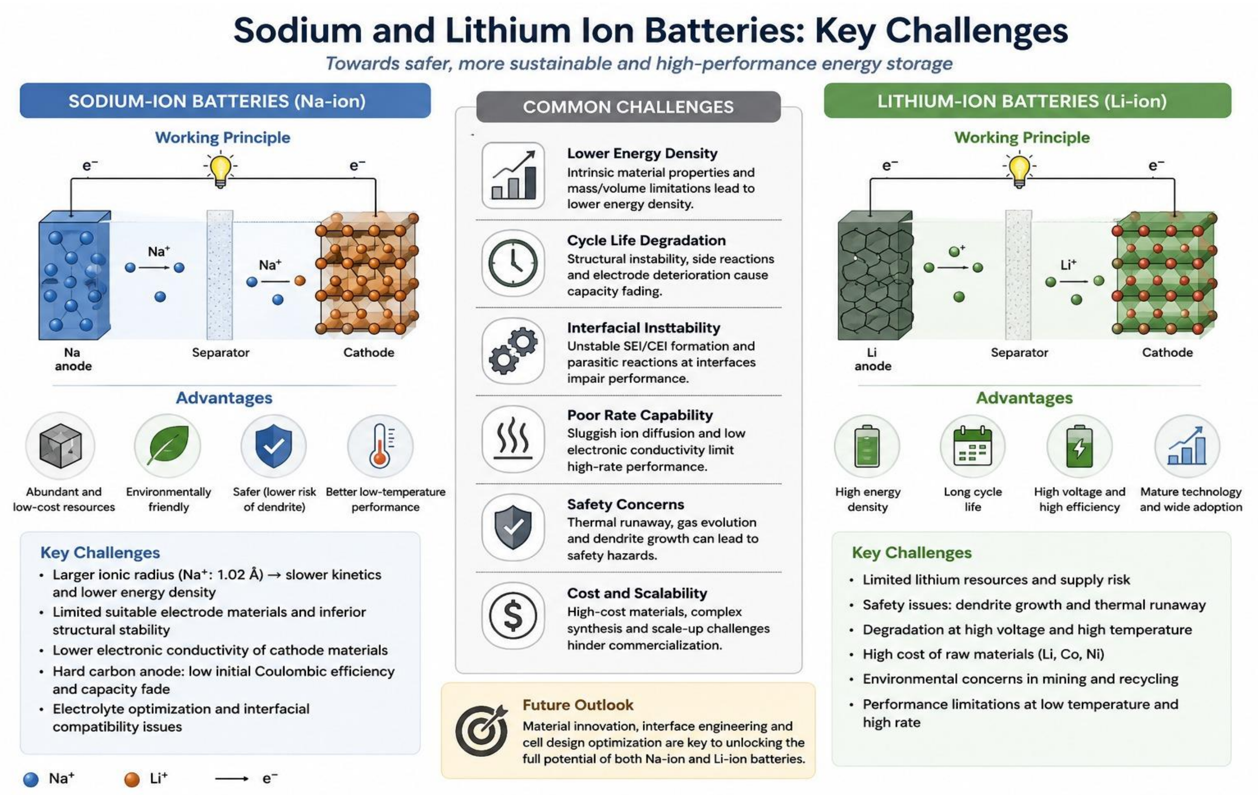
Critical manufacturing differences center primarily on material selection rather than process changes. Graphite, the standard anode material for commercial lithium ion batteries, cannot be used in sodium ion systems since the larger sodium ions do not intercalate readily into the graphitic structure This necessitates alternative anode materials development, though the fundamental manufacturing processes remain compatible. A significant manufacturing advantage for sodium ion batteries lies in current collector selection. Unlike lithium, sodium does not alloy with aluminum, allowing sodium ion batteries to use aluminum current collectors on both the anode and cathode sides instead of the expensive copper collectors required for lithium ion anodes, This substitution not only reduces manufacturing costs but also makes the battery safer and lighter weight, as aluminum is more affordable and lightweight than copper [24]. Despite the manufacturing similarities, some physicochemical differences between sodium and lithium create distinct behaviors in coordination preferences, desolation energies, and solid-electrolyte interphase component solubility. However, these differences primarily affect material formulation rather than fundamental manufacturing processes, maintaining the overall compatibility advantage that positions sodium ion batteries as a transformative technology for large-scale energy storage applications [25]. One practical design advantage is current collection: unlike LIB anodes, which normally require copper foil because aluminum alloys with lithium near low potential, many SIBs can use aluminum foil on both electrodes. This can reduce cost and mass, since battery-grade aluminum is reported to cost about three times less than battery-grade copper foil, though copper still has higher electronic conductivity. Cathode development is similarly a balancing act. Current SIB work focuses heavily on transition-metal oxides and Prussian blue analogs, while other reviews also discuss polynomic and organic options, each with different trade-offs in cost, stability, voltage, conductivity, and scalability. The hard part is that the larger Na+ ion drives stronger lattice strain and larger volume change during insertion and extraction, so electrode particles are more prone to cracking, structural collapse, and loss of cycling stability than analogous LIB materials. This same size effect also slows Na transport in many hosts, which makes it harder to achieve both high rate capability and long cycle life at the same time. In practice, this means sodium-ion cell design often has to be more conservative about electrode loading, particle morphology, porosity, and cutoff conditions to avoid mechanical damage and unstable interfaces (Model- Generated). Beyond active materials, cell engineering still matters a lot. Recent comparisons of commercial or near-commercial SIB cells show that differences in electrode coating, particle size, and cathode composition can translate directly into differences in electrical behavior, underscoring that sodium-ion performance is highly sensitive to manufacturing details and not just chemistry choice. [26-27]. Low-temperature operation is also a notable technical challenge in real cells: although some reviews argue SIBs can perform well across wide temperatures, found that maintaining sodium-ion performance, especially at low temperature, remains difficult in practice. So the technical picture is mixed but clear: SIBs benefit from abundant materials, lower-cost current collectors, and partial manufacturing compatibility with LIBs, but they still need better anodes, more stable cathodes, and tighter control of interphase and structural degradation before they can match the robustness of mature lithium-ion designs across a wide range of uses [28].

