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Research Report

March 2025

Advanced Battery Technologies

Bus, Heavy-Duty Vocational Truck, and Construction Machinery Applications

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Jingyuan Zhao, University of California, Davis

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Advanced Battery Technologies: Bus, Heavy-Duty Vocational Truck, and Construction Machinery Applications

A National Center for Sustainable Transportation Research Report

Andrew F. Burke, Institute of Transportation Studies, University of California, Davis

Jingyuan Zhao, Institute of Transportation Studies, University of California, Davis

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ACRONYMS

Abbreviation	Term
AI	Artificial Intelligence
ASSLB	All-Solid-State Lithium Battery
C-Rate	Charge Rate
CO_2	Carbon Dioxide
CTP	Cell-to-Pack
EOL	End-of-life
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
HDV	Heavy-Duty Vehicle
LAB	Lithium-Air Battery
LATP	Lithium Aluminum Titanium Phosphate
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LIB	Lithium-Ion Battery
LLTO	Lithium Lanthanum Titanium Oxide
LLZO	Lithium Lanthanum Zirconium Oxide
LTO	Lithium Titanate Oxide
LiAir	Lithium-Air
LiCl	Lithium Chloride
$LiFeMnPO_4$	Lithium Iron Manganese Phosphate
$LiFeVPO_4$	Lithium Iron Vanadium Phosphate
LiM	Lithium Metal
LiPS	Lithium Polysulfides
LiS	Lithium Sulfur
Li_2O	Lithium Oxide
Li_2O_2	Lithium Peroxide
$Li_7La_3Zr_2O_{12}$	Lithium Lanthanum Zirconium Oxide
NASICON	Sodium Super Ionic Conductor
NCA	Nickel Cobalt Aluminum
NCM	Nickel Cobalt Manganese
PEO	Polyethylene Oxide
SEI	Solid Electrolyte Interphase
SOC	State of Charge
SSB	Solid-State Battery
SSE	Solid-State Electrolyte
SiC	Silicon Carbide

Advanced Battery Technologies: Bus, Heavy-Duty Vocational Truck, and Construction Machinery Applications

EXECUTIVE SUMMARY

This report focuses on the development of advanced batteries with high energy density (>400 Wh/kg) and their role in the electrification of buses, vocational trucks, and construction machinery. Both vehicle and machinery electrification, along with advancements in battery technology, are actively progressing. Therefore, a key objective of this study is to assess the current status of advanced battery development and its impact on the further commercialization of these electrified systems.

For advanced batteries, an extensive literature review and evaluation of ongoing research and development on advanced lithium-ion and sodium-ion batteries were conducted to determine the current state of development and the challenges associated with commercializing the various battery technologies. The modeling of advanced battery technologies predicts that batteries with energy densities of approximately 500 Wh/kg and 1000 Wh/l will likely be developed and then commercialized in 7-12 years. These batteries are expected to enable the development of electrified construction vehicles and machinery with performance equal to or exceeding that of diesel-engine products currently available in the market. The results of the modeling, which considered various anode, cathode, and electrolyte chemistries, are summarized in Table ES-1.

Table ES-1. The model results for the performance of the advanced battery technologies.

Parameter	Gravimetric Energy Density (Wh/kg)	Volumetric Energy Density (Wh/l)	Resistance (mΩ)	Pulse Power (W/$kg_{95\%}$)
LiM/SSE/LiCl	532	1079	4.3	1353
LiM/SSE/L_2O	671	1143	6.0	1400
LiM/SSE/LiS	755	1355	5.9	1565
Grapht/Polymer/NCM	283	532	5.9	408
SiC/SSE/NCM	473	1055	4.3	879
LiSi/SSE/NCM (liquid)	465	1071	5.0	1200
LiSi/SSE/NCM (solid-state)	426	947	5.5	1100
Hard Carbon/Organic El./Na Nickelate	188	423	4.3	576
Hard Carbon/Organic El./Na Nickelate	127	285	3.1	533

Drawing from diverse sources—including scientific literature (peer-reviewed academic articles), market analyses (estimates from analysts, consultancy groups, and industry updates), and other non-peer-reviewed reports—it is evident that the electrification of construction trucks, machinery, transit buses, and intercity buses is advancing. This transition is being facilitated by the use of conventional lithium-ion batteries and electric drive components initially developed for passenger cars, SUVs, and medium- to heavy-duty trucks. For buses, electric models are already commercially available and are gaining traction in an expanding global market. Regarding construction trucks and machinery, various types of electrified equipment have been successfully utilized and demonstrated in real-world construction projects across the United States, China, and Europe. The battery and electric motor specifications of the electrified construction machinery currently available in the market are detailed in Table ES-2. The parameters presented are critical for evaluating the feasibility and performance of electric construction machinery. Gross weight (kg) influences energy consumption, power requirements, and structural constraints, directly affecting machine efficiency and durability. Energy storage capacity (kWh) determines operational autonomy, impacting productivity and the frequency of charging interruptions. Electric motor power (kW) dictates the performance of the machine in terms of load-handling capability and operational efficiency, ensuring that electric models can meet the demands of diesel-powered counterparts. In addition, operating time per charge (hr.) is essential for assessing the practicality of electric machinery in real-world applications, influencing scheduling, charging infrastructure requirements, and overall project efficiency. Together, these parameters provide a comprehensive assessment of the suitability of electric construction machines for various applications, guiding technological advancements and adoption strategies.

Table ES-2. Summary of the characteristics of electric construction machines.

Construction machine type	Gross weight (kg)	Energy storage (kWh)	Electric motor (kW)	Operating Time (hr./charge)
Excavators	2,675	20	18	4
	23,000	264	160	5
Front loaders	5,450	40	30	4
	20,000	282	180	5
Compactors	2,800	20	33	Up to 4
Cranes (wheeled)	60,000	226	200	Up to 7

In addition to producing near-zero emissions (eliminating both CO_2 and emissions from diesel engines), electrified construction machinery offers several advantages. It is more efficient, significantly quieter, and has lower operating costs due to reduced energy expenses and less frequent maintenance compared to diesel engines. Therefore, there are compelling reasons beyond CO_2 reduction to pursue the electrification of construction equipment. Manufacturers of electrified construction trucks and machinery appear to recognize these advantages and are optimistic about the market potential for their products. They anticipate growth in the near-to-medium term, particularly with the support of federal and state subsidies aimed at meeting CO_2 reduction mandates.

All electrification markets discussed in this report focus particularly on the United States. The cost of electrified products remains high compared to diesel-powered alternatives. However, continuous advancements in underlying technologies are driving improvements in performance and efficiency. Manufacturers increasingly recognize the advantages of electrification, reinforcing confidence in market expansion. In addition, federal and state subsidies play a crucial role in accelerating adoption, aligning with broader environmental mandates and policy objectives.

The development of advanced lithium batteries with significantly higher energy density than current commercially available batteries will be critical for the long-term progress of electrified products. In addition to higher energy density, advanced batteries are expected to offer enhanced safety (reduced risk of thermal runaway), longer cycle life, fast-charging capability, and somewhat lower costs ($/kWh). These improvements will enable manufacturers of construction equipment to enhance their products. With advanced batteries, electrified products will deliver performance equal to or better than engine-powered alternatives, while also being more cost-effective to operate. In addition, these products will provide inherent advantages such as being extremely quiet (no noise) and creating a clean work environment (no pollution) for operators and workers. Some companies developing silicon-based anodes and solid-state electrolyte batteries have set goals for mass production by 2030 or shortly thereafter.

Based on the findings of this study, Caltrans can procure electrified versions of most, if not all, of the trucks and construction machinery they require from established manufacturers. Initially, these vehicles and equipment will rely on conventional lithium-ion batteries, similar to those used in battery-electric cars and trucks in California. Charging infrastructure will be available from multiple manufacturers, though construction equipment may require significantly higher power levels—potentially in the megawatt range—necessitating further technological advancements. For heavy-duty vocational trucks, achieving a balance between high energy density, rapid charging capability, durability, and cost-effectiveness is critical to meeting demanding operational requirements. Integrating these vehicles with megawatt-scale charging infrastructure and advanced battery management systems will be essential to enhancing efficiency, minimizing downtime, and enabling large-scale electrification of vocational fleets. Although the current cost of electrified construction machinery remains high, precise cost projections are challenging due to various influencing factors beyond the relative costs of diesel engines, batteries, and electric motors. Nonetheless, this presents a strategic opportunity for Caltrans to begin electrifying its work vehicles and machinery. Early adoption would provide valuable operational experience with advanced battery technologies, potentially before 2030. The findings of this report may offer valuable guidance to other California agencies, such as the California Air Resources Board (CARB) and the California Energy Commission (CEC), in shaping future electrification strategies.

1. INTRODUCTION

This report explores the transition to electrified buses, vocational trucks, and construction machinery, emphasizing the role of advanced battery technologies in facilitating this shift. The electrification of heavy-duty vehicles (HDVs) is advancing alongside innovations in battery systems, driving the evolution of sustainable transportation. These electrified applications generally fall into three categories: low-cost transport, long-range transport, and high-utilization transport. Each category presents unique operational requirements and design considerations, shaping the selection and development of suitable battery technologies [1].

In the low-cost transport category, HDVs are designed for cost-effectiveness, measured in dollars per passenger-mile. These vehicles, including city buses and delivery trucks, primarily operate in urban environments with short travel distances and frequent stops. Their battery systems are engineered to balance affordability and reliability while meeting moderate energy and power demands. The emphasis in this segment is on minimizing operational costs and emissions. Conversely, long-range transport requires HDVs equipped with high-energy-density batteries to support extended routes with minimal recharging. This category includes intercity buses and long-haul trucks, where battery performance must sustain prolonged operation while maintaining efficiency. Achieving this necessitates advanced battery chemistries and robust thermal management systems to enhance both cycle life and calendar life. High-utilization transport presents an additional challenge, as HDVs in this category operate under intensive duty cycles, such as logistics and delivery services. Vehicles following a hub-and-spoke model, such as delivery vans and freight trucks, require battery systems capable of withstanding frequent charging cycles without compromising performance or longevity. These batteries must strike a balance between energy density and durability to ensure uninterrupted operation under rigorous conditions.

The diverse operational needs of HDVs require a range of battery technologies, each optimized for specific performance criteria such as energy density, power output, cycle life, and charging speed. While customizing batteries for distinct applications can enhance efficiency, it also results in lower production volumes and higher costs. A more cost-effective strategy may involve developing a limited number of battery designs that can accommodate multiple transport applications. This approach would help balance performance requirements while leveraging economies of scale to reduce manufacturing costs. Therefore, a crucial component of this study was to evaluate the current state of advanced battery development and its impact on the commercialization of HDVs, including buses, vocational trucks, and construction machinery.

To this end, a comprehensive literature review was conducted, examining ongoing research and development efforts on lithium and sodium-ion batteries. This review aimed to determine the current advancements and the challenges associated with the commercialization of various battery technologies. The findings from the literature review on industrial and academic advancements are detailed in Sections 2 and 3 of this report, respectively. Section 4 provides a detailed analysis of battery cell modeling, exploring emerging technologies such as silicon-based and lithium-metal anodes, metal oxide and sulfur cathodes, and lithium-air batteries. This section also presents the performance results of these advanced battery technologies. Section 5 discusses the progress in vehicle and construction machinery electrification and identifies the specific battery requirements needed to achieve successful electrification across different applications. It also examines how the performance of advanced batteries will support the commercialization of electrified HD trucks and construction machinery. The final outlook, presented in Section 6, provides a summary of the key findings of this study and discusses the benefits of electrification for construction project managers, workers, and communities. This section highlights the potential improvements in efficiency and sustainability that electrification could bring to the construction industry.

2. CHARACTERISTICS OF ADVANCED BATTERIES: COMPANY AND TEST DATA

In this section, the characteristics of advanced battery cells under development, along with test data from the literature, are reviewed. Most of the results presented here are sourced from [2], while additional data is drawn from publicly available materials on the internet regarding advanced battery technologies. The information in the following pages is organized by cell technology, covering a range from commercially available lithium 21700 cells to lithium-air research cells and sodium-ion cells. Each cell technology is discussed based on the available information for that specific advanced cell type.

