Journal of Nanotechnology and Innovative Materials

Review Article

A Mini-Review on Nano-Enabled Energy Storage and Conversion Systems

Gaurav Gupta[1] and **Baseem Khan**[2]

[1]Department of Electrical Engineering, Faculty of Engineering & Technology, University of Lucknow, University Road, Babuganj, Hasanganj, Lucknow 226007, Uttar Pradesh, India
[2]Department of Electrical and Computer Engineering, Hawassa University, P.O. Box 05, Hawassa, Ethiopia

Received: 27.02.2026 Accepted: 06.03.2026 Published: 31.03.2026

https://doi.org/10.54414/VULL4304

Abstract

It is well established that nanoscale design allows for the direct tuning of charge transfer, ion transport, catalytic activity, and interfacial stability as applied to electrochemical devices, making Nano-enabled energy conversion and storage systems an important frontier research area in support of electrification and decarbonization. This mini-review focuses primarily on nano-engineered materials and interfaces in key storage technologies, including lithium-ion batteries, sodium-ion batteries, solid-state batteries, and supercapacitors, while also discussing the broader implications of nanoscale design for electrochemical conversion platforms such as fuel cells, CO_2 reduction systems, and photoelectrochemical devices.

Keywords: energy conversion, nanocatalysts, lithium-ion batteries, fuel cells

1. Introduction

Nano-enabled energy technologies sit at the intersection of two bottlenecks that dominate modern electrification, i.e., interfacial losses and materials sustainability. The last decade's rapid scale-up of batteries for electric mobility and grid support has intensified both pressures, such as demand growth for automotive lithium-ion batteries has been steep, and critical-material supply chains remain concentrated, motivating chemistries and designs that reduce reliance on constrained elements while improving safety and performance [1], [2]. Nano-structuring addresses these constraints by changing the dominant physics and chemistry at device-relevant length scales. In electrochemical storage, nanoscale electrodes shorten diffusion lengths, increase electrochemically active surface area, and can accommodate strain, enabling higher rate capability and improved cycling, provided that the side effects of high surface area are mitigated through coatings, artificial interphases, and tailored electrolytes [3]. There are three broad themes in energy conversion with nano-catalysts like alloying, defect engineering, and single-atom, which expand active-site density and tune adsorption energetics. Nanoscale catalyst-layer architecture defines the mass transport, ionic conduction, and degradation pathways in a fuel cell electrode, so for fuel cells, the nanoarchitecture of electrodes is as important to performance as that of intrinsic catalyst activity [4]. Nanostructured catalysts and gas-diffusion electrodes (GDEs) seem to allow for industrially relevant current densities for CO_2 electroreduction, but with coupled stability problems that require a given device-level solution rather than just relying on catalyst design [5]. Then, for solar-to-fuel and photoelectrochemical (PEC) routes, these nanostructured photoelectrodes enhance light harvesting, charge separation, and catalytic turnover, whereas integrations of system-level assembly are becoming the key factor towards the realization of viable solar fuels [6], [7]. The overarching bottom line is that scale-up, reproducibility, and lifecycle impacts are constraints growing more acute; performance gains from nano-enabled innovations show every sign of being capped with scale-up, reproducibility, and lifecycle impacts. The most credible near-term pathway involves better-controlled interfaces at the minimally effective nanoscale via scalable processes, i.e., dry electrode fabrication, roll-to-roll coating, and selective atomic layer deposition, coupled with some consideration of safety, exposures, and sustainability [8], [9], [10], [11].

High energy storage, high power buffering, and efficient conversion of electrons to molecules and vice versa are structurally required for the indirect electrification of sectors difficult to electrify directly [1], [2]. For the energy transition in practice, the strategy must be a portfolio that includes lithium-ion and emerging battery chemistries for energy storage, supercapacitors and hybrid capacitors for high power transients, and electrochemical conversion platforms such as fuel cells, CO_2 reduction devices, and photoelectrochemical systems for conversion or diversified seasonal storage [4], [5], [6], [12], [13]. However, the scale of deployment turns materials constraints from curiosities at the lab test into system-level risk. However, as noted in previous analyses of electric vehicle (EV) battery supply chains and critical materials used across all applications, the competitive dynamics affect future resilience generation more than energy-density improvements with lower effective demand per km/travelled mile or per kWh delivered from vehicle energy storage, but chemistry choices are even more decisive, together with recycling [1], [2].