3. Performance characteristics and trade-offs

In performance terms, the central trade-off is that sodium-ion batteries usually deliver lower cell voltage, lower specific capacity, and therefore lower energy density than lithium-ion batteries, even when the two systems use broadly similar intercalation chemistry. This comes from sodium's more positive redox potential, higher atomic weight, and larger ionic rad ions, which together reduce voltage and capacity and also tend to slow reaction kinetics. As a result, practical sodium-ion cells are often reported in the roughly 75-200 Wh/kg range today, with many current systems clustering around about 100-150 Wh/kg or 125-150 Wh/kg, whereas mainstream lithium-ion chemistries are commonly higher and can reach around 180 Wh/kg for LFP and substantially more for ternary lithium-ion systems. A representative comparison cited by Paul et al. gives about 275 Wh/kg for an NMC/graphite lithium-ion cell versus around 200 Wh/kg for sodium-ion examples based on $NaCoO2$/hard carbon or $NaFePO4$/sodium metal, again showing the energy gap even when sodium-ion performance is respectable.[29-31]. Cycle life and durability are another mixed but important comparison point. Lithium-ion has the advantage of maturity and well-optimized long-life chemistries, but sodium-ion is improving quickly and is already reported to reach several thousand cycles in some advanced designs, with figures around 4,000 cycles noted in recent review literature [32]. At the same time, performance retention in sodium-ion cells remains strongly tied to material choice, especially cathode structural stability and the balance between extracting more capacity at high cut-off voltage and preserving long-term cycling stability. This means sodium-ion development often involves a sharper engineering trade-off between pushing energy upward and keeping cycle life, safety, and cost acceptable. [33-35]. Temperature behavior can also favor sodium-ion in some practical settings. Shu et al. report that sodium-ion cells can show a fairly linear relation between state of charge and open-circuit voltage, which can simplify battery management, and that capacity remains relatively stable from about 15 °C to 35 °C, though it drops significantly outside that range. Other recent reviews go further and describe sodium-ion batteries as potentially offering better temperature performance or all-climate suitability, although this should be taken as chemistry- and design-dependent rather than universal.. So the practical picture is clear: lithium-ion remains better when the goal is the most energy in the smallest and lightest pack, while sodium-ion becomes attractive when acceptable energy density, decent power, improving cycle life, and lower cost are a better fit than peak performance. In other words, lithium-ion wins the performance race overall, but sodium-ion can still be the better system-level choice when the trade-off shifts from “maximum energy” to “good enough performance at lower cost and larger scale”[36].