2.1 Commercial lithium cells – graphite/NCM

The development of LIBs has progressed significantly since the introduction of the rocking-chair battery concept in the 1970s (Figure 1). The commercialization of LIBs in the 1990s was marked by the adoption of graphite anodes and $LiCoO_2$ cathodes, achieving moderate energy densities and cycle life. In the 2010s, the integration of silicon into anodes enhanced battery performance by increasing energy density and cycle life, although challenges remained due to the volumetric expansion of silicon. Currently, many electric vehicles utilize lithium 21700 cells (Table 1), featuring graphite in the anode and either NCM (nickel, cobalt, manganese) or NCA (nickel, cobalt, aluminum) in the cathode. These cells have a gravimetric energy density of approximately 280 Wh/kg and a volumetric energy density of 800 Wh/l. In 2023, the cost of these cells is estimated to be $100–120 per kWh, with a cycle life of approximately 1,000–1,500 cycles. Cells with this chemistry are also manufactured in prismatic and cylindrical 18650 configurations and are commonly used in vehicle battery packs. Looking ahead to the 2030s, advancements in silicon-based anodes and high-capacity cathodes, such as Ni/Li-rich layered oxides, are expected to further improve energy storage capabilities. This evolution reflects ongoing efforts to develop high-performance, long-lasting batteries for next-generation energy applications.

Table 1. Characteristics of 21700 lithium cells.

Specification	Value
Cell format	21700
Dimensions	21.5 x 70.7 mm
Weight	71.7 g
Capacity	Nominal: 5.80 Ah, Cycle: 5.67 Ah
Current	Continuous: 10.8 A, Peak: 21.6 A
Energy	Nominal: 20.4 Wh
Power	Continuous: 36.4 W, Peak: 74.5 W
Energy density	Gravimetric: 285 Wh/kg, Volumetric: 796 Wh/l
Power density	Gravimetric: 1.04 kW/kg, Volumetric: 2.90 kW/l

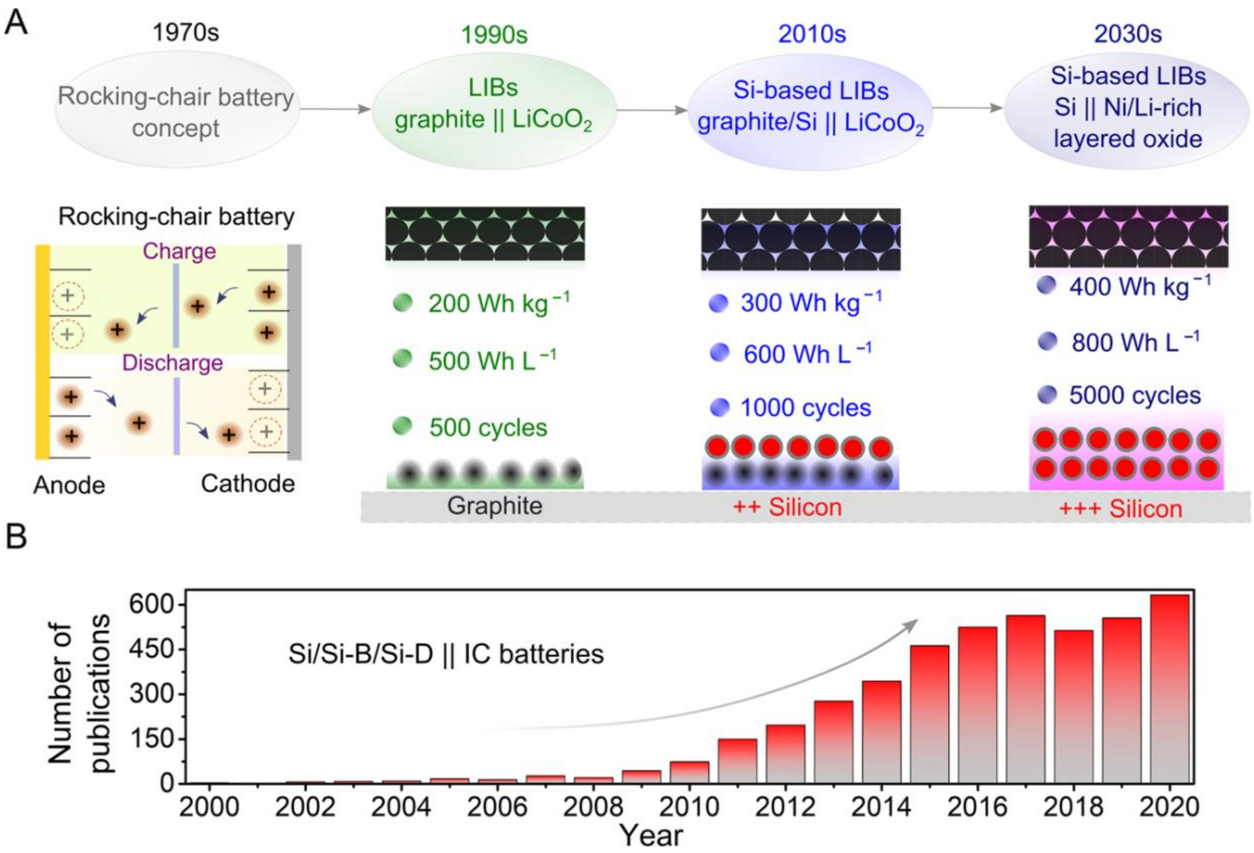


Figure 1. The evolution of LIBs. Copyright, Springer Nature, 2021 [3]. A. The development of LIBs from the rocking-chair battery concept to modern and next-generation Si-based systems. B. A summary of recent research in Si/Si-B/Si-D||IC battery technology.

2.2 Advanced lithium battery technology – silicon/ NCM

2.2.1 Amprius high power 2 Ah – 10 Ah cells (early commercialization)

The adoption of advanced silicon anode technologies marks a notable advancement in LIBs innovation. Amprius Technologies [4] has developed and commercialized silicon nanowire anode solutions, addressing the challenge of volume expansion during cycling—a long-standing issue for silicon-based anodes. Their silicon nanowire anode consists of a pure silicon composition supported by a robust nanowire framework. Figure 2 illustrates the characteristics of Amprius cells, which integrate silicon nanowires into the anode while retaining the conventional LIB architecture with liquid organic electrolytes. This silicon nanowire approach originated from research at Stanford University between 2005 and 2010 and has undergone further development at Amprius through 2024.

Amprius is in the early stages of scaling up production and marketing high-energy-density cells. The nanowire design eliminates the need for binders, graphite, or other inactive materials, which introduces several advantages. These features, as outlined in available documentation, include:

(a) Energy Density: Achieving up to 500 Wh/kg and 1,300 Wh/l, with validation in commercial applications.

(b) Cycle Life: The nanowire structure accommodates silicon expansion, enabling between 200 and 700 cycles, depending on operating conditions.

(c) Rate Capabilities: With up to 10C rate capabilities, the cells support rapid charge-discharge cycles, which is beneficial for applications such as electric mobility.

(d) Temperature Stability: Reliable operation across a broad temperature range (-30°C to 55°C).

(e) Fast Charging and Safety: The cells enable 80% charging within 15 minutes and include safety measures suitable for applications in consumer electronics, aviation, and EVs.

The current generation of lithium-ion cells typically achieves a cycle life of approximately 1,000 cycles. In comparison, cells incorporating advanced silicon nanowire anodes have demonstrated the potential for significantly longer lifespans, with cycle lives reported to reach up to 6,000 cycles. In addition, silicon nanowire cells exhibit fast-charging capabilities, achieving 80% state of charge (SOC) within six minutes under optimal conditions. While detailed cost data for Amprius cells is not readily available, publicly available estimates suggest that the current cost ranges between \$200 and \$300 per kWh. The power capacity of Amprius cells can be inferred from the resistance data. The matched impedance power ($V^2/4R$) is calculated to be 571 W/kg, while the pulsed power at 95% efficiency ($P = EF(1-EF)\, V^2/R$) is calculated at 678 W/kg. These values are consistent with the expected performance of high-energy-density LIBs. In addition, the safety characteristics of Amprius cells are demonstrated through the nail penetration test. Conventional Amprius cells with standard separators exhibit thermal runaway behavior comparable to that of traditional LIBs with graphite anodes, although they achieve relatively lower peak temperatures. In contrast, cells equipped with polymer gel separators exhibit improved safety performance. These cells entirely avoid thermal runaway, maintain lower temperatures during testing, and display a gradual voltage decline.

These observations indicate that silicon nanowire technology presents advancements in cycle life, fast-charging capability, and safety. Nonetheless, further investigation is required to evaluate the long-term performance, production scalability, and cost-effectiveness of this technology for its integration into next-generation energy storage systems.

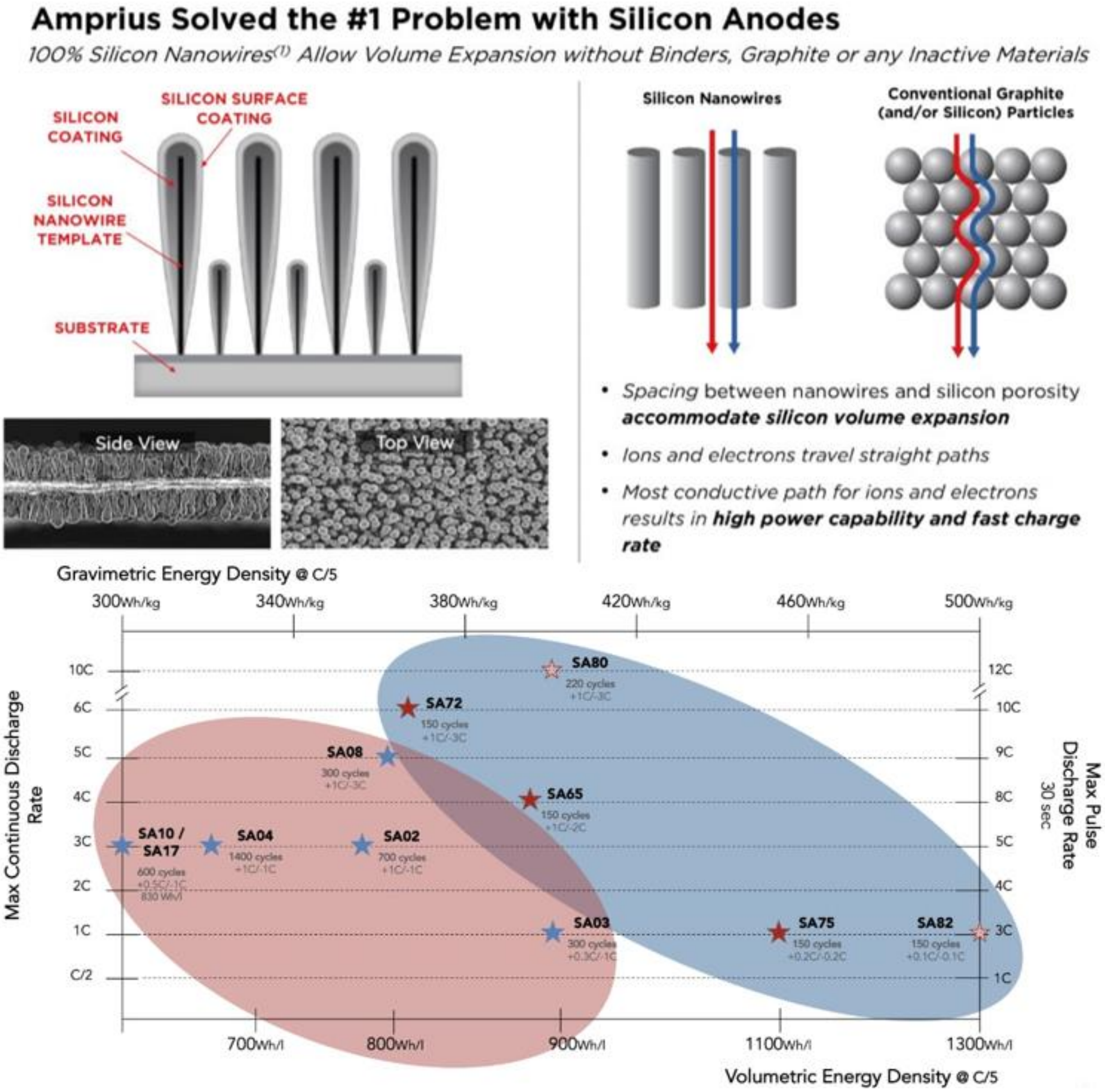


Figure 2. Characteristics of lithium cells of conventional configuration using silicon in the anode in place of graphite (Ampirus, CA, USA [4]).

