SODIUM-ION BATTERIES: AN INTERESTING ALTERNATIVE TO LITHIUM FOR ELECTRIC VEHICLES

Abstract

Sodium-ion batteries emerge as a sustainable and cost-effective alternative to lithium-ion batteries for electric vehicle applications. With concerns over the rising cost, limited availability, and environmental impact of lithium and cobalt, the global energy storage market is exploring sodium-based chemistry as a viable solution. Sodium is far more abundant and widely distributed than lithium, offering advantages in resource accessibility, geopolitical stability, and long-term affordability. This review critically examines the current state of sodium-ion battery research and its applicability to electric vehicles, focusing on recent technological advancements, material selection, safety features, and compatibility with existing lithium-ion manufacturing infrastructure. Key benefits such as improved thermal stability, reduced environmental footprint, and drop-in potential are weighed against major challenges including lower energy density, increased cell weight, and barriers to mass production. The paper also highlights commercial interest from major battery manufacturers and ongoing efforts to close the performance gap. As electric mobility accelerates globally, sodium-ion batteries may become a crucial component of next-generation, sustainable electric vehicle platforms.

Introduction

Electric vehicles (EVs) are rapidly being adopted by consumers, with global sales greatly increasing over the past decade. Figure 1 illustrates this growth, showing a steady rise in battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) sales from 2010 to 2022, ultimately surpassing 36 million units sold in 2022 alone [1].

This surge is driven by government incentives, such as tax credits and emission regulations, as well as growing public concern over climate change and energy sustainability. Many regulatory bodies, including government environmental agencies, have set incentives for the adoption of EVs which has led to a unprecedented increase in demand for electric vehicles [2]. This expanding demand for EVs has put pressure on the battery industry, which primarily relies on lithium-ion battery (LIB) technology. LIBs have been the dominant energy storage solution since their commercial introduction in 1991 [3], powering a wide range of consumer electrical devices, from smartphones to electric cars. However, the increase in LIB demand has exposed several critical limitations. These include volatile lithium prices, which spiked to record highs in 2022 due to supply bottlenecks and geopolitical constraints [4], as well as growing concerns over the environmental and social impacts of lithium and cobalt mining [3]. LIB production also faces challenges related to long-term sustainability and global resource distribution, raising questions about its viability as a mass-market solution for future EVs [5].

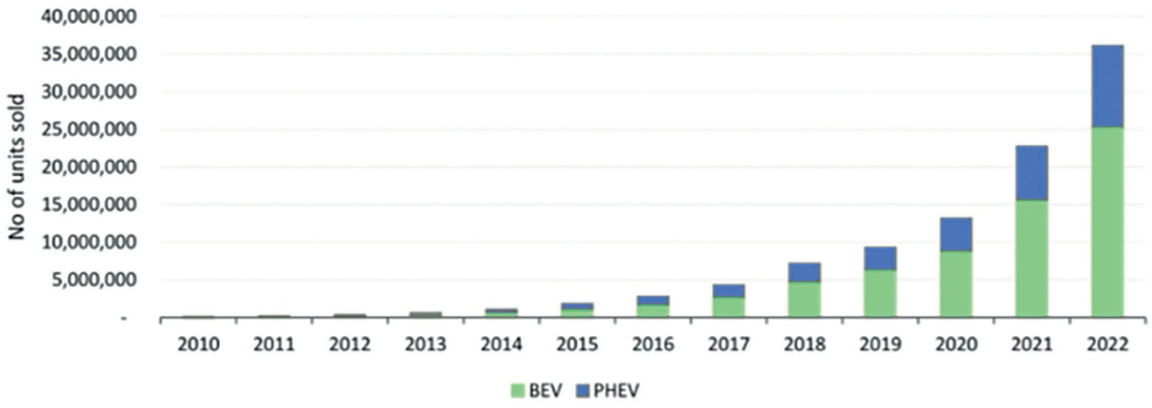


Figure 1. Global EV sales by year [1].