4. Current challenges and limitations

Sodium ion batteries face significant technical challenges including lower energy density due to sodium’s larger size and higher electrochemical potential, poor structural stability from volume changes during cycling, slower ion kinetics, and the inability to use standard graphite anodes, though these limitations are being addressed through ongoing research and development. The fundamental physical and electrochemical differences between sodium and lithium create substantial technical challenges that limit sodium ion battery performance. The larger ionic radius of sodium (1.02 Å compared to lithium's 0.76 Å) causes more severe structural problems during battery operation, as sodium ions produce more remarkable volume changes in the charge and discharge process, resulting in collapse and crushing of electrode structures. This size difference leads to inferior reversible capacity and poor lifespan, making sodium ions more prone to damaging the physical structure of active materials during insertion and extraction, ultimately decreasing material cycling stability [39]. The electrochemical limitations further compound performance challenges. Sodium's higher standard reduction potential (-2.71 V versus lithium's -3.04 V) creates an inherent energy density disadvantage, with the electrode potential gap of approximately 300 mV significantly affecting overall battery energy density. Additionally, the slower insertion and extraction speed of larger sodium ions in electrode materials compared to lithium ions creates significant challenges in cycle life and rate capability performance [40].



Sodium and Lithium Ion Batteries: Key Challenges

Towards safer, more sustainable and high-performance energy storage

SODIUM-ION BATTERIES (Na-ion)

Working Principle

Advantages

Key Challenges

- Larger ionic radius (Na⁺: 1.02 Å) → slower kinetics and lower energy density
- Limited suitable electrode materials and inferior structural stability
- Lower electronic conductivity of cathode materials
- Hard carbon anode: low initial Coulombic efficiency and capacity fade
- Electrolyte optimization and interfacial compatibility issues

COMMON CHALLENGES

Lower Energy Density
Intrinsic material properties and mass/volume limitations lead to lower energy density.

Cycle Life Degradation
Structural instability, side reactions and electrode deterioration cause capacity fading.

Interfacial Insttability
Unstable SEI/CEI formation and parasitic reactions at interfaces impair performance.

Poor Rate Capability
Sluggish ion diffusion and low electronic conductivity limit high-rate performance.

Safety Concerns
Thermal runaway, gas evolution and dendrite growth can lead to safety hazards.

Cost and Scalability
High-cost materials, complex synthesis and scale-up challenges hinder commercialization.

Future Outlook
Material innovation, interface engineering and cell design optimization are key to unlocking the full potential of both Na-ion and Li-ion batteries.

LITHIUM-ION BATTERIES (Li-ion)

Working Principle

Advantages

Key Challenges

- Limited lithium resources and supply risk
- Safety issues: dendrite growth and thermal runaway
- Degradation at high voltage and high temperature
- High cost of raw materials (Li, Co, Ni)
- Environmental concerns in mining and recycling
- Performance limitations at low temperature and high rate

Figure 5. (a) Figure shows comparisons challenges of sodium and lithium ion Batteries and key challenges.

Material compatibility issues present critical manufacturing challenges. Commercial graphite anodes cannot be directly used in sodium ion batteries due to the thermodynamic instability of sodium-graphite composites and small interlayer spacing (0.334 nm), resulting in limited specific capacity and low discharge voltage. This forces the development of alternative anode materials, which has become a research hotspot but remains an ongoing challenge. Performance characteristics reveal additional limitations compared to lithium ion systems. Many sodium ion electrode materials exhibit capacitor-like features with only sloping plateaus in charging and discharging curves, unlike lithium ion materials which display fine plateaus, resulting in inferior electrochemical performance ([41-43] The cycle life of sodium ion batteries is clearly inferior to that of lithium ion batteries, with overall lower energy density making them less suitable for applications where weight and space are critical factors. [44].

Table 1 Comparison of key properties of sodium-ion batteries (SIBs) and lithium-ion batteries (LIBs).

