

Sodium Ion Batteries a Cost Effective, Safer, and Longer Life Alternative for Commercial Use of Li-Ion Batteries

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Abstract

Lithium ion batteries deliver high energy density but face persistent limits—capacity fade with cycling, thermal runaway from flammable electrolytes, high and volatile costs tied to scarce lithium and cobalt, and environmental and supply chain pressures from mining and disposal—that constrain large scale commercial deployment. This research concentrates on sodium ion (Na ion) batteries as a practical alternative that prioritizes cost effectiveness, longer lifecycle, sustainability, safety, and delivered energy per cycle. Sodium ion systems leverage abundant sodium to reduce raw material cost and supply risk while approaching Li ion performance through optimized cathodes, hard carbon anodes, and electrolyte engineering. As one review observes, “Sodium ion batteries are becoming increasingly notable as a low cost and resource secure alternative to lithium ion batteries, since there is growing concern about the price and availability of lithium and cobalt.” Recent studies report layered oxide cathodes with capacities of $\sim 100\text{--}180\text{ mAh g}^{-1}$ and hard carbon anodes with reversible capacities near $220\text{--}430\text{ mAh g}^{-1}$, though first cycle losses and sodium transport remain limiting factors. This paper synthesizes cell level strategies, cathode selection (layered oxides, polyanionic, Prussian blue analogues), hard carbon anode optimization, SEI engineering, electrolyte stabilization, and electrode microstructure and map Na ion trade-offs to commercial segments. Quoting the broader survey. This research targets cost effective, higher life cycle, sustainable, safer, and more efficient battery solutions than current Li ion technology for commercial deployment. Key priorities for commercialization are improving first cycle efficiency, enhancing rate capability and low temperature performance, scaling manufacturing, and adopting standardized round trip efficiency and accelerated lifetime testing. With targeted materials and manufacturing advances, Na ion batteries can offer a viable, lower cost, and more sustainable solution for low cost electronics, stationary storage, and cost sensitive mobility.

Keywords: Sodium ion battery, Hard carbon anode, Layered oxide cathode, Prussian blue analogue, Polyanionic cathode, Electrolyte stabilization, SEI engineering, first cycle efficiency, Cycle life, Round trip efficiency, Cost effective energy storage, Supply chain security, Scalable manufacturing, Commercial deployment, Stationary storage.

1. Introduction

Lithium-ion batteries (LIBs) have become the dominant energy storage technology for electric vehicles, portable electronic devices, renewable energy systems, and grid-scale applications. Their widespread adoption is attributed to their high energy density, good cycle performance, and well-established manufacturing infrastructure. However, growing demand for lithium-ion batteries has

increased concerns about the availability and cost of raw materials, supply-chain concentration, environmental impacts, and battery safety. Sodium-ion batteries (SIBs) have emerged as a promising alternative because sodium is abundant, widely distributed, and potentially less expensive to source than lithium. These batteries operate using a similar principle to lithium-ion batteries, but sodium ions

move between the positive and negative electrodes during charging and discharging. Their chemistry can reduce dependence on lithium and, in certain designs, graphite, copper, and other constrained materials. Recent research highlights the potential of sodium-ion batteries for stationary energy storage, renewable energy integration, low-cost mobility, and applications where cost, resource availability, and temperature performance are more important than maximum energy density. Nevertheless, sodium-ion batteries do not universally outperform lithium-ion batteries in safety, cycle life, or cost. Their commercial suitability depends on electrode chemistry, cell design, manufacturing scale, operating conditions, and application requirements. Rechargeable batteries have become essential components of modern electrical and electronic systems. Their applications range from mobile phones and laptops to electric vehicles, renewable energy storage, telecommunications, and industrial backup systems. Lithium-ion batteries have achieved widespread adoption because of their high energy density, good round-trip efficiency, relatively long service life, and mature manufacturing ecosystem. Nevertheless, concerns regarding lithium supply chains, the cost of certain battery materials, thermal safety, and the environmental impacts of extraction have encouraged the development of alternative electrochemical storage technologies. Sodium-ion batteries are attracting considerable research and industrial interest because sodium is abundant and can be obtained from widely available mineral and salt resources. Unlike lithium, sodium does not depend on a similarly constrained global resource base. This characteristic may reduce exposure to certain supply-chain risks, although the final cost of a battery also depends on processing, electrode materials, manufacturing yields, and production scale. Sodium and lithium belong to the alkali-metal group and exhibit related electrochemical behaviour. Consequently, sodium-ion batteries can use a broadly similar operating principle to lithium-ion batteries: sodium ions move between the positive and negative electrodes during charging and discharging. However, sodium ions are larger and heavier than lithium ions, creating differences in electrode