In response to these challenges, sodium-ion batteries (SIBs) have emerged as a promising alternative. Sodium is vastly more abundant than lithium and is widely distributed across the globe [3]. These characteristics offer potential for cost reductions and reduced supply chain vulnerability. As a result, both academic researchers and industry leaders are actively exploring sodium-ion technology. In fact, manufacturers have already announced plans for more than 240 GWh of SIB production capacity by 2030, with investors such as CATL and BYD initiating pilot-scale manufacturing [6]. This paper reviews the current state of sodium-ion battery technology, focusing on its potential applications in EVs. The analysis will examine both the advantages, such as lower material cost and improved sustainability, and the limitations, including lower energy density and uncertain manufacturability at scale. As global demand for batteries continues to climb, the development of viable alternatives like SIBs may be essential for ensuring long-term, sustainable growth in the EV sector.

Benefits of Sodium-Ion Batteries in EVs

As mentioned earlier, sodium is one of the most abundant materials in the earth's crust. Due to this abundance, there is a theoretical lower cost for sodium to be extracted. This reduced cost contributes to a relatively cheaper cathode which can be seen in the cost model in Figure 2, where the lithium cathode costs $313, while the sodium cathode costs $276 [5].

As a result, SIBs are cheaper to produce for companies which can incentivize further research into their adoption for EV usage due to the reduced price of production when compared to some traditional counterparts. Furthermore, SIBs have been shown to have a smaller carbon footprint than LIBs. Most lithium-ion batteries use graphite as the anode, which must be mined or created by heating carbon-containing precursors, such as petroleum coke, a byproduct of oil refining. Sodium-ion batteries typically use hard carbon (a disordered form of carbon that cannot be converted to graphite using the previously described graphitization process) which is more sustainable and cheaper [5]. This reduces dependence on mined graphite and can lower both environmental and material extraction impacts. This further exemplifies sodium as a viable alternative component in EV batteries, due to its environmental sustainability [3]. Sodium-ion batteries have the added benefit of not suffering from as severe safety concerns as compared to their lithium counterparts. Lithium batteries are known for their instability after damage

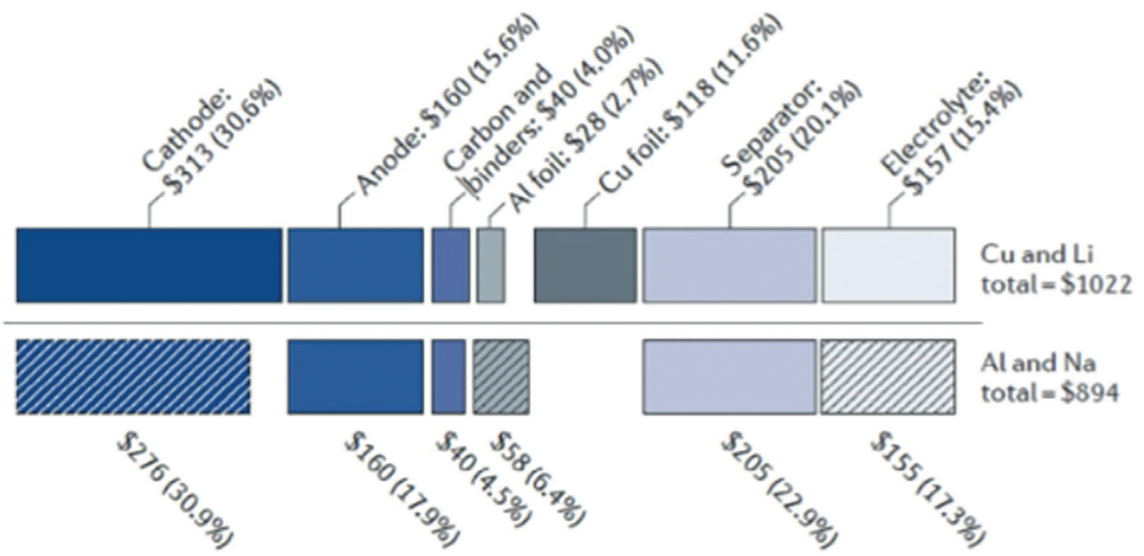


Figure 2 - Projected cost models for a LIB (top) vs. a SIB (bottom) [5]