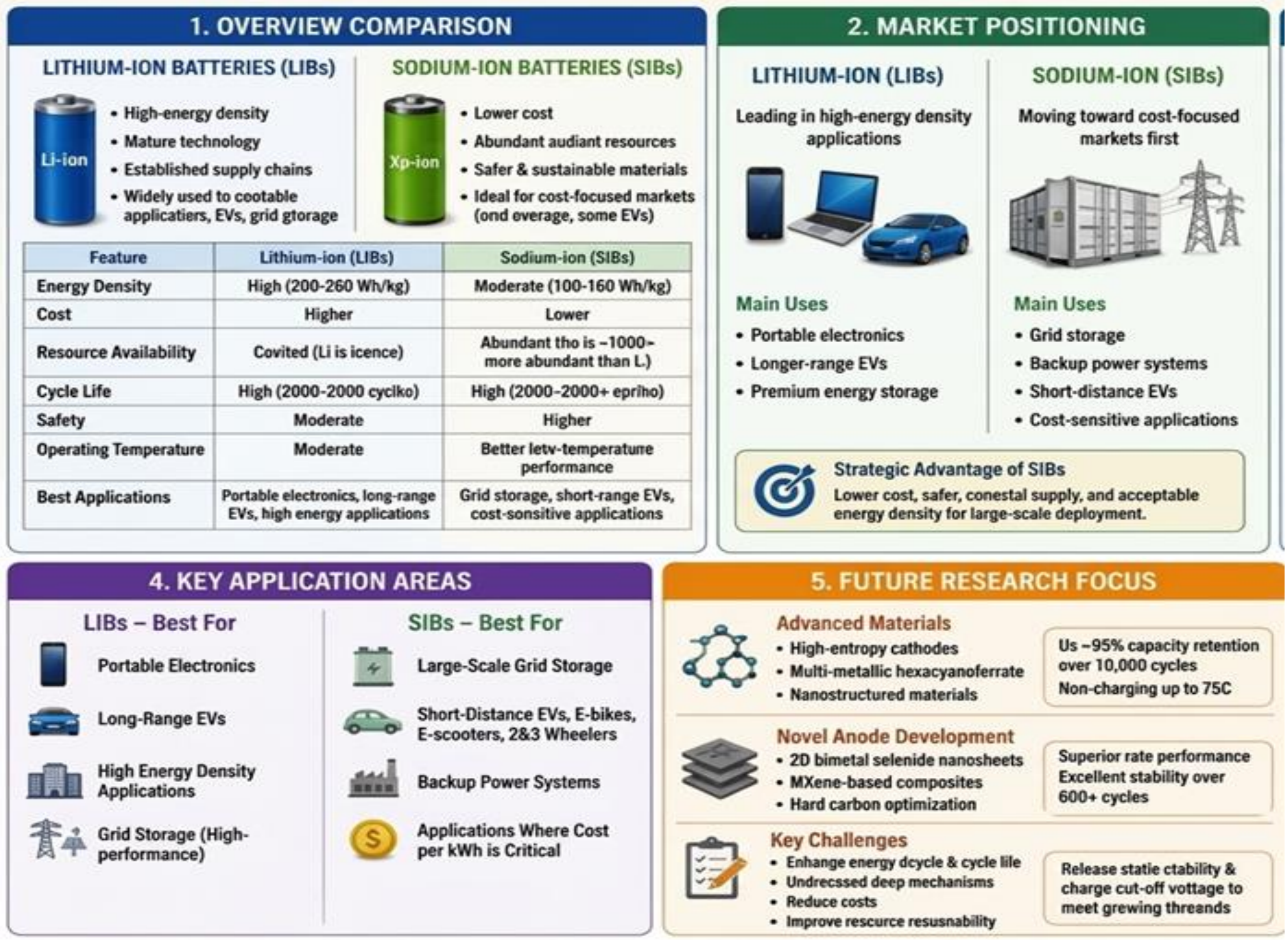
Properties	Sodium-Ion (SIB)	Lithium-Ion (LIB)
Charge Carrier	Na^+	Li^+
Ionic Radius	Large(≈1.02 Å)	Small (≈0.76 Å)
Redox Potential	-2.71 V	−3.04 V
Cell Voltage	Lower	Higher
Low temp Performance	Excellent	Limited
Safety	High stability	Thermal risk
Anode Material	Hard carbon / alloys	Graphite

Current Collector	Al (both electrodes)	Cu + Al
Resource Availability	Very abundant	Limited
Cost Potential	˜30% lower (projected)	Higher
Best Use Case	Grid & stationary storage	EVs & portable devices