structure, diffusion, voltage, and achievable energy density. The development of sodium-ion batteries has progressed from laboratory research toward commercial products and application-specific demonstrations. Research has concentrated on improving cathode stability, hard-carbon anodes, electrolyte formulations, electrode interfaces, and battery management systems [1] – [4].

2. Literature Review

2.1. Historical Development and Fundamental Principles of Sodium-Ion Batteries

Gao et al. (2024), in A 30-Year Overview of Sodium-Ion Batteries, presented a comprehensive review of the development of sodium-ion battery technology. The authors examined electrode materials, electrolytes, electrochemical mechanisms, and challenges associated with commercial full-cell development. Their work emphasized that laboratory results obtained from half-cell testing do not necessarily translate directly into commercial battery performance. The study identified electrode design, electrolyte optimization, sodium compensation, and cost-performance balancing as important research priorities.

2.2. Comprehensive Review of Sodium-Ion Battery Materials

Phogat, Dey, and Wan (2025) published Comprehensive Review of Sodium-Ion Batteries: Principles, Materials, Performance, Challenges, and Future Perspectives. The authors discussed sodium-ion battery operating principles, electrode materials, electrolyte systems, and emerging applications. Their study highlighted the potential benefits of sodium abundance, lower raw-material costs, and improved material design for stationary storage and renewable energy integration. It also identified energy-density limitations, material stability, and manufacturing performance as important barriers.

2.3. Engineering Challenges and Commercial Applications

Cai et al. (2024), in Challenges and Industrial Perspectives on the Development of Sodium Ion Batteries, examined the technological and industrial challenges associated with sodium-ion battery commercialization. The review addressed the relationship between material selection,

electrochemical performance, manufacturing requirements, and practical applications. It highlighted the need to improve the performance of sodium-ion cells while maintaining cost advantages and ensuring compatibility with large-scale production [5-8].

2.4.Applications and Performance Characteristics

Bača et al. (2025), in Sodium-Ion Batteries: Applications and Properties, reviewed the operating characteristics and potential applications of sodium-ion batteries. The authors examined battery chemistry, performance, and suitability for emerging energy storage applications. Their work contributes to understanding how sodium-ion technology may be used in stationary storage, electric mobility, and other applications where its specific performance characteristics offer practical advantages.

2.5.Recent Advances and Commercialization

The 2026 review Sodium-Ion Batteries: Advances, Challenges, and Roadmap to Commercialization evaluated developments in cathodes, anodes, electrolytes, interface engineering, and industrial progress. It discussed hard-carbon anodes, layered oxide cathodes, polyanionic compounds, and Prussian blue analogues. The review also identified challenges involving interfacial stability, volumetric expansion, manufacturing scale-up, and energy density.

2.6.Safety Assessment of Sodium-Ion Batteries

Recent research on sodium-ion battery safety has examined failure mechanisms at the electrode, cell, module, and battery-pack levels. The review Safety of Sodium-Ion Batteries: Evaluation and Perspective from Component Materials to Cells, Modules, and Packs emphasizes that safety depends on electrode chemistry, electrolyte properties, thermal behavior, mechanical design, and battery management. Sodium-ion batteries therefore should not be considered inherently safe under all operating conditions.

2.7.Commercial Competitiveness Compared with Lithium-Ion Batteries

The International Energy Agency (IEA, 2026), in its report Sodium-Ion Battery Momentum Grows, but Challenges Remain, evaluated recent developments

in sodium-ion battery manufacturing and commercial deployment. The IEA highlighted improved low-temperature performance, the potential to reduce dependence on lithium, and opportunities in stationary energy storage.