2.2.2 Blue Solutions –solid-state battery-lithium metal/polymer solid-state electrolyte/NCM, LFP (under development)

Blue Solutions [5] has been producing SSBs featuring a lithium metal anode, polymer solid-state electrolyte, and NCM or LFP cathodes for over a decade. These batteries have been deployed in transit buses and ride-sharing vehicles in Paris, France. The current generation of batteries achieves an energy density of approximately 300 Wh/kg and 600 Wh/l, a cycle life of 3,000 cycles, and demonstrates an absence of thermal runaway. Blue Solutions is now developing a fourth-generation SSBs (Gen 4) with projected energy densities of 450 Wh/kg and 900 Wh/l, a long cycle life (Figure 3).

The cycling performance of these batteries indicates consistent capacity retention and efficiency across different temperatures, particularly at 20°C and 40°C. Notably, at 40°C, the battery retains capacity more effectively, highlighting improved stability under elevated operating conditions. With a loading range of 1.1–1.7 mAh/cm^2, the battery maintains high efficiency over 1,000 cycles, demonstrating strong durability. In addition, the power performance data reveals that the battery sustains stable capacity with minimal degradation even after 1,000 cycles under rigorous charge and discharge protocols. At a loading of 1.1 mAh/cm^2, efficiency remains consistently high, emphasizing its capability for high-power applications without significant performance loss.

These findings highlight the technological capabilities of Blue Solutions solid-state lithium batteries, particularly their capacity to sustain long-term performance and efficiency. Such attributes position this technology as a promising solution for energy storage applications that require both reliability and durability. The Gen 4 battery is expected to enter mass production by 2028; however, no information is currently available regarding its cost. It is important to note that safety concerns have been raised regarding Blue Solutions batteries, as there have been reports of fires in buses using this technology. While solid-state batteries are generally considered safer than conventional lithium-ion batteries, this indicates that not all solid-state battery technologies offer the same level of safety. Further investigations and improvements may be necessary to enhance the safety profile of these batteries in large-scale applications.

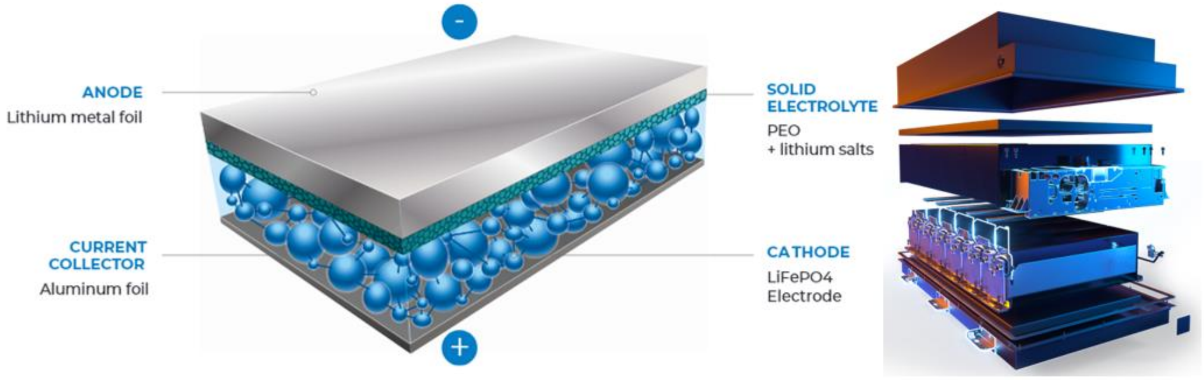


Figure 3. Schematic representation of the solid-state lithium battery design (Blue Solutions, French [5]).

2.3 Golden Feather new energy (early production)

Anode-free lithium metal batteries represent a significant advancement in energy storage by addressing persistent challenges associated with traditional lithium metal anodes. By eliminating the need for a dedicated anode, this design aims to maximize energy density, reduce production costs, and mitigate critical issues such as lithium dendrite growth and safety concerns. During charging, lithium ions deposit as a metal layer on the negative electrode, a process that is reversed during discharge as the metal dissolves back into the electrolyte. This architecture minimizes the irreversible loss of lithium resources typical in conventional batteries, potentially enhancing both cycle life and safety. The absence of an anode enables a lighter and more cost-effective design while maintaining competitive performance metrics.

Golden Feather [6] is advancing the development and industrialization of anode-free lithium metal batteries by integrating solid-state electrolyte separators and NCM811 cathodes (Table 2). Their semi-solid-state batteries incorporate liquid electrolytes within the cathode and utilize prismatic cells with thin-film stacked electrodes. The latest cells achieve energy densities of 474 Wh/kg and 1157 Wh/l, with a matched impedance power of 12 kW/kg and a 95% pulse power of 2250 W/kg. These metrics reflect high power capabilities, positioning the technology as a strong candidate for applications requiring substantial energy and power density. However, the cycle life of these batteries is currently limited to approximately 100 cycles, which poses a significant challenge for practical deployment. In terms of safety, the use of solid-state separators is expected to provide better performance than conventional LIBs, particularly in mitigating thermal runaway risks. However, the safety characteristics may not yet match those of fully SSBs with solid-state cathodes. This positions Golden Feather technology as a transitional phase within the energy storage landscape—offering promising advancements but requiring further development to address limitations in cycle life and safety.

Table 2. Characteristics of the Golden Feather lithium metal batteries.

Parameter	**Small batch lithium metal battery**	**High capacity battery**
Nominal voltage (v)	3.8 (0.1C)	3.65 (0.33C/1C)
Voltage window (v)	3.0 - 4.3	3.0 - 4.3
Capacity (mAh)	4480 (0.1C)	15700 (0.1C)
Energy density (Wh/kg)	>400	450
Volumetric energy density (Wh/l)	-	1250
Internal resistance (mΩ)	9±2	~3
Weight (g)	42.3	130±2
Cycle life (cycles)	≥350 (0.3C/0.5C)	>80
Working temperature (℃)	-20℃ to 55℃	-20℃ to 45℃
Instant discharge rate (C)	5C (up to 7C pulse power)	≥3
Safety test	Drop, vibration, short-circuit	External short, forced discharge, free fall, stress, vibration

2.4 QuantumScape lithium metal, anode-free/ceramic solid-state electrolyte

QuantumScape SSB technology [7] offers a potential alternative to conventional LIBs. Unlike traditional LIBs that utilize liquid electrolytes, QuantumScape employs a solid electrolyte, which addresses key challenges such as lithium dendrite formation and associated safety risks. The solid-state design also enables higher energy densities, reported to range between 800 and 1,000 Wh/l. This energy density surpasses that of most conventional LIBs, potentially enhancing the driving range of EVs. In addition, industry estimates suggest a gravimetric energy density of approximately 400 Wh/kg, further supporting the performance improvements of EVs in terms of weight efficiency. Test data indicates that at lower C-rates, such as C/10 and C/2 at a constant temperature of 25°C, QuantumScape cells exhibit higher discharge capacities while maintaining stable voltage profiles throughout most of the discharge cycle. This behavior demonstrates efficient capacity utilization under slower discharge conditions. The performance of these cells is influenced by key design features, including a cathode loading of 5.6 mAh/cm^2, a discharge current density range of 0.56 to 56 mA/cm^2, and the application of external pressure at 0.7 atm. In addition, the commercially relevant dimensions and six-layer configuration reflect efforts to balance high energy density with operational stability, indicating suitability for practical applications. The technology also highlights the trade-off between discharge rate and capacity retention, emphasizing the importance of tailoring cell performance to meet specific application requirements. These findings suggest that while QuantumScape SSBs show promising improvements in energy density and stability, further optimization may be necessary to enhance performance under varied operational conditions.

QuantumScape battery technology (Figure 4) has demonstrated significant durability in real-world testing. For instance, Volkswagen, a strategic partner of QuantumScape, tested the batteries and reported that they retained 95% of their capacity after 300,000 miles of simulated driving. This result underscores the durability and longevity of the technology, factors critical for advancing the adoption of EVs. However, further assessment of long-term scalability, manufacturing feasibility, and cost competitiveness is necessary to determine its potential for widespread deployment. The advancements of QuantumScape in SSB technology represent a notable step forward in the development of more sustainable and efficient energy storage systems. By addressing limitations inherent in conventional LIBs, this technology has the potential to make significant contributions to the electric vehicle market and other energy-intensive applications. However, ongoing research and industrial scaling efforts will be crucial to realizing its full potential.

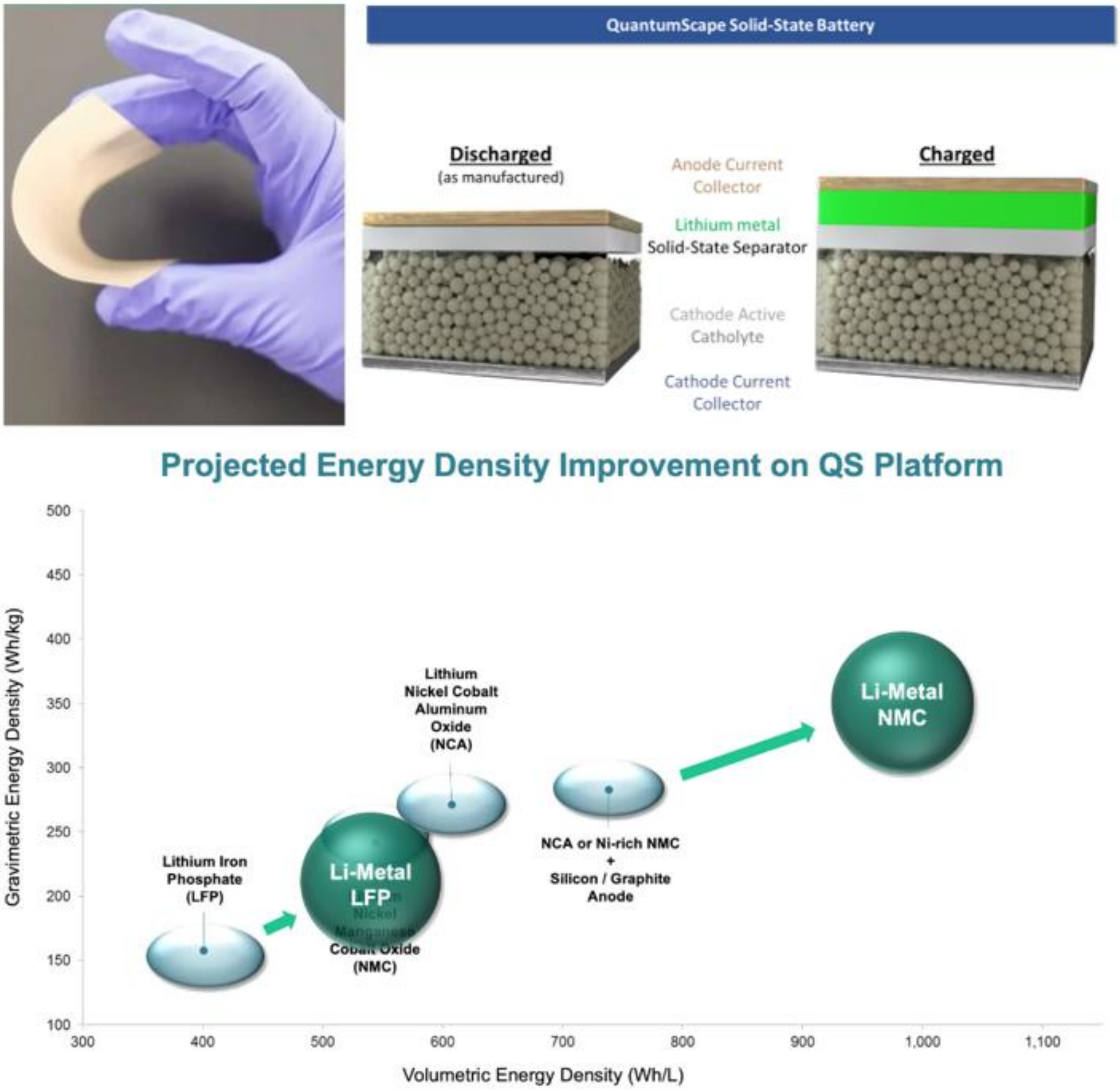


Figure 4. Characteristics of lithium metal, anode-free (QuantumScape, USA [7]).