Despite these significant challenges, ongoing research continues to address structural instability issues, develop new materials, and improve production efficiency for sodium ion batteries. Future development efforts focus on enhancing energy density, cycle stability, and rate capability while reducing costs to make sodium ion technology more competitive with established lithium ion systems. [42]. One practical design advantage is current collection: unlike LIB anodes, which normally require copper foil because aluminum alloys with lithium near low potential, many SIBs can use aluminum foil on both electrodes. This can reduce cost and mass, since battery-grade aluminum is reported to cost about three times less than battery-grade copper foil, though copper still has higher electronic conductivity. Cathode development is similarly a balancing act. Current SIB work focuses heavily on transition-metal oxides and Prussian blue analogs, while other reviews also discuss polynomic and organic options, each with different trade-offs in cost, stability, voltage, conductivity, and scalability. The hard part is that the larger Na+ ion drives stronger lattice strain and larger volume change during insertion and extraction, so electrode particles are more prone to cracking, structural collapse, and loss of cycling stability than analogous LIB materials. [43]. This same size effect also slows Na transport in many hosts, which makes it harder to achieve both high rate capability and long cycle life at the same time. In practice, this means sodium-ion cell design often has to be more conservative about electrode loading, particle morphology, porosity, and cutoff conditions to avoid mechanical damage and unstable interfaces (Model Generated). Beyond active materials, cell engineering still matters a lot. Recent comparisons of commercial or near-commercial SIB cells show that differences in electrode coating, particle size, and cathode composition can translate directly into differences in electrical behavior, underscoring that sodium-ion performance is highly sensitive to manufacturing details and not just chemistry choice. Low-temperature operation is also a notable technical challenge in real cells: although some reviews argue SIBs can perform well across wide temperatures. Found that maintaining sodium-ion performance, especially at low temperature, remains difficult in practice. So the technical picture is mixed but clear: SIBs benefit from abundant materials, lower-cost current collectors, and partial manufacturing compatibility with LIBs, but they still need better anodes, more stable cathodes, and tighter control of interphase and structural degradation before they can match the robustness of mature lithium-ion designs across a wide range of uses. [28-45].

5. Future Technology Development Commercialization Look and Applications.

Lithium-ion batteries will likely keep leading uses where high energy density and mature supply chains matter most, especially in portable electronics and longer-range electrical vehicles. Sodium- ion batteries are moving toward cost focused markets first, especially grid storage and some vehicles where lower cost, safer material supply, and acceptable rather than maximum energy density are the key needs. Sodium-ion batteries are positioned for rapid commercialization and market deployment, particularly in large-scale energy storage and grid applications where cost advantages outweigh energy-density limitations. Current commercial developments show promising performance, with energy densities of up to 160 Wh/kg and fast-charging capabilities. Future research is focused on enhancing electrode materials and addressing remaining technical challenges. The commercialization pathway for sodium-ion technology has accelerated significantly, and the technology is now considered to be on the brink of widespread market adoption. Based on outstanding results in power capability, and safety, sodium-ion battery commercialization is viewed as imminent. Real-world industrial progress further supports this momentum, with companies such as CATL producing sodium-ion batteries using Prussian white cathodes and porous hard-carbon anodes, achieving energy densities approaching those of lithium-ion batteries and demonstrating the ability to charge up to 80% within 15 minutes.[45-48]. The strategic positioning of sodium ion batteries centers on specific application domains where their advantages create compelling value propositions. Large-scale energy storage represents the primary target market, where sodium ion batteries are expected to replace or complement lithium ion batteries in medium and large battery markets. Grid-scale energy storage applications particularly benefit from sodium's cost advantages and abundance, positioning sodium ion technology as transformative for renewable energy integration and smart grid applications. The technology shows particular promise for stationary energy storage, short-distance electric vehicles, and applications where cost per kWh matters more than energy density [49].



1. OVERVIEW COMPARISON

LITHIUM-ION BATTERIES (LIBs)

- High-energy density
- Mature technology
- Established supply chains
- Widely used to cootable applicatiers, EVs, grid gtorage

SODIUM-ION BATTERIES (SIBs)

- Lower cost
- Abundant audiant resources
- Safer & sustainable materials
- Ideal for cost-focused markets (ond everage, some EVs)