3. Methodology

3.1.Operating Principle of Sodium-Ion Batteries

A sodium-ion battery consists of a positive electrode (cathode during discharge), a negative electrode (anode during discharge), an electrolyte, a separator, and current collectors. During charging, sodium ions move from the positive electrode through the electrolyte and are stored in the negative electrode. During discharge, the ions move back toward the positive electrode, while electrons flow through the external circuit and deliver electrical energy.

- **Cathode materials:** Common candidates include layered transition-metal oxides, polyanionic compounds, and Prussian blue analogues. Each offers a different balance of voltage, capacity, structural stability, safety, and cost.
- **Anode materials:** Hard carbon is among the most widely investigated practical anode materials because it can store sodium through adsorption, insertion, and pore-filling mechanisms. Its first-cycle irreversible capacity and initial coulombic efficiency remain important engineering considerations.
- **Electrolytes:** Liquid electrolytes containing sodium salts facilitate ion transport. Their composition influences conductivity, interface stability, temperature performance, and safety.
- **Separator:** The separator electrically isolates the electrodes while allowing sodium-ion transport through the electrolyte. Its mechanical and thermal properties contribute to cell safety.
- **Current collectors:** Aluminium can be used as a current collector on the negative side in many sodium-ion designs, potentially reducing reliance on copper compared with conventional lithium-ion anode configurations. The precise choice depends

on electrode chemistry and cell design. The performance of a sodium-ion battery is determined by the interaction of these components rather than by any single material property.

3.2.4-Switch Buck-Boost PMIC

A 4-switch buck-boost Power Management Integrated Circuit (PMIC) is a power-conversion device that regulates an output voltage when the input voltage may be either higher or lower than the

required output voltage. It uses four controlled semiconductor switches, typically MOSFETs, and an inductor to operate in both buck mode (step-down) and boost mode (step-up). This makes it useful in battery-powered devices, energy storage systems, electric vehicles, and portable electronics Shown in Figure 1.

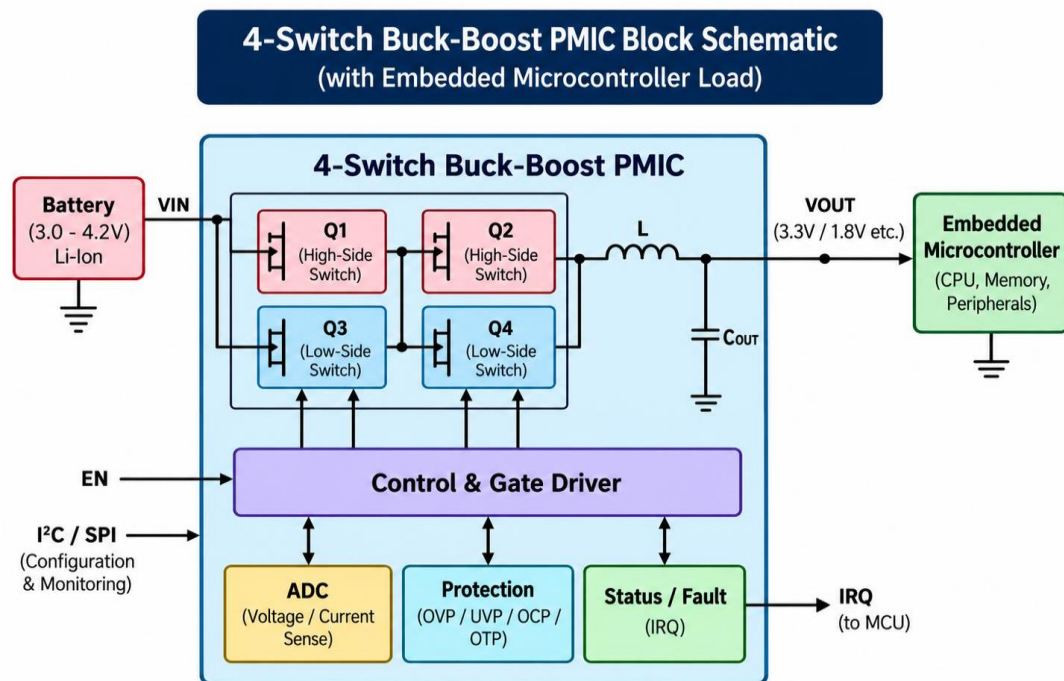


Figure 1 Block Schematic of a Four-Switch Buck–Boost Power Management Integrated Circuit (PMIC) with Embedded Microcontroller Load

