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BATTERIES FOR A SUSTAINABLE ENERGY FUTURE: FROM LITHIUM-ION DOMINANCE TO CIRCULAR STORAGE. A CRITICAL REVIEW

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Abstract:

Battery energy storage has transitioned from portable electronics to critical infrastructure for renewable electricity, e-mobility, distributed generation, and grid flexibility. Connecting electrochemical performance with resource security, manufacturing, safety, lifetime management, and recycling provides a comprehensive sustainability perspective. While lithium-ion systems remain dominant—with lithium-iron-phosphate (LFP) leading stationary storage due to cost, cycle life, and thermal robustness—sodium-ion, lithium-sulfur, and solid-state designs serve as complementary pathways. Abundant sodium diversifies material supplies, whereas solid-state batteries improve safety and energy density despite manufacturing hurdles. Consequently, sustainability extends beyond energy density to the full life cycle: raw-material extraction, electrode processing, cell fabrication, use-phase degradation, second-life deployment, and end-of-life recovery. Innovations in dry electrode processing, fluorine-free electrolytes, failure-informed recycling, and industrial life-cycle assessments increasingly mitigate value-chain impacts. Amid rapid renewable expansion, India exemplifies this surging storage demand. A five-pillar framework—material diversification, low-impact manufacturing, safety-by-design, lifetime maximisation, and closed-loop recovery—supports a technology-diverse landscape: near-term LFP deployment, sodium-ion for cost-sensitive stationary uses, and solid-state or lithium-sulfur systems for specialized niches. Integrating materials science, battery-management systems, digital health monitoring, techno-economic analyses, and recycling engineering ensures batteries deliver maximum useful energy per unit of resource, environmental burden, and cost.

Keywords: *Battery Energy Storage, Sustainable Energy, Lithium-Ion Batteries, Sodium-Ion Batteries, Battery Recycling.*

1. Introduction

The global transition from fossil-fuel-based energy systems to renewable and electrified systems is increasing the importance of rechargeable batteries. Solar and wind generation are variable, electricity demand is becoming more flexible and electrified, and modern power systems require fast balancing, reserve capacity, and time-shifting. Battery energy storage systems (BESS) can provide these services over timescales ranging from milliseconds to several hours. The International Energy Agency (1) reports that 108 GW of new battery-storage capacity was deployed worldwide in 2025, 40% more than in 2024. Lithium-iron-phosphate (LFP) batteries represented about 90% of deployments, illustrating the rapid shift toward a chemistry suited to frequent cycling and cost-sensitive applications.

This rapid expansion creates a sustainability paradox. Batteries enable renewable energy and electrification, but their production requires mining, chemical processing, energy-intensive manufacturing, and eventually end-of-life treatment. A sustainable battery system must therefore be assessed across its complete life cycle rather than through cell-level energy density alone. This paper contributes a practical framework that links chemistry, manufacturing, safety, lifetime, and circularity, with particular attention to the emerging Indian storage market.

2. Current global and Indian scenario

Lithium-ion technology remains the commercial reference because of its high round-trip efficiency, mature manufacturing ecosystem, high power capability, and wide range of cathode chemistries. LFP is particularly attractive for stationary storage because it avoids nickel and cobalt and generally offers long cycle life and good thermal stability. Nevertheless, sustainability depends on the entire production route: precursor preparation, electrode coating, drying, cell formation, electricity source, and recycling can materially change environmental performance. Tao *et al.* (2) note that conventional wet-slurry electrode processing is energy-intensive and that advanced dry-processing routes can substantially reduce manufacturing energy and cost.

India is entering a major storage-development phase. According to the Ministry of New and Renewable Energy (3), the National Electricity Plan 2023 projects an energy-storage requirement of 82.37 GWh in 2026–27, including 34.72 GWh from BESS, rising to 411.4 GWh in 2031–32, including 236.22 GWh from BESS. The long-term projection reaches 2,380 GWh by 2047. This trajectory means that battery sustainability is directly relevant to India's renewable-energy security, industrial policy, mineral strategy, and waste-management infrastructure.

3. Major battery pathways for sustainable storage

3.1 Lithium-ion and LFP batteries

Lithium-ion batteries store energy through reversible ion insertion, alloying, or conversion reactions. Commercial families include LFP, nickel-manganese-cobalt (NMC), nickel-cobalt-aluminium (NCA), and lithium-titanate systems. LFP has gained importance in grid and mobility applications because iron and phosphate reduce reliance on nickel and cobalt while maintaining useful power and cycle-life characteristics. The main sustainability opportunity is therefore not simply replacing LFP, but reducing the environmental burden of its manufacturing and extending its service life. Advanced electrode manufacturing, renewable electricity for factories, and intelligent thermal management can reduce the energy and material intensity of each delivered kilowatt-hour.