At least one functional length scale is in the 1–100 nm regime, which has a broadly defined class of materials and architectures known as nanomaterials. The reasoning behind this is that most electrochemical processes are interface-controlled, such as charge transfer, interphase formation, catalyst turnover, and degradation, all of which manifest at or near the surface. Increasing interfacial area and engineering of heterointerfaces via nano-structuring, coupled with nanoscale coatings to suppress unwanted parasitic pathways without necessarily compromising transport, are a few components in the toolbox. The mentioned principle is particularly apparent in silicon anodes, solid-state batteries, and catalyst-layer engineering [3], [4], [14]. Nano-enabling is not automatically beneficial. For example, high surface area may lead to enhanced electrolyte decomposition in batteries, catalyst dissolution or carbon corrosion in fuel cells, and also raise the risk of occupational exposure when handling the powder [10], [11]. The core challenge, then, is to engineer nano-bulky at the system scale without loss in stability of that material during manufacture. Table 1 gives an overview of important historical milestones related to the development of nanomaterials for energy storage and conversion technologies.

Table 1. Selected milestones linking nanomaterials to energy systems.

Year	Milestone in nano-enabled energy research
1991	Commercial lithium-ion batteries were introduced, establishing a practical platform for energy-dense portable storage [15].
2004	Graphene was isolated and characterized as an atomically thin conductive material, opening new directions in nanoscale energy materials research [16].
2011	MXenes were introduced as a new family of two-dimensional carbides and nitrides with strong potential for electrochemical applications [17].
2021	Gas-diffusion CO_2 electrolyzers were critically reviewed as a device-level pathway toward industrially relevant current densities [5].
2023	Solid-state batteries were extensively assessed with emphasis on interfaces, power capability, and manufacturability [18].
2024	Techno-economic analyses expanded to integrated photo-rechargeable storage systems and CO_2 conversion technologies [6].
2025	Perovskite-driven photoelectrochemical devices demonstrated solar-driven C_2 hydrocarbon production in tandem configurations [7].

2. Review Scope and Approach

This work is a narrative review of nano-enabled energy storage and conversion systems, highlighting issues of interfacial engineering, nanostructured electrodes, and practical device-level limitations. The review focuses on representative, high-impact literature covering lithium-ion batteries, sodium-ion batteries, solid-state batteries, supercapacitors, fuel cells, electrochemical CO_2 reduction, and photoelectrochemical conversion systems. Instead of using formal systematic-review screening criteria, the manuscript synthesizes foundational manuscripts, recent review articles, and selected publications to classify major classes of materials, bottlenecks in their performance, and stabilization methods, as well as newly proposed directions. This is not an exhaustive bibliometric survey, but a synthetic technical review across domains.

3. Nano-Enabled Electrochemical Energy Storage

Coupled transport, reaction kinetics, and degradation processes govern electrochemical performance. Nano-structuring alters such couplings via shortening diffusion paths, such as with nanotubes, increasing density of reaction-site availabilities, or introducing interfacial effects, for example, with coatings, heterostructures, and grain boundaries that stabilize metastable phases or mitigate unwanted side reactions [3], [14], [18]. The same mechanisms generate trade-offs. This could also lead to stronger parasitic reactions and faster growth of solid-electrolyte interphase (SEI) or cathode-electrolyte interphase (CEI), resulting in increased impedance and cyclable ions being consumed more [3], [14]. It is, therefore, in the context of interfacial engineering that modern nano-enabled storage approaches are most appropriate. Not maximum surface area, but controlled surface chemistry with transport-accessible porosity is important.