3.3.Cost-Effectiveness and Resource Availability

Sodium Abundance

The availability of sodium is a major motivation for sodium-ion battery development. Sodium-containing raw materials are widely distributed, which can reduce dependence on concentrated lithium supply chains. However, abundance alone does not guarantee a cheaper finished battery. Costs also depend on purification, active-material synthesis, electrolyte production, cell assembly, quality control, and manufacturing scale.

Potential Manufacturing Advantages

Sodium-ion batteries share several manufacturing principles with lithium-ion batteries, including

electrode coating, cell assembly, electrolyte filling, and formation cycling. Existing facilities may therefore be adapted, although chemistry-specific equipment settings, process controls, and quality requirements may need modification [9] & [10].

Potential cost benefits include:

- Reduced exposure to lithium price fluctuations.
- Opportunities to use abundant iron- and manganese-based materials.
- Possible reductions in current-collector costs.
- Potential manufacturing synergies with established battery production.
- Greater supply-chain diversification.

These advantages must be confirmed through detailed manufacturing and cost analyses.

3.4. Safety and Thermal Stability

Safety Considerations

Battery safety is a critical factor in electric mobility

and stationary energy storage. Thermal runaway can occur when internal heat generation exceeds heat dissipation and may result in cell venting, fire, or propagation to neighbouring cells Shown in Figure 2.

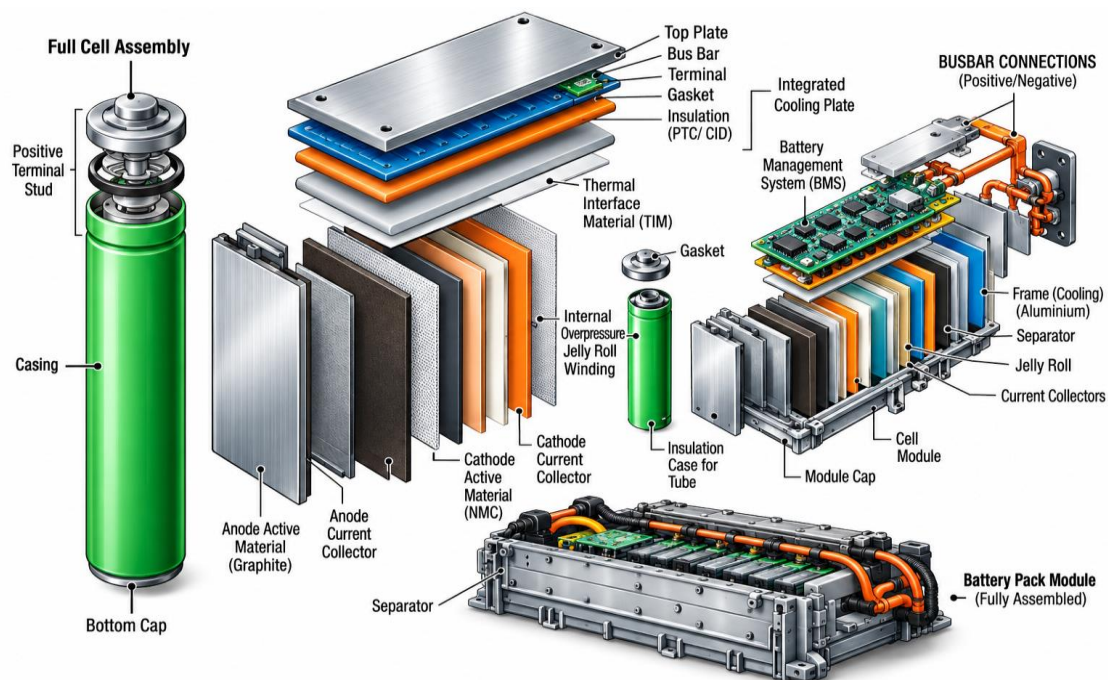


Figure 2 Exploded Structural View of a Lithium-Ion Battery Cell and Electric Vehicle Battery Pack Assembly with Internal Components and Electrical Connections