3.2 Sodium-ion batteries

Sodium-ion batteries (SIBs) are one of the most promising complementary technologies because sodium is abundant and geographically widespread. Current research includes layered transition-metal oxides, Prussianblue analogues, polyanionic cathodes, hard-carbon anodes, and new electrolyte formulations. Recent reviews identify progress in materials and cell engineering while recognising lower energy density and remaining challenges in stability and cycle life (4, 5). Their strongest near-term opportunity may be stationary storage, where cost, safety, resource availability, and lifetime can be more important than maximum gravimetric energy density. A 2026 *Nature Sustainability* perspective further argues that sodium-ion technology is moving from laboratory development toward market-relevant applications in mobility and grid storage (6).

3.3 Lithium-sulfur and solid-state batteries

Lithium-sulfur batteries offer high theoretical specific energy and use sulfur, an abundant element. Their practical development is limited by polysulfide migration, electrode-volume change, low sulfur conductivity, lithium-metal instability, and cycle-life degradation. Solid-state batteries replace flammable liquid electrolytes with solid ion conductors and may enable lithium-metal anodes, potentially increasing energy density and safety. However, interfacial resistance, mechanical contact, dendrite formation, and manufacturing complexity remain significant barriers. Most importantly for sustainability, next-generation chemistries must be designed with end-of-life recovery in mind rather than assuming that new chemistry automatically means lower environmental impact.

4. Sustainable manufacturing and electrolyte innovation

Battery manufacturing is a major opportunity for reducing life-cycle impacts. Conventional wet electrode production requires solvent handling, coating, and extensive drying. Tao *et al.* (2) review dry processing, radiation curing, advanced wet processing, and 3D printing, reporting that dry processing can reduce manufacturing energy consumption by more than 46% relative to conventional routes under the analysed conditions. Such approaches can also reduce waste and simplify factory layouts. However, commercial adoption should be evaluated with techno-economic and life-cycle analysis rather than laboratory energy figures alone. Zeng (7) emphasises that techno-economic analysis combined with life-cycle assessment can identify process bottlenecks, capital requirements, and environmental trade-offs during scale-up.

Electrolytes are another sustainability frontier. Conventional lithium batteries commonly use fluorinated salts and additives because they support electrochemical stability, but fluorinated components can create environmental, safety, and recycling concerns. Wang *et al.* (8) review fluorine-free salts, solvents, additives, and interphases and show that fluorine is not intrinsically necessary for every function required from a lithium-battery electrolyte. Development of safer, lower-toxicity, and recyclable electrolytes should therefore proceed alongside improvements in electrode materials.

5. Battery lifetime, safety, and intelligent management

The environmental impact of a battery is strongly affected by how long it remains useful. A battery that delivers twice the useful lifetime from essentially the same manufacturing burden can provide a substantially lower material burden per delivered unit of energy. Battery-management systems should therefore evolve from basic protection toward predictive health management. Monitoring temperature, voltage imbalance, impedance, and degradation signatures can support adaptive charging, early fault detection, and maintenance. Second-life use can further extract value from batteries that no longer satisfy demanding vehicle requirements but remain suitable for stationary applications, provided safety, testing, and economics are favourable.

Safety is equally important. Thermal runaway can cause asset loss, hazardous emissions, and reduced public confidence. Stable electrode chemistries, robust separators, thermal propagation barriers, safer electrolytes, and predictive BMS algorithms should be treated as a unified safety system. Sustainability should include risk reduction because preventing catastrophic failure also prevents loss of embodied materials and energy.

6. Circular battery economy: recycling and regeneration

A sustainable battery economy requires recovery of valuable materials and, where possible, preservation of functional electrode structures. Conventional recycling may combine mechanical separation with pyrometallurgical or hydrometallurgical recovery. These routes can recover metals but may require high temperatures or chemical reagents. Zhang *et al.* (9) systematically discussed material and energy flows in lithium-ion recycling and highlighted the need to integrate recycling with battery production, design, and battery-management systems.

A more advanced approach is direct regeneration, in which the structure and composition of degraded electrode materials are restored rather than completely reduced to elemental constituents. Zheng *et al.* (10) show that understanding degradation from the particle to the cell scale is important for selecting appropriate recycling and regeneration pathways. This supports a design-for-recycling philosophy: battery manufacturers should consider disassembly, material identification, binder selection, and recovery chemistry before commercial deployment.

Recycling is also relevant to future solid-state systems. Ahuis *et al.* (11) show that recycling strategies must account for different solid electrolytes and cell architectures, meaning that next-generation batteries should not repeat the historical mistake of treating end-of-life processing as an afterthought. Industrial-scale evidence further indicates that electricity consumption can be a dominant contributor to recycling environmental impacts, making low-carbon electricity an important part of circular battery supply chains.

7. Proposed five-pillar sustainability framework

Based on the recent literature and the present analysis, a sustainable battery system can be evaluated using five interconnected pillars:

i. **Material diversification:** prioritise abundant elements and reduce dependence on geographically concentrated critical minerals.
ii. **Low-impact manufacturing:** reduce solvent use, drying energy, production waste, and formation losses, while increasing renewable electricity in factories.
iii. **Safety-by-design:** combine stable chemistry, robust cell architecture, thermal management, and predictive battery-management systems.
iv. **Lifetime maximisation:** use adaptive charging, thermal control, health estimation, repairability, and carefully evaluated second-life operation.
v. **Closed-loop recovery:** design cells for safe disassembly, direct regeneration where feasible, high-value material recovery, and traceable recycling.