Feature	Lithium-ion (LIBs)	Sodium-ion (SIBs)
Energy Density	High (200-260 Wh/kg)	Moderate (100-160 Wh/kg)
Cost	Higher	Lower
Resource Availability	Covited (Li is icence)	Abundant tho is ~1000~ more abundant than L.)
Cycle Life	High (2000-2000 cyclko)	High (2000-2000+ epriho)
Safety	Moderate	Higher
Operating Temperature	Moderate	Better letv-temperature performance
Best Applications	Portable electronics, long-range EVs, high energy applications	Grid storage, short-range EVs, cost-sensitive applications

2. MARKET POSITIONING

LITHIUM-ION (LIBs)

Leading in high-energy density applications

Main Uses

- Portable electronics
- Longer-range EVs
- Premium energy storage

SODIUM-ION (SIBs)

Moving toward cost-focused markets first

Main Uses

- Grid storage
- Backup power systems
- Short-distance EVs
- Cost-sensitive applications

Strategic Advantage of SIBs

Lower cost, safer, conestal supply, and acceptable energy density for large-scale deployment.

4. KEY APPLICATION AREAS

LIBs – Best For

- Portable Electronics
- Long-Range EVs
- High Energy Density Applications
- Grid Storage (High-performance)

SIBs – Best For

- Large-Scale Grid Storage
- Short-Distance EVs, E-bikes, E-scooters, 2&3 Wheelers
- Backup Power Systems
- Applications Where Cost per kWh is Critical

5. FUTURE RESEARCH FOCUS

Advanced Materials

- High-entropy cathodes
- Multi-metallic hexacyanoferrate
- Nanostructured materials

Us ~95% capacity retention over 10,000 cycles
Non-charging up to 75C

Novel Anode Development

- 2D bimetal selenide nanosheets
- MXene-based composites
- Hard carbon optimization

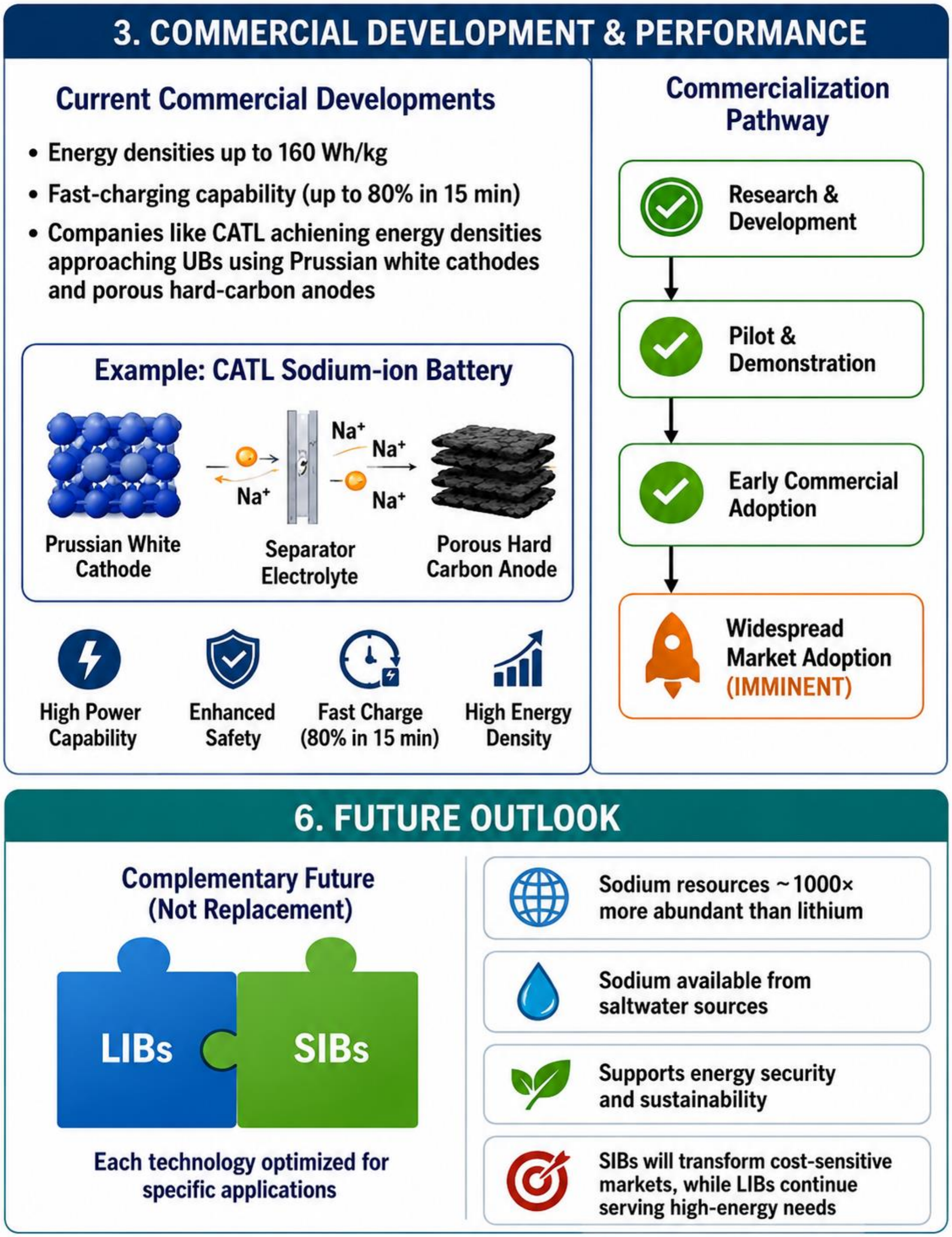
Superior rate performance
Excellent stability over 600+ cycles