or poor materials, as shown in numerous cases of lithium-ion batteries exploding or overheating in personal electronic devices [7]. The reason for this disparity in safety is due to lithium's vulnerability to thermal runaway. Thermal runaway in batteries, especially lithium-ion types, is a hazardous condition involving a self-perpetuating cycle of heat buildup that can result in fire or explosion. It is typically initiated by events such as overcharging, internal short circuits, or mechanical damage. Once triggered, the heat increases uncontrollably, causing the battery to overheat, emitting flammable gases, and potentially catch fire [7]. Sodium-ion batteries are generally considered to have a lower risk of thermal runaway compared to lithium-ion batteries due to their inherent chemical and structural differences. Unlike lithium, sodium does not form highly reactive dendrites as readily, which reduces the likelihood of internal short circuits that can initiate runaway reactions [8]. Additionally, many sodium-ion battery designs use aqueous or solid-state electrolytes, which are less flammable than the organic solvents commonly used in lithium-ion systems. The lower energy density of sodium-ion batteries also contributes to their improved thermal stability, as they generate less heat under abuse conditions. These factors make sodium-ion batteries inherently safer and less prone to catastrophic failure, making them an attractive option for applications where safety is a primary concern [8]. This safety consideration is further improved due to sodium-ion batteries ability to serve as a "drop in" technology. Sodium-ion batteries are increasingly being developed as a drop-in replacement for lithium-ion batteries, meaning they can be integrated into existing manufacturing infrastructure with minimal changes [9]. Many sodium-ion cells share similar form factors, such as cylindrical or pouch designs, and use comparable materials for current collectors and separators. This compatibility allows battery producers to repurpose lithium-ion production lines without the need for significant retooling [9]. Furthermore, sodium-ion technology operates at similar voltages and follows the same general principles of ion transport and intercalation, making it easier for engineers and manufacturers to adapt to the new chemistry. As a result, sodium-ion batteries offer a practical pathway for transitioning away from lithium while leveraging global investment in lithium-ion battery production [9].

Limitations of Sodium-Ion Batteries

Despite these positives of SIBs, there are many drawbacks that occur. Firstly, sodium ions are larger than lithium ions (1.02 atomic radius to 0.76) [10]. As a result, cathode materials would have to conform to the size difference, meaning that the overall battery size increases. This size difference will also directly increase weight, which is a serious problem in electric vehicles. Since many cars are already designed to be lightweight and sleek, having a bulkier and heavier battery will oppose this design which compromises the functionality of the car. Unlike with a traditional combustion engine vehicle, the infrastructure for EV charging ports is still in its infant stages. Because of this, EV manufacturers are encouraged to place a higher emphasis on the range of electric vehicles. Heavier engines directly contribute to shorter maximum ranges which is disadvantageous towards the consumer. Due to the dominance of the LIB, sodium-ion batteries have not yet achieved maturity in mass production. Many companies are adjusted to mass producing LIBs, meaning that a switch to mass produce SIBs can be challenging.

One of the most critical limitations of sodium-ion batteries in EV applications is their relatively low energy density when compared to lithium-ion batteries. Energy density, measured in watt-hours per kilogram (Wh/kg), determines how much energy a battery can store relative to its mass. This metric is particularly important in the context of EVs, where battery weight and size have a direct impact on vehicle range, efficiency, and overall performance [11]. Currently, most commercial lithium-ion batteries, depending on the chemistry, offer energy densities ranging from 200 to 300 Wh/kg. High-performance variants such as those using nickel manganese cobalt or nickel cobalt aluminum cathodes can reach even higher values. In contrast, sodium-ion batteries generally fall within the range of 100 to 160 Wh/kg, which is significantly lower [11]. This discrepancy poses a fundamental challenge for sodium-ion technology in the EV sector, where consumers demand long driving ranges and automakers aim to minimize vehicle mass and maximize space efficiency. The specific capacity of electrode materials in sodium-ion batteries is inherently lower. For example, graphite, the standard anode material in lithium-ion cells, performs poorly with sodium due to the size mismatch between the sodium ion and the graphite interlayer spacing. This has led researchers to explore alternative anode materials such as hard carbon or titanium-based compounds, which offer better compatibility but do not match the energy storage capacity of graphite-lithium systems [11]. On the cathode side, sodium-based materials also tend to have lower voltage plateaus and less favorable redox potentials, which reduce the total energy output per unit mass. Although progress has been made in developing layered oxide and polyanionic cathode chemistry, these materials still fall short of the electrochemical performance seen in advanced lithium-based counterparts [11]. In addition to the limitations imposed by material properties, the lower energy density of sodium-ion batteries impacts the design and packaging of EV battery systems. To achieve a comparable driving range, a sodium-ion battery pack would need to be physically larger or heavier than a lithium-ion pack. This increase in weight reduces vehicle efficiency and may require structural reinforcements, which add cost and complexity. For smaller EVs or those designed for urban use, this may be acceptable. However, for long-range electric sedans, SUVs, or commercial vehicles that must travel several hundred miles per charge, sodium-ion technology is currently not competitive. The added mass also affects acceleration, braking, and overall vehicle dynamics, further complicating its integration into high-performance electric vehicles [11].