At the QuantumScape battery showcase, data were presented demonstrating the cycle life performance of the company SSB technology under demanding test conditions. These conditions included high charge/discharge rates, simulated racing track driving, and low temperatures of -10°C (Figure 5). Typically, battery cycle life tests are conducted at a C/3 rate, where cells are charged and discharged over three hours. In contrast, QuantumScape employed more rigorous conditions, utilizing a 1C rate, where a full charge and discharge cycle occurs within one hour. Despite these challenging parameters, the single-layer cells achieved over 1,000 cycles while retaining more than 90% of their initial energy.

The company reports energy retention values that account for factors such as voltage fade and impedance growth over the cycles. Testing was conducted at near-room temperature

(30°C) with commercially relevant parameters, including a current density of 3.2 mA/cm^2, cathode loading of 3.2 mAh/cm^2, a 100% depth of discharge, modest external pressure of 3.4 atm, and cells of commercial size. Importantly, no lithium was present on the anode. According to QuantumScape, no other SSB technology has achieved this level of performance under all these conditions simultaneously—criteria the company identifies as critical for commercial viability. The cycle life and energy retention demonstrated by QuantumScape SSBs highlight the progress made in addressing key challenges in SSB development. However, while these results indicate significant technological advancements, further evaluation is needed to assess long-term performance, scalability, and cost-effectiveness for mass-market adoption. This data suggests that QuantumScape technology is a strong candidate in the development of next-generation energy storage solutions, particularly for electric vehicle applications.

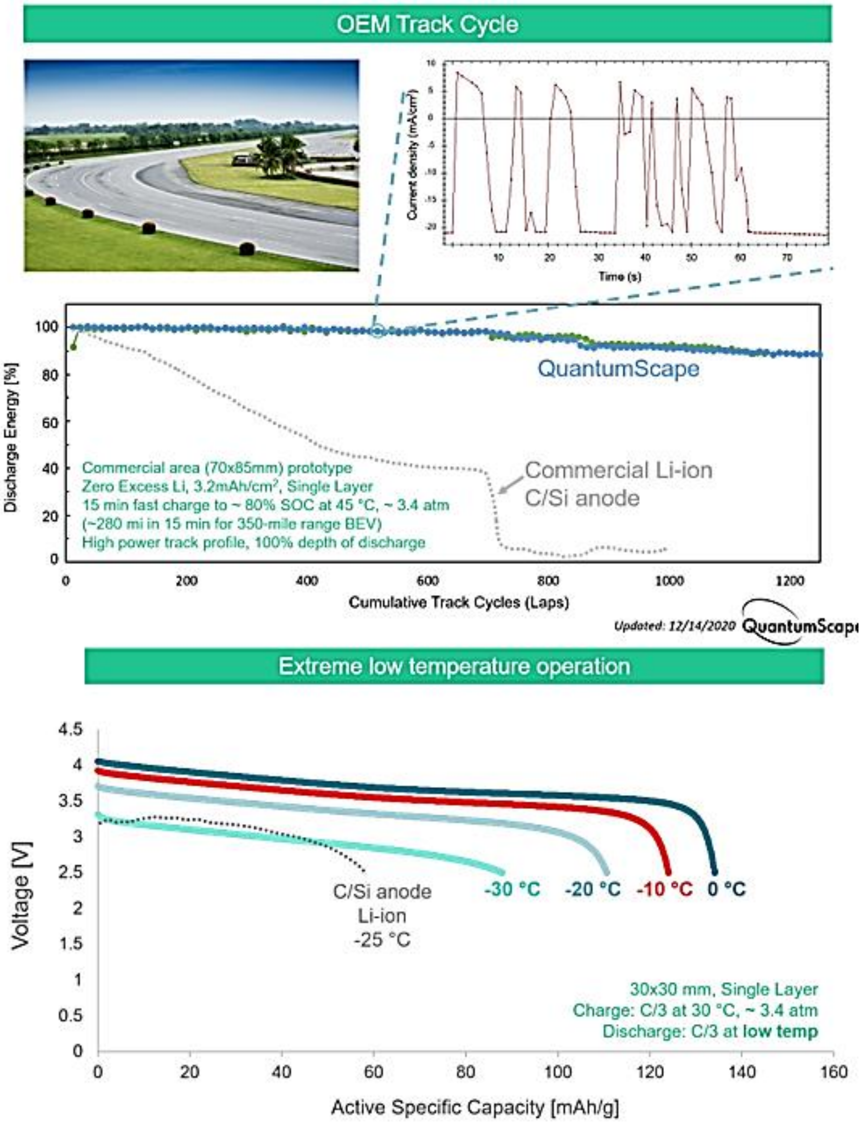


Figure 5. Cycling and low-temperature performance of the QuantumScape lithium metal solid-state battery.

QuantumScape SSB technology addresses critical safety concerns associated with traditional LIBs. Differential scanning calorimetry data indicate that when lithium contacts the separator in these batteries, no exothermic reaction occurs, unlike systems with liquid electrolytes. This result suggests improved safety for QuantumScape cells, as the combustible polymer separator commonly used in LIBs has been replaced with a thermally stable and non-oxidizable alternative. This replacement provides a more effective barrier between the anode and cathode, improving overall system safety. The primary focus of QuantumScape is to stack multiple single-layer cells to create a multilayer cell with a target energy density of 1,000 Wh/l. This energy density would significantly exceed the energy density of current state-of-the-art commercially available cells, such as those in the Tesla Model 3, which achieves 713 Wh/l according to CleanTechnica. Achieving this higher energy density could extend the driving range of EVs while also reducing production costs. The absence of an anode material eliminates the need for an anode manufacturing line and simplifies the formation and aging processes, which are among the most expensive steps in battery manufacturing. In addition, QuantumScape employs generally inexpensive precursor materials and processes suitable for high-volume continuous flow production, which further enhances the cost-effectiveness of its SSB technology. By addressing safety and energy density while focusing on cost-effective manufacturing, QuantumScape SSB technology demonstrates progress toward advanced energy storage solutions for EVs and other applications. However, further evaluation is required to assess long-term reliability, scalability, and economic feasibility.

2.5 Lithium-air research in the laboratory

Lithium-air batteries are an emerging energy storage technology that offers the potential for significantly higher energy densities compared to conventional LIBs. Figure 6 illustrates the operation of a solid-state lithium-air battery cell over 1000 cycles, with charge and discharge potentials of 2.95 V and 2.90 V relative to Li/Li+ at the end of the rest cycle. The cell achieves a total energy capacity of 56 Wh, with a mass of 82 g and a volume of 47 cm^3. It delivers an energy density of 677 Wh/kg and 1179 Wh/l, supported by a cell mass density of 1.73 g/cm^3, demonstrating a highly efficient and compact design for lightweight energy storage. Figure 6c highlights the variations in coulombic efficiency (red), energy efficiency (green), and polarization gap (blue) during continuous cycling. The battery maintained a remarkable coulombic efficiency of 100% over 1000 cycles. The polarization gap increased from 50 mV during the rest cycle to approximately 430 mV by the 1000th cycle. Energy efficiency, initially 92.7% at the rest cycle, gradually declined to 87.7% after 1000 cycles, reflecting the predictable performance evolution of the solid-state Li-air battery under extended cycling. The results shown above for the lithium-air technology research at ANL are for a very small cell (1 cm2) that is rechargeable and charged and discharged at relatively high rates. The data presented by ANL demonstrates promise for the future development of rechargeable lithium-air batteries with high energy density, high power, fast charging capability, and long cycle life. However, despite these advancements, significant challenges remain before commercialization can be realized. Issues such as electrolyte stability, cathode degradation, and efficient oxygen management must be addressed to ensure long-term reliability and scalability. Continued research and engineering efforts will be essential to transition this promising technology from laboratory-scale demonstrations to practical applications.

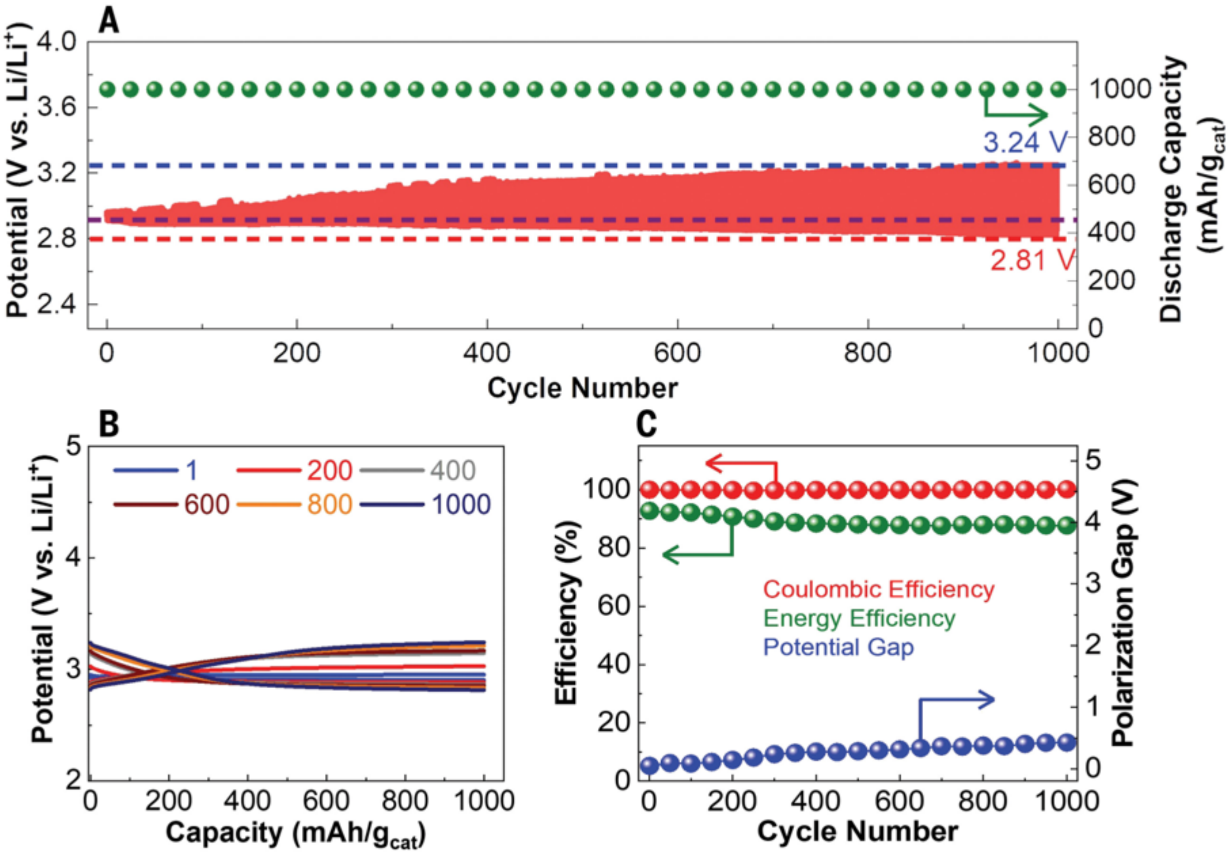


Figure 6. Solid-state Li-air battery at a constant current density of 1 A/g and a limited capacity of 1 Ah/g.Galvanostatic cycling over 1000 cycles. (B) Discharge/charge profiles at different cycles. (C) Coulombic efficiency (red dots), energy efficiency (green dots), and polarization gap at the end of cycle (blue dots) over 1000 cycles. Copyright, American Association for the Advancement of Science, 2023 [8].