Key Challenges

- Enhange energy dcycle & cycle lile
- Undrecssed deep mechanisms
- Reduce costs
- Improve rescurce resusnability

Release statie ctability & charge cut-off vottage to meet grewing threands

Figure 6. (a) Figure shows the overview comparison on lithium-ion vs sodium-ion batteries with key application



3. COMMERCIAL DEVELOPMENT & PERFORMANCE

Current Commercial Developments

- Energy densities up to 160 Wh/kg
- Fast-charging capability (up to 80% in 15 min)
- Companies like CATL achiening energy densities approaching UBs using Prussian white cathodes and porous hard-carbon anodes

Example: CATL Sodium-ion Battery

Commercialization Pathway

- Research & Development
- Pilot & Demonstration
- Early Commercial Adoption
- Widespread Market Adoption (IMMINENT)

6. FUTURE OUTLOOK

Complementary Future (Not Replacement)

Each technology optimized for specific applications

- Sodium resources ~1000× more abundant than lithium
- Sodium available from saltwater sources
- Supports energy security and sustainability
- SIBs will transform cost-sensitive markets, while LIBs continue serving high-energy needs

Figure 7. (b) Performance and future outlook shows the overview comparison on lithium-ion vs sodium-ion batteries with key application.

Lithium-ion batteries will likely keep leading uses where high energy density and mature supply chains matter most, especially in portable electronics and longer-range electric vehicles. Sodium-ion batteries are moving toward cost-focused markets first, especially grid storage and some vehicles where lower cost, safer material supply, and acceptable rather than maximum energy density are the key needs. Lithium-ion remains the default for high-energy mainstream markets. Lithium-ion batteries are still the most widely used option in electric vehicles, portable electronics, and grid storage because they offer high energy and power density and already have a large commercial base. That makes LIBs the safer near-term choice when manufacturers want proven performance, established suppliers, and broad field experience. [50] Sodium-ion is strongest first in cost-sensitive stationary storage. The clearest early application for sodium-ion is grid and other stationary energy storage, where low cost, material abundance, and supply security can matter more than minimizing battery weight or volume. This matches the broader view that Na-ion is a practical alternative where pressure on critical mineral supply is a concern and where sustainable large-scale storage is a priority. [51-54]. Electric vehicles are possible for both, but likely in different segments. The literature points to sodium-ion batteries as a possible contributor to future EVs, but not necessarily as a full replacement for lithium-ion across all vehicle classes. A more realistic outlook is market segmentation: LIBs remain favored for longer-range and weight-sensitive vehicles, while SIBs can fit lower cost EVs, short-range urban vehicles, two- and three-wheelers, buses, or hybrid pack designs where cost and supply resilience matter more than maximum range.[52]. Future research and development efforts focus on addressing remaining technical limitations through advanced materials design and engineering approaches. Nanotechnology applications have emerged as a key strategy for overcoming challenges related to sodium ion extraction and insertion during charge-discharge cycles, efficiently improving sodium storage capacity, energy density, and cycle performance[55-57].Advanced cathode materials research includes high-entropy concepts and multi-metallic hex cyanoferrate systems, with some achieving impressive cycling stability of 95% capacity retention after 10,000 cycles and outstanding fast-charging capability up to 75C.Novel anode development strategies involve two-dimensional bimetal selenide Nano sheets coupled with MXene substrates, delivering superior rate performance and excellent stability over 600 cycles.[58-61] The future technological landscape anticipates complementary roles for both battery chemistries rather than complete replacement scenarios. Sodium ion batteries are expected to form a complementary industrial pattern with lithium ion batteries, with each technology optimized for specific applications. As science and technology advance and sodium ion battery technology improves, the expectation is that sodium ion batteries will eventually replace lithium ion batteries in cost-sensitive applications while lithium ion technology continues serving high-energy-density requirements. Future development challenges for both technologies include enhancing capacity and cycle performance, elucidating deep mechanisms, reducing costs, and improving resource sustainability, with particular focus on balancing cycle stability and charge cut-off voltage to meet growing battery application demands. [62]. the strategic significance extends beyond technical performance to encompass energy security and resource sustainability considerations. With sodium resources globally surpassing lithium reserves by approximately 1000-fold, sodium ion technology offers substantial advantages for countries seeking energy storage independence. The abundant presence of sodium, particularly in saltwater sources, combined with the ability to avoid cobalt, copper, and nickel in favor of more readily available iron-based materials, positions sodium ion batteries as a sustainable alternative for large-scale deployment. This resource advantage, coupled with manufacturing compatibility and demonstrated commercial viability, suggests sodium ion technology will play an increasingly important role in the global transition to sustainable energy storage systems. [63-64].