4. Nanomaterials for Different Types of Batteries and Their Components

4.1. Cathodes

For high specific energy, high-Ni layered oxide cathodes are promising, but they demonstrate surface reactivity that couples to impedance rise and capacity fade. More recently, microcracking is seen as an effect due to surface instability rather than a cause, with the focus shifted to control of nanoscale surface chemistry [19], [20].

4.2. Anodes

To host massive volume change and maintain electrical percolation, silicon’s high theoretical capacity drives extensive nanoengineering. Recent reviews in electrochemical-to-mechanical coupling reveal that stable cycling can be achieved with 3D silicon designs or nano-structured to accommodate large volume expansion; however, low tap density, a high first-cycle loss, and processing complexity are universal issues. These issues are becoming more and more important in terms of the feasibility of commercialization [3]. A secondary industry-oriented strategy is regulated prelithiation and interface engineering [21].

4.3. Solid-State Batteries

On the other hand, solid-state batteries have higher safety and potentially higher specific energy, but the main bottlenecks are still interfacial [14], [18]. Halide-based conductors are also being highlighted in solid electrolytes for their compatibility advantage, but toxic failure mechanisms ensure interfacial engineering is required [22]. One convergent nano-enabled approach is artificial interphases, which are thin, conformal layers applied by atomic layer deposition (ALD), sol-gel routes, or mechanochemical processing, to control reaction pathways and maintain low interfacial resistance across cycling [14].

5. Nano-Structuring in Sodium-Ion Batteries and Emerging Chemistries

Sodium-ion batteries have moved from a conceptual alternative to early commercialization interest because sodium is abundant and can reduce dependence on some supply-constrained battery materials [23], [24]. Roadmap analyses in [24] argue that techno-economic competitiveness depends on manufacturing learning rates, materials costs, and matching Na-ion performance to segments where energy density is good enough, rather than head-to-head competition with the highest-energy lithium-ion packs [24].

From a nano-enabled materials viewpoint, three families dominate near-term Sodium-ion battery (SIB) design, such as hard carbon anodes, layered oxide cathodes, and Prussian blue analogues (PBAs) [23], [24]. Recent roadmap and competitiveness analyses indicate that sodium-ion deployment will depend not only on chemistry performance but also on manufacturing scale, cost learning, and materials recovery as the technology matures [24], [25].