2.6 Faradion - Sodium-ion battery

Founded in 2015, Faradion has been developing sodium-ion batteries for nearly 30 years. The company focuses on high-energy-density batteries utilizing an organic electrolyte, designed as a direct replacement for lithium-ion batteries due to their maximum cell voltage of 4.2 V [8]. The sodium-ion batteries developed by Faradion feature a hard carbon anode and a layered metal oxide cathode. The electrolyte consists of a mixture of organic solvents—ethylene carbonate, diethyl carbonate, and propylene carbonate—with 1M $NaPF_6$ as the supporting salt. As shown in Figure 7, the cells can be charged above 4.0 V and discharged down to 0 V, though they typically operate between 4.0 V and approximately 1.0 V. Notably, some cells have demonstrated durability over 1,000 charge-discharge cycles, with no degradation observed after six months at 0 V. Figure 8 illustrates Faradion sodium-ion batteries, including their cell design, applications, and performance in cycle life and calendar life.

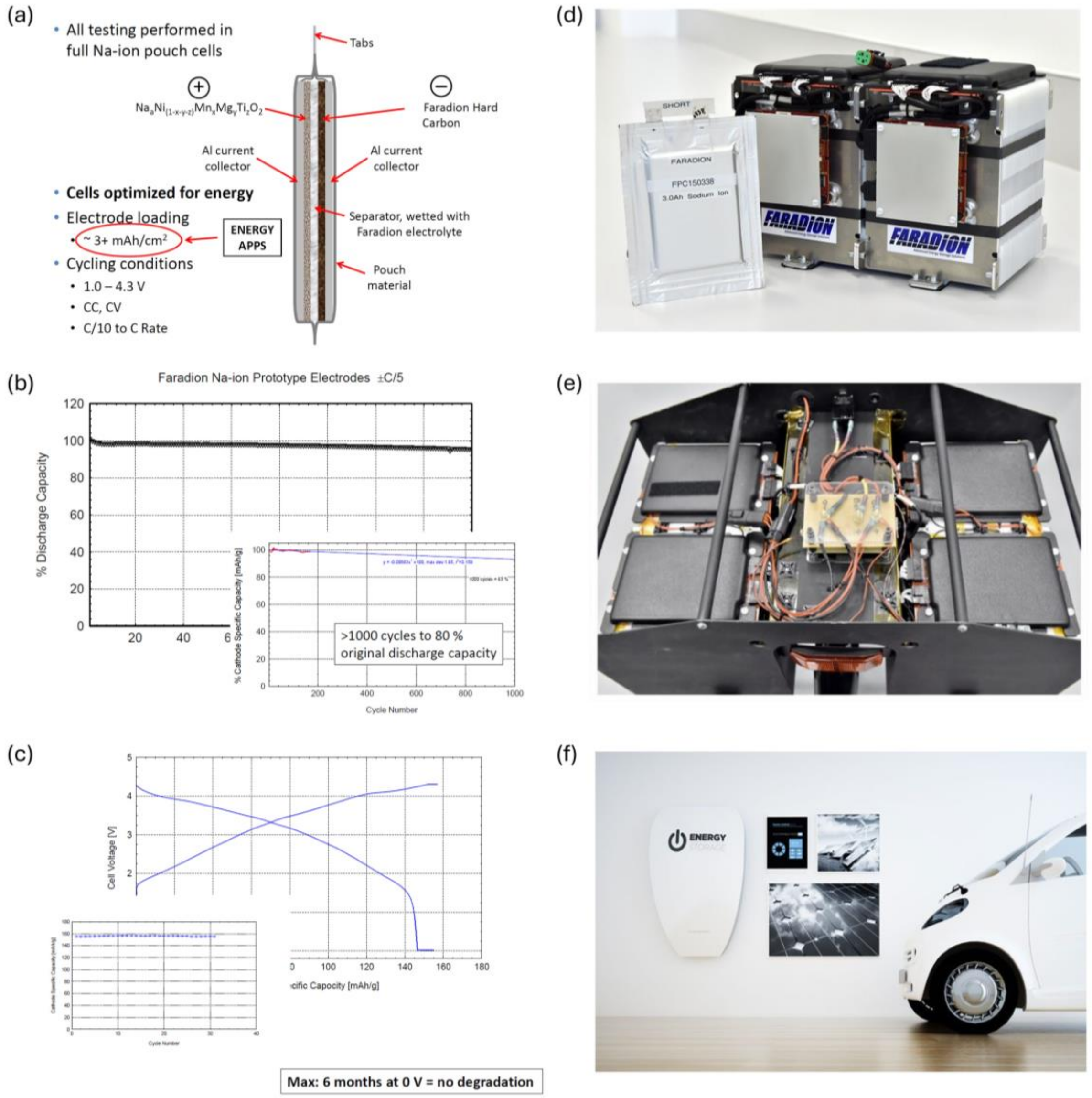


Figure 7. Faradion sodium-ion batteries: products, applications, and performance in cycle life and calendar life. (a) Cross-sectional diagram of a Na-ion pouch cell; (b) performance graph of Faradion Na-ion prototype electrodes at a C/5 rate; (c) voltage vs. capacity curve for the Na-ion cell, along with a stability test; (d) Na-ion battery packs and a pouch cell prototype; (e) an integrated battery system in a large-scale application; (f) electric vehicle applications, demonstrating the potential of Na-ion technology in residential and transportation sectors.

3. Literature Survey on Advanced Batteries: Academic Progress

This section provides a comprehensive review of advanced battery technologies, focusing on their current state of development, key performance characteristics, and challenges in transitioning from prototypes to commercialization. In addition, it examines safety considerations to address concerns regarding their adoption across various applications. By summarizing the existing knowledge base and identifying research gaps, this section establishes a foundation for subsequent modeling and analysis.

3.1 Advanced lithium batteries

3.1.1 Introduction

The 2019 Nobel Prize in Chemistry awarded to John Goodenough, M. Stanley Whittingham, and Akira Yoshino marks a milestone in battery technology [10]. Their work laid the groundwork for LIBs that now power technologies ranging from portable electronics to EVs and grid-scale storage. The development of LIBs started during the 1970s oil crisis as a response to the need for alternative energy sources. Early batteries such as lead-acid and nickel-cadmium were inadequate for the demands of high-energy output. Whittingham was the first to explore lithium intercalation into transition metal disulfides, paving the way for rechargeable lithium batteries. Goodenough advanced this by developing the lithium cobalt oxide ($LiCoO_2$) cathode [11], significantly increasing the voltage and energy density. The major breakthrough was achieved through the development of the first practical LIB prototype by Yoshino, which utilized carbonaceous material anodes and avoided the use of reactive metallic lithium anodes prone to dendrite formation. This advancement led to the commercialization of the first LIB prototypes by Sony, significantly improving energy density and safety through the introduction of novel electrolyte formulations.

Research continues to focus on overcoming LIB limitations by exploring new materials such as lithium-metal and developing advanced cathodes from layered Ni-Mn-Co oxides. These efforts aim to enhance voltages and capacities, expanding the possibilities for energy density and battery life. Building on the established foundations, the goals are to increase energy and power, enhance safety, reduce costs, and extend battery life. Integrating nanotechnology and new electrolyte systems could unlock the potential of lithium-metal anodes, setting the stage for next-generation batteries. The evolution of batteries showcases the synergy between scientific discovery and engineering innovation. With ongoing research and investment, the future of battery technology promises a sustainable, electrified world. The narrative of battery innovation is ongoing, continuously driving technological progress.

In recent years, LIBs have become the dominant energy storage technology for consumer electronics and transportation electrification. The price of LIBs has declined significantly, driven by advancements in material production and high-speed manufacturing. However, despite increased lithium production, prices have not continued to decline as expected since the 2020s. The COVID-19 pandemic, sustained high demand, and supply chain constraints have disrupted the anticipated cost reductions. Since 2021, lithium prices have surged by 300%, alongside sharp increases in nickel prices [12]. In addition, ethical and environmental concerns surrounding cobalt mining raise questions about the sustainability of LIBs [13]. As of 2024, the commercialization of high-nickel cathode materials such as NMC811, NMC955, and NCA is progressing steadily, driven by the demand in the EV industry for batteries with higher energy density and lower cobalt dependence [14]. Tesla, for instance, has transitioned to an NMC955 composition to enhance energy density and reduce cobalt usage [15]. The increased nickel content in these chemistries enables higher capacity and greater range, but balancing safety—particularly mitigating thermal runaway [16],[17], characterized by gas generation and fire—and longevity remains a technical challenge. As a result, the development of next-generation batteries is accelerating, with a focus on affordability, sustainability, and energy security. These advancements are critical for reducing dependence on fossil fuels and signal an important shift toward innovative energy storage solutions. The future of battery technology will likely involve diverse approaches tailored to meet various performance needs effectively.

The advancement of battery technology is increasingly centered on enhancing key performance metrics such as energy density, cost reduction, and cycle life (Figure 8), to meet the diverse needs of different market segments. Energy density, in particular, has emerged as a critical factor for market penetration, given its direct influence on vehicle range and overall battery performance. Amidst intensifying competition, a range of advanced battery technologies has either entered commercial use or is approaching commercialization, as depicted in Figure 9. This includes the development of high-energy-density materials, such as nickel-rich cathodes and silicon-dominant anodes, which enable batteries to store more energy per unit mass or volume. Furthermore, novel solid-state electrolytes (SSE) are advancing the safety and energy performance of next-generation batteries by eliminating the risk of leakage and thermal runaway. In parallel, advanced high-speed manufacturing processes—such as roll-to-roll coating, high-precision electrode stacking, and laser-patterned electrodes—have facilitated large-scale battery production without compromising quality or performance. Altogether, these interdisciplinary efforts in material science, manufacturing, and digital technologies are paving the way for batteries that not only deliver higher energy density and longer cycle life but also align with the economic and environmental goals of the rapidly growing electric vehicle market (Table 3). This continuous innovation is essential for meeting the demands of next-generation EV applications, where higher performance, safety, and sustainability are paramount.