6. Conclusion

This comparative review shows that lithium-ion batteries and sodium-ion batteries are both important technologies for future energy storage applications. Lithium-ion batteries currently dominate the rechargeable battery market because of their high energy density, long cycle life, high operating voltage, and mature commercial development.

1. Lithium-ion batteries are widely used in portable electronics, electric vehicles, and advanced energy storage systems. However, they still face several challenges, including the high cost and limited availability of lithium, cobalt, and nickel, as well as environmental concerns related to mining and battery production.
2. Sodium-ion batteries are emerging as a promising alternative because sodium is abundant, inexpensive, and widely distributed. These advantages make sodium-ion batteries suitable for low-cost and large-scale stationary energy storage applications, especially for renewable energy storage and grid-scale systems.
3. Despite their advantages, sodium-ion batteries still have technical limitations, including lower energy density, slower ion diffusion, electrode instability, low initial Coulombic efficiency, and capacity fading during long-term cycling. These limitations are mainly related to the larger ionic radius and heavier atomic mass of sodium compared with lithium.
4. Overall, lithium-ion and sodium-ion batteries should be considered complementary technologies rather than direct competitors. Lithium-ion batteries are more suitable for high-energy and compact applications, while sodium-ion batteries have strong potential for sustainable, safe, and cost-effective future energy storage systems.

7. Future Study

1. Future studies should focus on developing advanced electrode materials with higher capacity, better structural stability, and improved cycling performance. For lithium-ion batteries, more attention should be given to cobalt-free cathodes, high-voltage cathodes, and silicon-based anodes. For sodium-ion batteries, hard carbon anodes, layered oxide cathodes, Prussian blue analogues, and polyanionic cathode materials require further improvement.
2. More research is needed on electrolyte development to improve battery safety, stability, and lifetime. Solid-state electrolytes, gel polymer electrolytes, ionic liquid electrolytes, and highly concentrated electrolytes should be further explored to reduce electrolyte decomposition, dendrite growth, gas generation, and thermal runaway.
3. Future research should investigate interface engineering and solid electrolyte interphase control because unstable electrode-electrolyte interfaces are major causes of capacity fading and poor cycle life. Protective coatings, artificial SEI layers, electrolyte additives, and surface modification strategies can help improve long-term electrochemical performance.
4. Further studies should compare lithium-ion and sodium-ion batteries from a sustainability perspective. Future research should include recycling, raw material availability, carbon footprint, environmental impact, production cost, resource recovery, and life-cycle assessment to evaluate the long-term feasibility of both battery technologies.
5. Large-scale practical testing is necessary before wider commercial application. Future studies should evaluate both lithium-ion and sodium-ion batteries under real operating conditions, including electric vehicles, renewable energy storage, and grid-scale storage systems. Long-term cycling tests, fast-charging studies, temperature stability analysis, safety evaluation, and cost-performance comparison are essential to confirm their practical reliability.

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