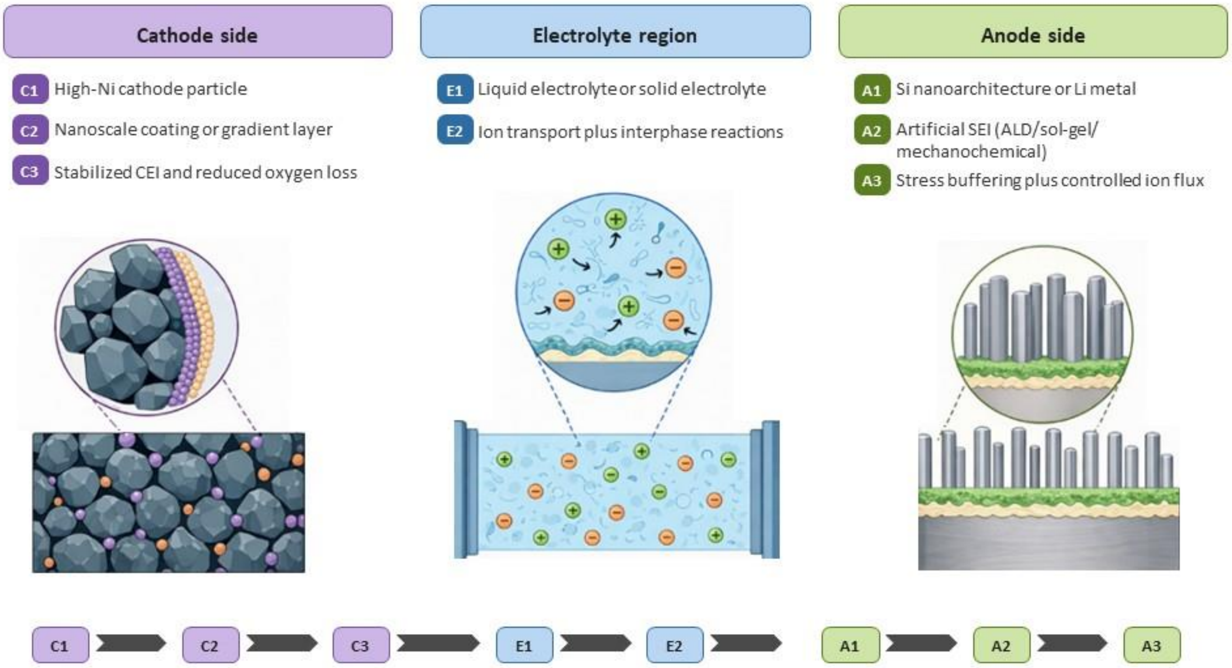

Figure 1. Conceptual schematic of nano-enabled interface regulation in representative battery systems, synthesized from the literature on silicon anodes, solid-state batteries, and interfacial engineering strategies [3], [14], [18], [19], [20], [21], [22].

6. Nanostructured Supercapacitors and Hybrid Capacitors

Supercapacitors occupy the performance space between conventional capacitors and batteries. They provide high power density and long cycle life but lower energy density, making them important for pulse power, regenerative braking, and power smoothing [12], [13]. Nano-enabled supercapacitor design follows two principal routes. Firstly, electric double-layer capacitor enhancement using nanostructured carbons such as activated carbon, mesoporous carbons, carbon nanotubes, and graphene derivatives to maximize accessible surface area and tune pore size to electrolyte ions, and secondly, pseudocapacitive or hybrid architectures using transition-metal oxides, sulfides, conductive polymers, or two-dimensional materials such as MXenes, to add fast surface or near-surface redox storage while retaining high-rate behavior [12], [13], [17]. A useful quantitative framing is the Ragone relationship, in which batteries can achieve higher energy density, whereas supercapacitors can provide far higher specific power but traditionally lower energy density, which motivates ongoing efforts to increase device voltage and pseudo-capacitance [12], [13].

7. Comparative Analysis of Nano-Enabled Storage Materials

Table 2 compiled and synthesized representative material classes, synthesis approaches, and performance metrics, with an explicit focus on device-relevant measures using literature on high-Ni cathodes, silicon anodes, solid-state batteries, sodium-ion batteries, and supercapacitors [3], [12], [13], [14], [18], [19], [20], [21], [22], [23], [24].

Table 2. Representative nano-enabled energy storage materials, synthesis routes, and performance metrics [3], [12], [13], [14], [18], [19], [20], [21], [22], [23], [24].

Technology	Representative nano-enabled materials	Common synthesis	Key performance metrics	Dominant degradation modes	Stabilization mechanisms
Li-ion cathodes	high-Ni layered oxides with nanoscale coatings or gradients	wet-chemical coating, sol-gel, nanoscale surface reconstruction control	high specific energy up to cell-level hundreds of Wh/kg	surface reconstruction, oxygen loss, impedance rise, microcracking linked to surface reactivity	conformal coatings, gradient compositions, interface regulation from nano to macro
Li-ion anodes	Si nanoarchitectures	templating, electrospinning-derived composites, carbon coating, prelithiation plus SEI engineering	higher specific capacity; improved initial Coulombic efficiency and pouch-cell cycle retention	volume-change driven fracture, unstable SEI, low tap density, first-cycle loss	stress-buffering architectures, conductive networks, robust SEI plus controlled prelithiation
Solid-state batteries	Sulfide or oxide or halide solid electrolytes plus artificial SEI or CEI	Atomic layer deposition (ALD) or Molecular layer deposition (MLD) coatings, sol-gel, mechanochemical routes	safety plus higher specific energy potential, power limited by composite transport and interfaces	interphase growth, contact loss, Li-metal instability, composite cathode transport limits	engineered interphases, particle-size or processing control, interface-compatible electrolyte selection
Sodium-ion batteries	hard carbon anodes, layered oxides, Prussian blue analogues (PBAs)	biomass-derived carbon tuning, defect or water control in PBAs, surface stabilization	low-T performance for targeted segments	interfacial instability, structural transitions, defect-mediated parasitics	Surface or defect engineering, dehydration control, scalable processing, plus recycling planning
Supercapacitors	nanoporous carbons, metal oxides, conductive polymers, MXenes or 2D hybrids	Activation or templating, hydrothermal or solvothermal, etching plus delamination, electrode architecture control	high power (kW/kg class), long cycle life	electrolyte decomposition at high voltage, pore blockage, redox material dissolution	Pore or ion matching, stable electrolytes, hybrid electrode design, termination, or interlayer tuning