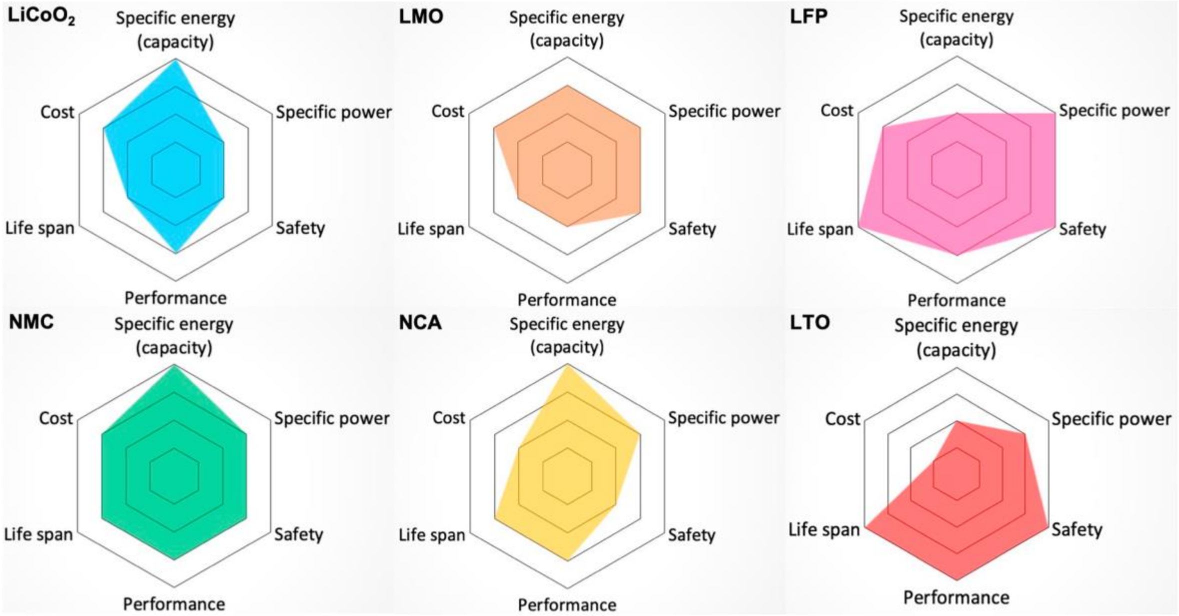
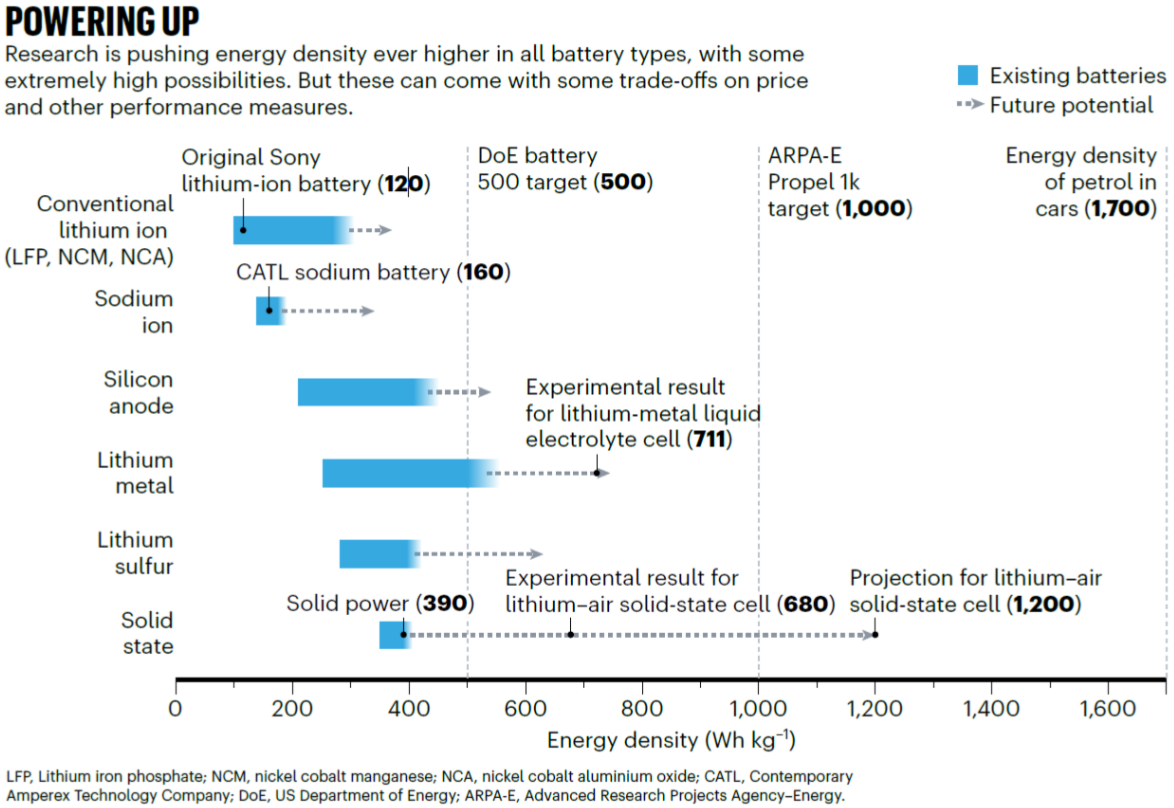


Figure 8. Different types of lithium-ion batteries used in electric vehicles (Please note that LTO is an anode and is paired with LMO or NMC) [18].


POWERING UP

Research is pushing energy density ever higher in all battery types, with some extremely high possibilities. But these can come with some trade-offs on price and other performance measures.

LFP, Lithium iron phosphate; NCM, nickel cobalt manganese; NCA, nickel cobalt aluminium oxide; CATL, Contemporary Amperex Technology Company; DoE, US Department of Energy; ARPA-E, Advanced Research Projects Agency–Energy.

Figure 9. Energy density of advanced battery technologies. Copyright, Nature [19].

Table 3. Overview of advanced battery technologies.

Technology	Advantages	Challenges	Application Scenarios	Electrode
Ternary lithium-ion battery	High energy density, long cycle life, low self-discharge	Cost, thermal stability, safety concerns	Long-range transport, high-utilization transport	NCM /Graphite
Solid-state batteries	Improved safety, higher energy density, longer lifespan	Manufacturing complexity, cost, scalability	Long-range transport, high-utilization transport	NCM /Li-metal or Si
Sodium-ion batteries	Abundant raw materials, lower cost	Lower energy density, shorter cycle life	Low-cost transport	Sodium-based cathode/Hard carbon anode
Lithium-metal batteries	Extremely high energy density, lightweight	Safety concerns, dendrite formation, high cost	Long-range transport, high-utilization transport	NMC or Sulfur/Li-metal
Silicon-based batteries	Higher capacity, energy density	Volume expansion, cycle life, manufacturing complexity	Long-range transport, high-utilization transport	NCM/Si

3.1.1.1 Ternary lithium-ion battery

Ternary LIBs, particularly those using high-nickel layered oxides such as nickel-manganese-cobalt (NCM) and nickel-cobalt-aluminum (NCA), evolving from lithium cobalt oxide (LCO), have become central to modern electric automobiles due to their enhanced performance and adaptable compositions [20]. Their elemental versatility allows for the fine-tuning of battery properties to meet diverse requirements. The shift towards EVs has brought into focus the challenge of sourcing raw materials. These batteries primarily depend on nickel (Ni) and cobalt (Co), elements critical in achieving desired performance. In addition, in 2021, the first high-capacity NCMA (Nickel Manganese Cobalt Aluminum) battery in the world was introduced [21]. NCMA batteries are a variation of NMC chemistry, with aluminum added to improve thermal stability, cycle life, and energy density.

Transitioning the global light-duty vehicle fleet to electric power will significantly increase the demand for these materials. The current supply, however, is limited, with approximately 2.5 million tonnes of Ni [22] and only 140 thousand tonnes of Co [23] available annually. Therefore, an important goal is to reduce or completely eliminate cobalt from cathode compositions to alleviate supply constraints and address ethical concerns associated with its extraction, alongside exploring possibilities for increased energy density [24]. This approach not only meets the urgent need for sustainable material sourcing but also contributes to the global effort to enhance EV battery energy efficiency, propelling the future of electrified transportation.

While efforts to eliminate cobalt from battery cathodes are gaining momentum, divergent viewpoints emphasize the critical role of cobalt in maintaining the thermodynamic stability of layered battery structures. This stability is essential for achieving higher energy densities without compromising either performance or safety, a balance that could mitigate the impact of higher raw material costs by lowering the overall cost per kWh of batteries.

Studies suggest that the anticipated demand for cobalt in cathode materials—essential for powering an estimated 1.3 billion EVs by 2050—could be met if supply trends follow those of other major industrial metals [25]. In addition, recycling is expected to play a key role in supplementing primary supply [26]. However, the geopolitical distribution of cobalt resources remains a significant concern, as it could lead to supply instability. The Democratic Republic of Congo currently supplies more than 70% of the mined cobalt worldwide [27], making the global supply chain heavily dependent on a single region. The cobalt conundrum highlights the broader challenge of evaluating the full life cycle of new energy technologies—from raw material extraction and refining to fabrication, processing, distribution, operation, recycling, and reuse. Addressing these challenges requires designing technologies with sustainability in mind from the outset, ensuring that environmental, ethical, and supply chain considerations are integrated into the development process. To mitigate supply risks associated with cobalt, one solution is to shift toward cathode chemistries that reduce or eliminate cobalt content. For example, next-generation nickel-rich cathodes such as NMC811 and NMC955 contain less than 5% cobalt, significantly reducing dependence on this critical material.

3.1.1.2 Lithium iron phosphate batteries

LFP batteries are gaining renewed attention due to their improved safety, lower cost, and cobalt-free, nickel-free composition, which addresses ethical and supply chain challenges associated with cobalt. This revival is pivotal in making EVs more economically competitive with internal combustion engine vehicles, especially as LFP technology becomes increasingly affordable, with prices dropping below $100 per kWh (pack-level: $130/kWh, cell-level: $95/kWh) as of 2023 [28]. In addition, the enhanced durability of LFP cells contributes to a longer battery life, a key concern for consumers.

The primary challenge for LFP technology has been its lower energy density relative to ternary oxide cells. However, advancements in cell-to-pack (CTP) technology, as demonstrated by BYD blade battery [29], are narrowing the energy density gap. These blade batteries utilize larger and thinner cells for higher integration efficiency, potentially matching or surpassing the energy density of ternary batteries at the pack level. The progress in LFP technology, particularly with thermally modulated LFP (TM-LFP) blade batteries, indicates a bright future for its adoption in mass-market EVs [30]. By addressing key challenges such as cost efficiency, rapid charging, and range anxiety, LFP cells have become significant contributors to the electric mobility landscape. However, a major limitation remains: the maximum energy density of LFP battery systems has stagnated at around 160 Wh/kg at the cell level over the past two years. This energy constraint poses challenges for long-range EV applications, which demand greater driving distances and reduced reliance on frequent charging. To overcome this limitation, recent research and development efforts have focused on enhancing LFP energy density through material modifications. One promising approach is doping LFP with manganese to create lithium manganese iron phosphate (LMFP). LMFP exhibits a 15–20% increase in energy density compared to conventional LFP, reaching levels comparable to NCM 523 or even NCM 622, while maintaining the inherent cost and safety advantages of LFP [31]. In addition, vanadium (V) doping has emerged as another effective method for improving LFP performance. By introducing a small amount of vanadium into the lithium sites of the $LiFePO_4$ crystal structure, researchers have induced lithium vacancies, facilitating better ion mobility and charge storage capacity. As a result, the capacity of V-doped LFP increases from 138 mAh/g (pristine $LiFePO_4$) to 155 mAh/g, demonstrating a measurable improvement in electrochemical performance [32]. These advancements in Mn- and V-doped LFP suggest that continuous innovation in cathode materials could enable LFP batteries to achieve higher energy densities, making them more viable for a broader range of EV applications.

3.1.1.3 Lithium titanate oxide batteries

Lithium Titanate Oxide (LTO) batteries provide a well-established alternative to LIBs with graphite anodes. In these batteries, LTO serves as the anode material and is typically paired with LMO or NCM cathodes. Operating within a voltage range of 2.5–2.0 V, LTO batteries deliver an energy density of approximately 100 Wh/kg and 180 Wh/l. While this energy density is lower compared to conventional LIBs, LTO batteries possess several key advantages: (1) low resistance and high power output, (2) the ability to recharge in as little as 10 minutes, (3) a cycle life of 3,000–5,000 cycles, and (4) reliable operation at low temperatures (below -10°C)[33]. Despite their higher cost, largely driven by the expensive LTO powders, the longer cycle life of these batteries offsets the initial investment over time [34]. This makes them particularly well-suited for applications requiring relatively small batteries (20–30 kWh) with high power demands and fast recharging capabilities, such as smaller construction machinery. The extended lifespan of LTO batteries ensures years of operation before replacement becomes necessary. Currently, LTO batteries are being explored and deployed in select medium and heavy-duty truck applications [35], highlighting their potential relevance in commercial and industrial transportation. While not yet mass-produced at the scale of NMC or LFP batteries, LTO technology has been adopted in specific fleet operations where rapid charging and long cycle life provide advantages [36].

3.1.1.4 Lithium-metal batteries

Lithium-metal batteries (LMBs) have emerged as a potential solution, promising higher specific energy than current lithium-ion technology. The key focus has been on addressing dendrite formation and enhancing cell architecture for improved performance [37]. Li-metal, with its ultra-high theoretical specific capacity and low electrochemical redox potential, is a frontrunner for next-generation energy storage systems when paired with a high-capacity cathode such as NMC 811. These materials, when utilized in a practical cell, must meet several requirements, including high specific energy, long cycle life, stability over a broad temperature range, safe operation, and more.