Some sodium-ion chemistries exhibit promising thermal behaviour, and certain designs may reduce particular safety risks. However, sodium-ion batteries are not inherently immune to thermal runaway, internal short circuits, electrolyte flammability, or manufacturing defects. Safety depends on the cathode and anode chemistry, electrolyte, cell design, operating temperature, state of charge, protection circuitry, and pack-level engineering.

Battery Management System

A battery management system (BMS) monitors voltage, current, and temperature and estimates state of charge (SOC) and state of health (SOH). It protects the battery against operation outside specified limits and helps balance cells within a pack. Sodium-ion batteries require chemistry-specific calibration because their voltage curves, temperature responses, and ageing characteristics may differ from those of lithium-ion batteries. Accurate estimation of SOC

and SOH is important for maximizing usable capacity and maintaining safe operation.

4. Commercial Use of Li-Ion Batteries

Lithium-ion batteries (LIBs) are widely used in commercial and industrial applications because of their high energy density, rechargeable nature, good energy efficiency, and relatively long cycle life. They play a major role in electric transportation, consumer electronics, renewable energy storage, telecommunications, and industrial power systems. For your research paper on sodium-ion batteries as an alternative to lithium-ion batteries, the following commercial applications are important to review.

Electric Vehicles (EVs)

Lithium-ion batteries power electric cars, buses, electric two-wheelers, and commercial delivery vehicles. They provide the energy needed for vehicle propulsion and regenerative braking Shown in Figure 3.



Figure 3 Electric Vehicle Skateboard Chassis Architecture with Integrated Battery Pack, Electric Drivetrain, and Suspension Systems

Renewable Energy Storage

Lithium-ion battery systems store electricity generated by solar panels and wind turbines for use when renewable generation is low. They also support grid balancing and peak-load management.

Consumer Electronics

Smartphones, laptops, tablets, cameras, and wearable devices use lithium-ion or lithium-polymer battery technologies because of their compact size and high energy density.

Telecommunications and Backup Power

Battery systems provide backup electricity for mobile network towers, data centers, hospitals, and uninterruptible power supplies (UPSs) during grid outages Shown in Figure 4.



Figure 4 Battery Energy Storage System (BESS) Integration for Telecommunication Tower Backup Power Applications

Industrial Equipment and Material Handling

Lithium-ion batteries power cordless tools, automated guided vehicles, warehouse forklifts, robotics, and portable industrial equipment.

Electric Two-Wheelers and Micromobility



Figure 5 Electric Scooter with Removable Lithium-Ion Battery Pack and Integrated Battery Compartment

Electric scooters, motorcycles, bicycles, and shared mobility fleets rely on rechargeable battery packs for economic daily transportation Shown in Figure 5.

Conclusion

Sodium-ion batteries represent a promising complementary technology to lithium-ion batteries because of sodium's abundance, potential supply-chain advantages, and suitability for selected stationary and cost-sensitive applications. Their related electrochemical operating principles may also enable adaptation of established battery manufacturing methods. Nevertheless, sodium-ion batteries generally face an energy-density disadvantage compared with leading lithium-ion chemistries, and their safety, cost, and cycle-life performance vary according to chemistry and system design. Their commercial success will depend on improvements in electrode materials, electrolyte stability, first-cycle efficiency, battery management, manufacturing consistency, and recycling. The most appropriate strategy is not to treat sodium-ion batteries as a universal replacement for lithium-ion batteries, but to identify applications in which their

advantages align with operational requirements. Stationary energy storage, renewable integration, backup power, and selected mobility segments are promising opportunities. Rigorous comparative testing and lifecycle cost assessment will be essential for establishing their long-term commercial value.

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