8. Nanomaterials in Electrochemical Conversion Systems

Nano-enabled energy conversion systems rely on many of the same interfacial design principles that govern advanced batteries, but their dominant bottlenecks often arise at catalyst layers, gas-liquid-solid interfaces, and photoactive junctions. In these systems, gains in activity or selectivity at the nanoscale are meaningful only when they remain stable under realistic mass-transport, crossover, and integration constraints [4], [5], [6], [7]. Nanoscale catalyst layers, ionomer distribution, transport limitations, and durability in fuel cells [4]. Nanomaterials also constitute the basis of all electrochemical CO_2 reduction, including gas-diffusion electrodes, catalyst restructuring, flooding or drying, and stability at the device level [5]. These nanomaterials have been extensively used in photoelectrochemical systems and integrated photo-rechargeable architectures from light harvesting, charge separation, to tandem designs, as well as integrated conversion storage concepts [6], [7].

9. Discussion

This manuscript has demonstrated through a short literature review that the metric of surface area or particle size is no longer at face value an indicator of nanomaterial worth in energy systems. In contrast, best-reproduced improvements arise from engineering this interface in a controlled manner, such as when nanoscale design is applied carefully to boost ionic conduction, charge transfer, catalytic turnover, and bulk stability without significantly increasing parasitic processes or process complexity. It is not limited to lithium-ion, sodium-ion batteries, solid-state batteries or supercapacitors, reflected in the recent trend of shifting focus from just further scaling down the physical dimensions of electrodes via nano-structuring to surface coating and artificial interphase formation focusing on interface processes, defect regulation, component self-stabilization and hierarchical architecture-design, focused on structural stability [3], [12], [13], [14], [18], [19], [20], [21], [22], [23], [24]. This indicates a similar trend in energy-conversion systems. Nanoscale catalysts can increase the density of active sites and tune reaction pathways in fuel cells, CO_2 electroreduction devices, and photoelectrochemical platforms. However, device performance is ultimately limited by mass transport, interfacial degradation, product crossover, i.e., flooding or drying, and long-term stability. This implies that catalyst-level improvements need to be critically analyzed alongside an appropriately engineered electrode architecture, electrolyte environment, as well as system integration [4], [5], [6], [7]. Another significant takeaway is that minimum-effective nanoscale design tends to be more credible than random nano-structuring. Nanomaterials have the characteristic of shortening diffusion lengths and enhancing kinetic processes, but they also intensify side reactions, increase processing complexity, and may result in greater safety and lifecycle burdens [8], [9], [10], [11], [14].

10. Conclusion

Nano-enabled energy storage and conversion systems pose significant opportunities for enhancing electrochemical performance, although their real-world use requires the design of stable, manufacturable, and sustainable devices that fully realize the effectiveness of the nanoscale approach, reports. Despite the increase in rate capability, catalytic activity, and available reaction sites that nano-structuring can provide, these gains are frequently limited by interphase growth, structural degradation, transport bottlenecks such as active ion movement from the bulk to the surface, and scale-up issues, according to this review. In summary, the most promising path is not that of maximum utilization of nanoscale features but rather a rapid and appropriate application of nano-engineered interfaces only where they are most beneficial in terms of performance versus durability, safety, cost, and lifecycle. The focus should be on achieving these objectives with interface stability measurable over at least months, reproducible studies at scales in the kg to ton range, device-level validation of devices beyond half-cells and the development of circularity-aware materials strategies.