LMBs are a pivotal innovation driving the energy storage capabilities of EVs to new heights. Distinguished by the integration of lithium metal as the anode material rather than traditional graphite, LMBs unlock the potential for markedly elevated energy storage capacities. This is attributed to the superior specific capacity of lithium, which is 3860 mAh/g, and its exceptionally low electrochemical potential. Such advancements are crucial for transcending the nearing theoretical energy density boundaries imposed by existing LIB technologies, thereby heralding a new epoch of enhanced performance and efficiency in energy storage solutions. However, the shift to lithium-metal anodes introduces several challenges that must be meticulously addressed to ensure the feasibility of LMBs. One of the most critical issues is the formation of dendrites during lithium deposition, which can pierce the battery separator and cause short circuits, leading to potential battery failure or even safety hazards such as thermal runaway. The dendritic growth problem is exacerbated by the highly reactive nature of lithium metal with the electrolyte, leading to the formation of a heterogeneous solid electrolyte interphase (SEI) that consumes electrolyte components and degrades battery performance over time.

To mitigate these challenges, research and development efforts are focusing on advanced electrolyte formulations that can stabilize the lithium-metal interface, innovative separator technologies that can prevent dendrite penetration, and novel cell designs that encourage uniform lithium deposition. Furthermore, protective coatings on the lithium metal anode and the adoption of SSE are being explored as strategies to enhance the stability and safety of LMBs. Despite these technical hurdles, the potential benefits of LMBs, such as their high energy density and the prospect of faster charging times, drive ongoing research. The development of LMBs holds the promise of significantly extending the driving range of EVs and enabling more compact and longer-lasting portable electronics, marking a significant leap forward in battery technology. In summary, while LMBs offer a highly attractive pathway towards high-energy-density storage solutions, overcoming their intrinsic challenges necessitates concerted efforts in materials innovation, cell design optimization, and an in-depth understanding of lithium metal electrochemistry. The successful deployment of LMBs will likely hinge on breakthroughs in these areas, paving the way for a new era of energy storage.

Developing a long-cycling, high-energy rechargeable lithium metal battery is a complex endeavor that challenges the limits of current battery technology [38]. To achieve practical usage of a lithium anode in a cell with high cathode loading, a lean electrolyte volume, and a limited negative-to-positive (N/P) ratio, innovative strategies must be employed. The crux of advancing lithium metal battery technology lies in understanding and mitigating cell-level failure mechanisms, which can be elucidated through advanced measurement techniques and new characterization tools. These tools are essential for quantifying the behavior of both active and inactive lithium during battery cycling. Progress in electrolyte chemistry, specifically through the development of concentrated or localized high-concentration electrolytes, has shown promise in reducing reactivity and enhancing the stability of lithium deposition. However, substantial research is still necessary to promote uniform, dense lithium deposition rather than porous formations that compromise battery integrity and performance. In addition, the integration of ultrathin and flexible solid electrolytes could provide a critical barrier between the lithium metal and the liquid electrolyte, enhancing safety and stability [39]. Beyond conventional approaches, exploring mechanically and electrochemically stable polymers other than polyethylene oxide (PEO) could yield breakthroughs in solid electrolyte development [40]. The future of high-energy lithium metal batteries may also hinge on the utilization of extremely thin layers of lithium and innovative lithium host structures within the anode. These host structures must not only fit within stringent cell design parameters but also be scalable and manufacturable on an industrial scale.

Understanding and applying coulombic efficiency (CE) in LMBs is crucial for evaluating their performance and longevity. One work has explored the differences and similarities of CE in LIBs and rechargeable LMBs [41], emphasizing the distinct principles that govern CE and cycling life in various cell configurations such as anode-free cells, Li/Cu cells, and Li/Li symmetrical cells. CE is influenced by several factors, including the electrochemical window, electrolyte compatibility, original lithium thickness, electrolyte type and content, and cathode mass loading. These parameters must be carefully considered to fully understand CE and its impact on the lifespan of LMBs. It is also important to address the artificial inflation of CE in rechargeable metal batteries, a common issue that can skew testing results. To address these complexities, a protocol for measuring CE in different coin cell configurations has been proposed [41]. This protocol aims to clarify the fundamental relationships between these cell types and apply CE measurements to estimate the cycle life of realistic high-energy LMBs. The insights gained from this work are not only applicable to lithium-based systems but also extend to other metal-based battery technologies such as magnesium, zinc, and sodium batteries, highlighting the broad relevance of this research in advancing battery technology.

The ultimate goal for lithium metal batteries, especially those intended for EVs and consumer electronics, extends beyond achieving high energy density and long cycle life. It also involves ensuring the safety and reliability of the batteries under practical conditions. Another significant challenge is the production of inexpensive, ultra-thin lithium metal foils, as excessive lithium usage can negatively impact both energy efficiency and safety. This constraint underscores the need for a concentrated effort to address cell-level challenges, aligning new materials and technological advances with the real-world demands of battery performance and manufacturing. By tackling these barriers, the industry can accelerate the deployment of lithium metal battery innovations, making them a viable and essential component of modern energy solutions.

3.1.1.5 Silicon-containing batteries

The advancements in silicon (Si) anodes for LIBs have primarily focused on mitigating the significant volume changes that occur during charge and discharge cycles. However, this emphasis on mechanical stability overlooks other crucial aspects of cell aging, including both cycling and calendar life degradation. Silicon offers a theoretical capacity of 3,579 mAh/g, which is nearly ten times higher than that of graphite (372 mAh/g). However, due to the challenges associated with volume expansion, SEI instability, and continuous lithium consumption, the practical capacity of silicon anodes is typically limited to ~1,500 mAh/g to ensure reasonable cycle life. To improve performance, silicon-carbon (Si-C) composites have emerged as a promising alternative, balancing the high capacity of Si with the structural stability of carbon. While 100% Si anodes maximize theoretical capacity, they suffer from severe mechanical stress and poor cycling stability, leading to rapid capacity fade and shorter calendar life. In contrast, lower-percentage Si-C composites (e.g., ≤20% Si content) have demonstrated improved structural integrity, longer lifespan, and enhanced SEI stability, making them a more viable option for commercial applications. Calendar aging in Si-based anodes remains an underexplored challenge, particularly in comparison to the well-established SEI formation protocols in graphite anodes [53]. Extending these graphite-based best practices to Si could help optimize formation protocols and enhance long-term stability. Furthermore, cell-stack pressure has recently been identified as a key factor influencing SEI evolution and overall battery longevity. Notably, Enovix has demonstrated that higher stack pressures can improve the calendar life of Si-rich cells [54], likely due to enhanced electrode contact, better SEI passivation, and reduced interfacial resistance. This suggests that stack pressure optimization could be a crucial design parameter in the commercialization of durable Si-based batteries. Overall, a comprehensive approach—incorporating Si-C composite strategies, optimized SEI formation, and stack pressure control—is necessary to overcome the calendar life limitations of Si anodes and enable their widespread adoption in high-energy-density applications.

The stability of the Si SEI is particularly challenging, as it tends to degrade even without cycling. This degradation prompts a need to shift focus from cycle-based evaluations to time-based assessments, where SEI composition, porosity, and conductivity are monitored over time. Understanding how these properties evolve can provide critical insights into mitigating the calendar life issues of Si anodes. From a practical standpoint, the effectiveness of coatings on Si particles needs rigorous evaluation. It is crucial to ensure these coatings remain intact and conformal following multiple expansion and contraction cycles. Identifying the precise conditions under which Si is exposed to the electrolyte is essential for refining fabrication processes to enhance long-term stability. In addition, there is a need for methods to quantify the effective surface area of Si particles post-cycling and determine the extent to which active material remains electronically connected. Such assessments require advanced characterization techniques ranging from in situ to post mortem analyses. At a more fundamental level, Si and graphite anodes exhibit similar potentials for electrolyte reduction but differ significantly in their passivation behaviors. The absence of a comprehensive modeling framework that accounts for these differences is a major barrier to developing Si electrodes with adequate calendar life. Integrating models across different scales—from atomistic to electrode-level—could improve the accuracy and utility of these models. Such integration could leverage recent advances in characterization techniques to refine and apply SEI models specifically for Si, providing deeper insights into the causes of instability and guiding improvements in SEI properties. Finally, the lengthy process of diagnosing and developing solutions for calendar aging presents a significant challenge. To bridge the gap between conceptualization and validation, accelerated aging studies at elevated temperatures are often employed. However, this approach may introduce non-representative aging mechanisms, particularly in Si-rich cells. Developing fast, reliable chemical and electrochemical assays to assess long-term stability could be crucial in advancing the use of Si in commercial battery applications, helping to match the pace of innovation with the practical demands of battery manufacturing and deployment.

In the development of silicon-containing lithium-ion batteries (LIBs), achieving high laboratory performance does not inherently ensure commercial viability. Studies indicate that while certain strategies enhance the cycle life of silicon anodes, they do not necessarily improve calendar life [55], highlighting the necessity for a comprehensive evaluation framework. Bridging the gap between laboratory innovation and practical implementation requires rigorous testing across all relevant performance metrics to ensure real-world reliability. The findings underscore the importance of holistic evaluation protocols that extend beyond conventional performance metrics, facilitating the advancement of next-generation battery anodes capable of meeting the evolving demands of energy storage technologies.

3.1.1.6 Solid-state batteries

SSBs present a remarkable leap forward in electrochemical energy storage, with their potential for safe, stable, high-energy, and high-rate power sources. A decade after lithium solid electrolytes first demonstrated superior conductivity, the emphasis has shifted to address practical concerns. Advanced SSBs are expected to outperform current LIBs due to potential bipolar stacking and the use of lithium metal or silicon anodes, alongside anticipated enhancements in safety. The push for vehicle electrification has been bolstered by the efficient mass production of LIB cells. However, as the limits of LIBs approach, SSBs are investigated intensively. Promising reports from industry leaders such as Samsung, Solid Power, QuantumScape, and Toyota, among others, have showcased significant advances [42],[43]. Yet, these are set against a backdrop where the LIB is a dynamic target, with progress potentially overshadowed by concurrent improvements and engineering challenges in the LIB space.

The diverse array of materials and procedures implicated in the development of SSBs introduces substantial intricacies, particularly owing to the physicochemical expansion and compression experienced by electrode substances throughout battery operation. Such phenomena can instigate significant mechanical stresses at the material interfaces, underscoring the necessity for a meticulously engineered microstructure within cathode composites. This demands a strategic approach to optimizing the architecture of these components to mitigate adverse effects and enhance battery performance. The diversity of research approaches, with interdisciplinary teams working on materials, design, and production methods, is pivotal for SSB evolution. It is this multifaceted approach, engaging expertise across various scientific domains, that will address the myriad challenges facing SSBs and guide them towards a successful commercial future. Continuous innovation and diversified approaches in materials and designs are key to establishing long-term, commercially viable SSBs.

Recent advancements in SSBs demonstrate their potential to outperform LIBs with greater safety, energy density, and power output. Nonetheless, achieving their commercial viability involves overcoming substantial challenges [44]. The success of SSBs hinges significantly on the design of composite cathodes that can withstand chemomechanical stresses. These stresses arise from interactions between active materials and solid-state electrolytes, often leading to microstructural damage such as cracking, which in turn degrades performance. Effective ionic and electronic conductivities within these composites are essential and require optimization of particle size distribution and binder usage to enhance long-term stability. There is also a pressing need for SSE with high ionic conductivities to facilitate rapid charging and discharging. Current research focuses on developing SSE that exceed the ionic conductivity of traditional liquid electrolytes. Promising materials include $Li_{10}GeP_2S_{12}$ and various lithium argyrodites. Interface stability between the SSE and electrodes is crucial for the longevity of SSBs [45]. Although coatings on cathode materials can mitigate chemical degradation, they need to be engineered to maintain their protective properties under operational stresses. Exploring different materials for cathodes and anodes could also enhance the energy density and stability of SSBs. Silicon anodes, for example, offer higher capacities but pose challenges related to volume expansion and interface stability with SSE. Combining solid and liquid or gel-polymer electrolytes might address some limitations of fully solid systems, such as mechanical stresses and interface instabilities. However, these hybrid designs must balance the benefits of solid components with the operational stability provided by liquid elements.

For SSBs to be commercially viable, production processes must be scalable and cost-effective. This involves not only optimizing the materials used but also integrating these materials into existing battery manufacturing processes. While there are technical challenges, the concerted effort from the research community and industry stakeholders is paving the way for innovative solutions that may soon lead to the practical realization of SSBs. This dynamic field continues to evolve, promising to revolutionize the approach to energy storage with safer, more efficient battery technologies.