The central proposition is that the sustainable battery should be defined by service delivered per unit of total life-cycle burden, not by laboratory energy density alone. This metric favours different technologies in different applications. LFP lithium-ion batteries are currently well positioned for large-scale deployment; sodium-ion batteries can reduce resource pressure in suitable stationary applications; and solid-state or lithium-sulfur systems may become attractive where higher energy density or specific safety characteristics justify their manufacturing complexity.

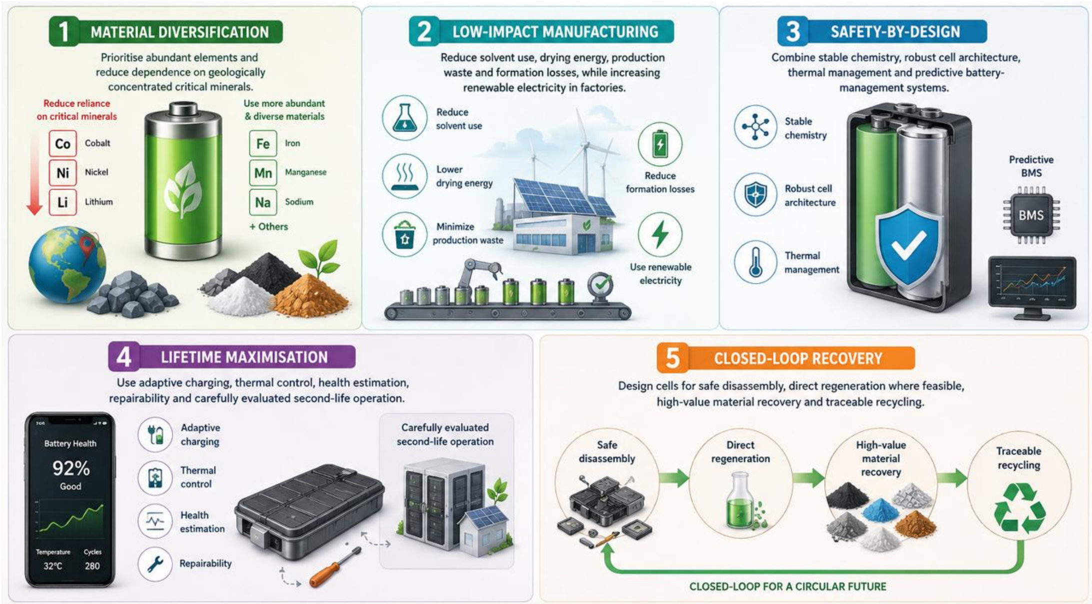

Figure 1: Five-pillar sustainability framework for advanced battery energy storage systems

8. Research priorities for India and the next decade

Five research priorities are especially relevant. First, full-cell studies should use realistic electrode loading, limited electrolyte, and scalable manufacturing conditions. Second, battery papers should report sustainability indicators alongside electrochemical performance, including critical-material content, embodied energy, carbon intensity, water use, and recyclability. Third, sodium-ion and other abundant-material chemistries should be developed for stationary applications rather than judged only against lithium-ion EV energy density. Fourth, recycling and regeneration research should be developed simultaneously with new chemistries. Fifth, digital twins, machine learning, and physics-informed degradation models should be connected to BMS platforms to extend useful lifetime and reduce premature replacement.

Figure 2: Decadal research priorities and strategic implementation roadmap for the battery ecosystem in India

For India, these priorities should be linked to domestic cell manufacturing, renewable electricity for factories, mineral-resource diversification, safe transportation, collection networks, and regional recycling facilities. The projected growth of BESS provides an opportunity to establish circularity standards before very large quantities of retired batteries appear. Such early integration is likely to be more effective than retrofitting recycling systems after market expansion.

9. Conclusion

Battery storage is becoming core infrastructure for renewable electricity, electrified transport, and resilient grids. Lithium-ion technology, particularly LFP, currently provides the strongest combination of maturity, cost, and performance for large-scale deployment. Yet a sustainable energy future cannot depend on a single chemistry or on a linear mine-to-manufacture-to-disposal model. Sodium-ion batteries offer an important route for resource diversification; lithium-sulfur and solid-state technologies may serve future high-energy niches; and improved electrolytes, manufacturing, and recycling can reduce the impacts of established lithium-ion systems. The decisive transition is therefore from a "more batteries" paradigm to a "better battery life cycle" paradigm. Material efficiency, clean manufacturing, safety, lifetime extension, intelligent management, and circular recovery must be developed together. For India, the rapid expansion of renewable generation and BESS is an opportunity to build a technologically diverse, economically viable, and circular storage ecosystem. Batteries can then become not merely devices that store energy, but durable infrastructure for sustainable development.

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