Moreover, the energy density disadvantage also has implications for charging infrastructure and user convenience. Lower energy density means that more frequent charging is required to support daily driving needs. This puts additional strain on public and private charging networks and may reduce consumer acceptance, particularly in regions with limited infrastructure. It also affects battery longevity, as more frequent charge-discharge cycles can accelerate degradation, even if the underlying sodium chemistry is more thermally stable. This limitation can undermine one of the key advantages of sodium-ion batteries, which is their enhanced safety profile. In real-world use cases, safety and performance must be balanced, and lower energy density makes it harder to justify trade-offs in favor of sodium. That said, some efforts have been made to narrow the gap. Research into novel cathode and anode materials, such as Prussian blue analogues and engineered hard carbons, has shown promise in improving the energy density of sodium-ion cells. Additionally, the development of advanced electrolytes and cell designs has the potential to boost voltage windows and enhance performance [11]. Despite these advancements, the fundamental limitations imposed by the chemistry of sodium remain a major barrier. In the absence of a technological breakthrough that radically improves sodium's electrochemical efficiency, it is unlikely that sodium-ion batteries will be able to replace lithium-ion batteries in premium or long-range EV segments. However, it is important to acknowledge that energy density is not the only factor in battery selection. Cost, resource availability, thermal stability, and environmental impact also play major roles. Sodium is far more abundant and geographically distributed than lithium, which makes it attractive for regions seeking energy independence or supply chain diversification. For short-range EVs, electric scooters, or buses operating on fixed urban routes, sodium-ion batteries could offer a viable and safer alternative, even with their lower energy density. In such applications, where range requirements are modest and cost is a primary concern, the benefits of sodium may outweigh its limitations. Still, for widespread adoption in mainstream electric vehicles, the challenge of energy density must be overcome before sodium-ion batteries can be considered a truly equal replacement for lithium-based systems.

Conclusion

Sodium-ion batteries offer a promising pathway toward sustainable energy storage for electric vehicles, particularly in light of rising concerns over lithium's cost, limited availability, and environmental impact. Sodium is significantly more abundant and widely distributed, making it a lower-cost and more geopolitically stable alternative. The technology also benefits from improved safety characteristics and compatibility with existing lithium-ion manufacturing infrastructure, which reduces the barrier to commercial adoption. However, sodium-ion batteries face a substantial challenge in their lower energy density, which limits driving range and increases the size and weight of battery packs. This drawback is especially critical in long-range electric vehicles, where space and performance constraints are tightly coupled with energy storage capabilities. Despite this limitation, recent research into advanced cathode materials such as Prussian blue analogues and layered oxides, along with improvements in hard carbon anodes and electrolyte formulations, has shown potential to close the performance gap. Industrial interest is growing, with major companies like CATL and BYD investing in pilot-scale production and aiming to enhance energy density through material innovation. These developments suggest that sodium-ion batteries may find early success in applications such as short-range vehicles, public transit, and stationary storage systems, where cost, safety, and sustainability are prioritized over maximum range. With continued research and growing commercial support, sodium-ion technology could evolve into a scalable and reliable alternative to lithium-ion batteries, supporting the broader electrification of transportation and helping meet global climate and energy resilience goals.

Sources

[1] S. Abdul Qadir, F. Ahmad, A. Mohsin A B Al-Wahedi, A. Iqbal, and A. Ali, "Navigating the complex realities of electric vehicle adoption: A comprehensive study of government strategies, policies, and incentives," Energy Strategy Rev., vol. 53, p. 101379, May 2024, doi: 10.1016/j.esr.2024.101379.

[2] E. Narassimhan and C. Johnson, "The role of demand-side incentives and charging infrastructure on plug-in electric vehicle adoption: analysis of US States," Environ. Res. Lett., vol. 13, no. 7, p. 074032, July 2018, doi: 10.1088/1748-9326/aad0f8.

[3] L. Zhao et al., "Engineering of Sodium-Ion Batteries: Opportunities and Challenges," Engineering, vol. 24, pp. 172–183, May 2023, doi: 10.1016/j.eng.2021.08.032.