Author Contributions

Both authors participated in the study design, manuscript preparation, and approval of the final version of the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

Funding

This study was not supported by external funding.

Acknowledgment

The authors sincerely acknowledge all individuals and organizations whose support and cooperation contributed to the successful completion of this study.

Abbreviations

Carbon Dioxide (CO_2), Gas-Diffusion Electrodes (GDEs), Photoelectrochemical (PEC), Electric Vehicle (EV), Solid-Electrolyte Interphase (SEI), Cathode-Electrolyte Interphase (CEI), Atomic Layer Deposition (ALD), Sodium-Ion Battery (SIB), Prussian Blue Analogues (PBAs), Molecular Layer Deposition (MLD).

References

[1] International Energy Agency. Global EV Outlook 2023: Catching up with climate ambitions. Paris: International Energy Agency; 2023 [cited 2026 February 21]. Available from: https://lib.icimod.org/records/4z884-k1s46

[2] International Renewable Energy Agency. Geopolitics of the energy transition: critical materials. Abu Dhabi: IRENA; 2023 [cited 2026 February 21]. Available from: https://www.irena.org/publications/2023/Jul/Geopolitics-of-the-Energy-Transition-Critical-Materials

[3] Feng K, Li M, Liu W, Kashkooli AG, Xiao X, Cai M, Chen Z. Silicon-based anodes for lithium-ion batteries: from fundamentals to practical applications. Small. 2018 Feb;14(8):1702737. https://doi.org/10.1002/smll.201702737

[4] Holdcroft S. Fuel cell catalyst layers: a polymer science perspective. Chemistry of materials. 2014 Jan 14;26(1):381-93. https://doi.org/10.1021/cm401445h

[5] Rabiee H, Ge L, Zhang X, Hu S, Li M, Yuan Z. Gas diffusion electrodes (GDEs) for electrochemical reduction of carbon dioxide, carbon monoxide, and dinitrogen to value-added products: a review. Energy & Environmental Science. 2021;14(4):1959-2008. https://doi.org/10.1039/d0ee03756g

[6] Qiu T, Zhang W, Hao X, Sun K. integrated photo-rechargeable batteries: configurations, design principles, and energy loss mechanisms. Small Science. 2025 Jun;5(6):2400598. https://doi.org/10.1002/smsc.202400598

[7] Andrei V, Roh I, Lin JA, Lee J, Shan Y, Lin CK, Shelton S, Reisner E, Yang P. Perovskite-driven solar C2 hydrocarbon synthesis from CO2. Nature Catalysis. 2025 Feb;8(2):137-46. https://doi.org/10.1038/s41929-025-01292-y

[8] Park J, Kim J, Kim J, Kim M, Song T, Paik U. Sustainable and cost-effective electrode manufacturing for advanced lithium batteries: the roll-to-roll dry coating process. Chemical Science. 2025;16(16):6598-619. https://doi.org/10.1039/d5sc00059a

[9] Ma L, Nuwayhid RB, Wu T, Lei Y, Amine K, Lu J. Atomic layer deposition for lithium-based batteries. Advanced Materials Interfaces. 2016 Nov;3(21):1600564. https://doi.org/10.1002/admi.201600564

[10] Galey L, Audignon S, Brochard P, Debia M, Lacourt A, Lambert P, Le Bihan O, Martinon L, Bau S, Witschger O, Garrigou A. Strategies to assess occupational exposure to airborne nanoparticles: systematic review and recommendations. Safety and Health at Work. 2023 Jun 1;14(2):163-73. https://doi.org/10.1016/j.shaw.2023.02.002

[11] Huang YH, Bauer C, Burkhardt S, Dasgupta NP, Ellingsen LA, Gaines LL, Hao H, Hischier R, Hu L, Huang YM, Janek J. Advancing the Sustainability of Batteries: A Tongji University. Nature Sustainability Expert Panel Report. 2022.