[4] A. Yao, S. M. Benson, and W. C. Chueh, "Critically assessing sodium-ion technology roadmaps and scenarios for techno-economic competitiveness against lithium-ion batteries," Nat. Energy, vol. 10, no. 3, pp. 404–416, Mar. 2025, doi: 10.1038/s41560-024-01701-9.

[5] "Optimization Strategies Toward Functional Sodium-Ion Batteries - Chen - 2023 - ENERGY & ENVIRONMENTAL MATERIALS - Wiley Online Library." Accessed: July 26, 2025. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1002/eem2.12633

[6] "Sodium-ion battery technology: So near and yet so far," S&P Automotive Insights. Accessed: July 26, 2025. [Online]. Available: https://www.spglobal.com/automotive-insights/en/blogs/2025/06/sodium-ion-battery-technology

[7] O. S. Mahdy et al., "Quantitative evaluation of thermal runaway in lithium-ion batteries under critical heating conditions to enhance safety," Sci. Rep., vol. 15, no. 1, p.

24004, July 2025, doi: 10.1038/s41598-025-07824-7.

[8] A. R. Boozula, K. Bagheri, R. G. Lampuse, S. Shah, and J. J. Thakkar, "Review of thermal runaway risks in Na-ion and Li-ion batteries: safety improvement suggestions for Na-ion batteries," J. Eng. Appl. Sci., vol. 72, no. 1, p. 106, July 2025, doi: 10.1186/s44147-025-00668-y.

[9] R. Carter, G. H. Waller, C. Jacob, D. Hayman, P. J. West, and C. T. Love, "First Look at Safety and Performance Evaluation of Commercial Sodium-Ion Batteries," Energies, vol. 18, no. 3, Art. no. 3, Jan. 2025, doi: 10.3390/en18030661.

[10] S. K. Sapra, J.-K. Chang, and R. S. Dhaka, "Improved Electrochemical Performance of NASICON Type Na3V2–xCox(PO4)3/C (x = 0–0.15) Cathode for High Rate and Stable Sodium-Ion Batteries," ACS Appl. Mater. Interfaces, vol. 16, no. 33, pp. 43535–43547, Aug. 2024, doi: 10.1021/acsami.4c07348.

[11] H. Kim, "Sodium-Ion Battery: Can It Compete with Li-Ion?," ACS Mater. Au, vol. 3, no. 6, pp. 571–575, Nov. 2023, doi: 10.1021/acsmaterialsau.3c00049.

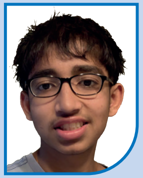
About the Authors

Dr. Raj Shah is a Director at Koehler Instrument Company in New York, Holtsville, NY. He is an elected Fellow by his peers at ASTM, IChemE, CMI, STLE, AIC, NLGI, INSTMC, AOCS, Institute of Physics, The Energy Institute and The Royal Society of Chemistry. An ASTM Eagle award recipient, Dr. Shah recently coedited the bestseller, "Fuels and Lubricants handbook", details of which are available at ASTM's Long-Awaited Fuels and Lubricants Handbook 2nd Edition Now Available (https://bit.ly/3u2e6GY). He earned his doctorate in Chemical Engineering from The Pennsylvania State University and is a Fellow from The Chartered Management Institute, London. Dr. Shah is also a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute and a Chartered Engineer with the Engineering council, UK. Dr. Shah was recently granted the honourific of "Eminent engineer" with Tau beta Pi, the largest engineering society in the USA. He is on the Advisory board of directors at Farmingdale university (Mechanical Technology) , Auburn Univ (Tribology), SUNY, Farmingdale, (Engineering Management) and State university of NY, Stony Brook (Chemical engineering/ Material Science and engineering). An Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical engineering, Raj also has approximately 700 publications and has been active in the energy industry for over 3 decades. More information on Raj can be found at https://shorturl.at/Xm60b and at https://bit.ly/3QvfaLX

Contact: rshah@koehlerinstrument.com

Mr. Mathew Roshan and **Mr. Parth Patel** are part of a thriving internship alternative energy program at Koehler Instrument company in Holtsville.

Mathew Roshan



Parth Patel

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company • Holtsvile, NY11742 USA

• Email: rshah@koehlerinstrument.com • Web: www.koehlerinstrument.com