[12] Dissanayake K, Kularatna-Abeywardana D. A review of supercapacitors: Materials, technology, challenges, and renewable energy applications. Journal of Energy Storage. 2024 Aug 15;96:112563. https://doi.org/10.1016/j.est.2024.112563

[13] Kumar N, Kim SB, Lee SY, Park SJ. Recent advanced supercapacitor: a review of storage mechanisms, electrode materials, modification, and perspectives. Nanomaterials. 2022 Oct 21;12(20):3708. https://doi.org/10.3390/nano12203708

[14] Tan DH, Banerjee A, Chen Z, Meng YS. From nanoscale interface characterization to sustainable energy storage using all-solid-state batteries. Nature nanotechnology. 2020 Mar 1;15(3):170-80. https://doi.org/10.1038/s41565-020-0657-x

[15] Royal Swedish Academy of Sciences: lithium-ion batteries. NobelPrize.org; 2019 [cited 2026 February 21]. Available from: https://www.nobelprize.org/prizes/chemistry/2019/advanced-information/

[16] Royal Swedish Academy of Sciences. Graphene. Stockholm: The Nobel Prize; 2010 [cited 2026 February 21]. (Advanced Information on the Nobel Prize in Physics 2010). Available from: https://www.nobelprize.org/prizes/chemistry/2019/advanced-information/

[17] Naguib M, Kurtoglu M, Presser V, Lu J, Niu J, Heon M, Hultman L, Gogotsi Y, Barsoum MW. Two-dimensional nanocrystals produced by exfoliation of Ti3AlC2. InMXenes 2023 Aug 24 (pp. 15-29). Jenny Stanford Publishing. https://doi.org/10.1201/9781003306511-4

[18] Janek J, Zeier WG. Challenges in speeding up solid-state battery development. Nature Energy. 2023 Mar;8(3):230-40. https://doi.org/10.1038/s41560-023-01208-9

[19] Lee S, Su L, Mesnier A, Cui Z, Manthiram A. Cracking vs. surface reactivity in high-nickel cathodes for lithium-ion batteries. Joule. 2023 Nov 15;7(11):2430-44. https://doi.org/10.1016/j.joule.2023.09.006

[20] Zhang F, Lou S, Li S, Yu Z, Liu Q, Dai A, Cao C, Toney MF, Ge M, Xiao X, Lee WK. Surface regulation enables high stability of single-crystal lithium-ion cathodes at high voltage. Nature Communications. 2020 Jun 16;11(1):3050. https://doi.org/10.1038/s41467-020-16824-2

[21] Ham SY, Sebti E, Cronk A, Pennebaker T, Deysher G, Chen YT, Oh JA, Lee JB, Song MS, Ridley P, Tan DH. Overcoming low initial coulombic efficiencies of Si anodes through prelithiation in all-solid-state batteries. Nature Communications. 2024 Apr 6;15(1):2991. https://doi.org/10.1038/s41467-024-47352-y

[22] Wang Q, Zhou Y, Wang X, Guo H, Gong S, Yao Z, Wu F, Wang J, Ganapathy S, Bai X, Li B. Designing lithium halide solid electrolytes. Nature communications. 2024 Feb 5;15(1):1050. https://doi.org/10.1038/s41467-024-45258-3

[23] Hwang JY, Myung ST, Sun YK. Sodium-ion batteries: present and future. Chemical Society Reviews. 2017;46(12):3529-614. https://doi.org/10.1039/c6cs00776g

[24] Yao A, Benson SM, Chueh WC. Critically assessing sodium-ion technology roadmaps and scenarios for techno-economic competitiveness against lithium-ion batteries. Nature Energy. 2025 Mar;10(3):404-16. https://doi.org/10.1038/s41560-024-01701-9

[25] Charge the Future. EUROBAT launches Battery Innovation Roadmap 2030 White Paper. Brussels: Charge the Future; 2020 [cited 2026 February 21]. Available from: https://chargethefuture.org/news/eurobat-publishes-innovation-roadmap-2030-white-paper/