Recent advancements in SSBs and their electrolytes over the last two decades have led to significant phase and material discoveries that challenge conventional manufacturing approaches. Traditionally, the production of solid lithium electrolytes relied heavily on high-temperature sintering, contributing to high costs. However, alternative methods such as tape processing now suggest that these costs could be substantially overestimated and that future manufacturing might bypass high-temperature sintering altogether. Innovations in ceramic film production, particularly those ranging from 1–20 μm, could replace polymer separators in LIBs, offering higher electrochemical stability and compatibility with lithium [46]. This shift is supported by advancements in materials such as lithium aluminum titanium phosphate (LATP), lithium lanthanum titanium oxide (LLTO), and lithium lanthanum zirconium oxide (LLZO), which eliminate the need for traditional sintering thanks to scalable wet-chemical processes. Moreover, these new ceramic processing techniques allow for the creation of grain-boundary-free, amorphous solid Li+

electrolyte ceramics, enhancing design flexibility and broadening the operational electrochemical stability window in SSBs. As evolving from high-temperature to lower temperature ceramic processing, precise control over lithium stoichiometries is essential for ensuring phase stability and optimal performance. This transformation in SSB manufacturing not only marks a shift in how batteries are produced but also compels the SSB community to innovate and adapt, paving the way for next-generation batteries suitable for EVs. However, one of the significant challenges in this transition is the manufacturing of thin SSE. These materials are inherently brittle and require high pressure to ensure optimal contact between battery components, as poor interfacial contact can lead to increased resistance, particularly over time, degrading performance.

One study benchmarks the performance of all-solid-state lithium batteries (ASSLBs) using a simplified system with a lithium metal anode, β-Li_3PS_4 solid electrolyte, and a $Li(Ni_{0\cdot6}Co_{0\cdot2}Mn_{0\cdot2})O_2$ cathode [47]. By reducing the battery to its essential components, the researchers offer a standardized reference for evaluating key metrics such as energy density, power, and efficiency. Their findings highlight critical research targets for improving ASSLBs, particularly in solid electrolyte materials and electrode design, to advance practical high-energy, high-power batteries for commercial use. More recently, another study addresses the critical issue of interlaboratory comparability and reproducibility in the cycling performance of ASSLBs, an area that remains poorly understood due to the absence of standardized assembly procedures and set-up parameters [48]. By providing 21 research groups with commercially sourced battery materials—$LiNi_{0\cdot6}Mn_{0\cdot2}Co_{0\cdot2}O_2$ for the positive electrode, Li_6PS_5Cl as the solid electrolyte, and indium (In) for the negative electrode—this study systematically quantifies the variability in cell assembly and performance. Each group was instructed to follow a uniform electrochemical protocol but use their own cell assembly methods. The findings reveal significant variability in both assembly techniques and electrochemical performance, with key differences observed in processing pressures, pressing durations, and In-to-Li ratios. Despite these variations, the study identified that an initial open circuit voltage between 2.5 and 2.7 V vs. Li+/Li is a reliable predictor of successful cell cycling when using these specific electroactive materials. It concludes by recommending a standardized set of parameters for reporting cycling results of ASSLBs to improve reproducibility across laboratories. It also emphasizes the importance of reporting data in triplicate to account for variability and ensure more accurate and comparable results across different research efforts.

3.1.1.7 Lithium-sulfur batteries

"Li-S batteries have garnered significant attention due to their exceptionally high theoretical specific energy, reaching approximately 2600 Wh/kg at the material level, far exceeding that of conventional LIBs. This advantage arises from the multi-electron transfer in the conversion reaction of sulfur, making it a cost-effective and abundant cathode material. However, despite these benefits, Li-S batteries face substantial challenges that impede commercialization, including polysulfide dissolution, poor sulfur utilization, and lithium dendrite formation. One of the most critical issues is the shuttle effect caused by the dissolution of lithium polysulfides, which results in capacity fading and low Coulombic efficiency. Recent research has demonstrated that modifying the separator can effectively mitigate this issue. For example, a lepidolite-modified polypropylene (C-Lepidolite@PP) separator has been shown to suppress polysulfide diffusion while accelerating its conversion [49]. The strong Si–S bonds formed with polysulfides weaken their S–S bonds and enable rapid redox kinetics. In addition, the ultralow lithium-ion diffusion barrier of lepidolite facilitates lithium-ion migration, improving high-rate operation and reducing self-discharge rates. Another key factor influencing the performance of Li-S batteries is the compromise between mass and energy-level efficiency. Comprehensive studies have identified descriptors that quantify trade-offs between sulfur mass loading, sulfur mass ratio, electrolyte-to-sulfur ratio, and negative-to-positive electrode material ratio [50]. These parameters are crucial for optimizing energy density and ensuring practical implementation of Ah-level Li-S batteries.

To address the inherent conductivity issues of sulfur, innovative cathode designs incorporating electrocatalytic and conducting materials have been explored. One promising approach involves using pre-lithiated metallic 1T-phase two-dimensional molybdenum disulfide ($LixMoS_2$) as a sulfur host [51]. This material enhances lithium polysulfide adsorption, improves Li^+ transport, and accelerates electrochemical reaction kinetics. Consequently, Li-S pouch cells incorporating $LixMoS_2$ cathodes have demonstrated high energy density and stable cycling performance, even under lean electrolyte conditions. In addition to cathode and separator advancements, interfacial challenges remain a significant hurdle for Li-S batteries. The unstable multi-interfaces between electrodes and electrolytes contribute to capacity degradation and cycling instability. Strategies such as artificial solid electrolyte interphase layers, composite anode structures, and interface engineering have been developed to enhance interfacial stability and prolong cycle life [52]. Advanced characterization techniques have also provided deeper insights into lithium-sulfur electrochemistry, guiding future research in interfacial optimization. While significant progress has been made, achieving commercial viability requires further advancements in cycle life, energy density, and manufacturability. Future research should continue to focus on material innovations, electrolyte formulations, and interface engineering to unlock the full potential of Li-S technology for next-generation energy storage applications.

3.1.1.8 Lithium-air batteries

Lithium-air batteries represent a transformative advancement in energy storage, offering a theoretical energy density far exceeding that of conventional lithium-ion systems [56]. This cutting-edge technology is based on the electrochemical reaction between lithium and oxygen, yielding lithium peroxide (Li_2O_2) or lithium oxide (Li_2O), depending on the electrolyte composition and operating conditions. With a theoretical energy density of approximately 11,680 Wh/kg, lithium-air batteries approach the energy content of fossil fuels, positioning them as promising candidates for high-energy applications such as EVs. However, the practical energy density of lithium-air batteries is significantly lower due to inefficiencies in both the anode and cathode, as well as the additional weight of auxiliary components such as pumps, diffusion layers, and electrolyte management systems. These factors contribute to energy losses and reduce the overall system-level energy efficiency, limiting their immediate feasibility for real-world applications. Unlike traditional lithium-ion batteries, lithium-air batteries utilize oxygen from the environment as the cathode active material, which is reduced during discharge to form solid lithium oxides or peroxides. This operational mechanism introduces additional challenges related to oxygen transport, cathode clogging, and reaction reversibility, necessitating further research into electrode design, electrolyte stability, and system integration to realize their full potential.

Challenges in materials and design currently impede the commercialization of Lithium-air batteries, despite their significant theoretical potential. Key limitations include electrode degradation, side reactions involving electrolytes, poor cycle life, and restricted oxygen diffusion [57]. However, advances in materials science and system design offer promising solutions. The selection of cathode materials is particularly important for managing discharge products and supporting oxygen transport. Porous carbon materials with high surface areas and catalytic properties are receiving substantial attention [58]. Electrolyte stability also remains a critical issue, as reactive oxygen species can cause degradation [59]. Promising alternatives include SSE and ionic liquid-based systems, which enhance chemical stability and compatibility. Catalysts that facilitate oxygen reduction during discharge and oxygen evolution during charging, such as transition metal oxides, perovskites, and nanostructured materials, are being intensively studied to improve reaction efficiency [60],[61]. Effective oxygen management, including the use of selective membranes to regulate oxygen intake and block contaminants such as water and CO_2 is crucial for maintaining system performance and extending battery life.

Prototype lithium-air batteries have recently achieved significant advancements in energy density and cycle life. For instance, solid-state systems have demonstrated stable performance over hundreds of cycles, though they remain below the thresholds needed for commercial use [62]. At very low discharge rates, lithium-air batteries have reached approximately 685 Wh/kg at the cell level; however, when accounting for the balance of plant components—including blowers, filters, and system controls—practical energy density is significantly reduced for real-world applications. In addition, the commercialization timeline for lithium-air batteries remains uncertain, with projections suggesting that achieving modest energy densities at commercially viable costs may take another 10–20 years due to challenges in scalability, material stability, and manufacturing efficiency.

A major area of research is enabling operation in ambient air rather than pure oxygen, which would enhance practicality and reduce system complexity [63]. Cost analysis highlights the importance of scalable manufacturing methods for cathodes and electrolytes to achieve economic viability. In the automotive sector, they offer the energy density and range required to replace internal combustion engines, supporting the transition to fully electrified transportation. However, advancing lithium-air battery technology will require a multidisciplinary approach integrating materials science, computational modeling, and electrochemical engineering. Moreover, testing under real-world conditions across diverse environments is critical to ensure scalability, reliability, and eventual commercial adoption beyond laboratory demonstrations.

3.1.2 Commercialization: From laboratory to large scale manufacturing

The transition from LIBs to post-lithium-ion battery (PLIB) technologies presents significant challenges and opportunities in adapting existing manufacturing infrastructure [64]. While some production processes for PLIBs closely mirror those used for LIBs, the development and commercialization of these emerging battery technologies necessitate substantial research and development. This includes the establishment of new manufacturing capabilities and the creation of specialized machinery tailored to the unique material and design needs of these advanced technologies. To compete effectively with LIBs, which currently dominate the market, PLIBs must meet or exceed performance metrics in terms of energy density, power output, safety, longevity, and cost. Addressing these factors requires innovative approaches to material composition and cell design specific to each PLIB technology. The considerable technical challenges involved in producing PLIBs raise questions about the feasibility and timing of these technologies potentially overtaking LIBs in the market. For any new battery technology to challenge the dominance of LIBs, it must not only demonstrate substantial improvements but also justify the extensive capital investments needed to upgrade or replace current production facilities. This is particularly pressing given the vast production capacities already dedicated to LIBs. Only with clear and significant advantages in key performance areas will new battery technologies attract the necessary investments to become viable alternatives in the mass market, suggesting a cautious but focused progression toward industrialization of these innovative battery systems.

The translation of laboratory innovations into full-scale materials manufacturing for lithium-based batteries presents a set of complex and unique challenges that are distinct from small-scale materials research and development. The process of scaling up materials, combined with the nuances of electrode processing and cell design, requires a deep understanding of materials science to ensure quality and cost-efficiency throughout the production process [65]. In materials manufacturing for lithium-based batteries, choosing cost-effective raw materials is paramount. These materials need to be affordable without compromising on electrochemical performance. It is crucial to thoroughly understand how impurities in these raw materials can influence the final product because even small amounts of impurities can significantly impact the functionality and durability of the battery. Establishing strong quality control measures is essential to ensure the purity and performance of these materials are maintained at an industrial scale. Electrode processing is another critical area where the scalability of coating techniques needs to be addressed to optimize the use of active materials at the electrode level. This involves not only the application of the materials but also ensuring that the coatings are uniform and contribute to the overall performance of the cell.

The bridge between fundamental academic research and industrial application is pivotal. Academic research provides a rich source of innovative ideas that can enhance reaction homogeneity, heat transfer, and material purity at scale. However, these innovations must be aligned with the practical needs of the industry. Understanding these needs is the first step toward developing materials and processes that can significantly enhance yield and performance consistency when scaled. In addition, by integrating high-resolution techniques with advanced online gauging systems, manufacturers can monitor key parameters such as coating homogeneity, electrode alignment, and early defect detection, thereby improving yield and reducing costs. Smart manufacturing, powered by artificial intelligence (AI), leverages data from offline and online characterizations to optimize processes, lower costs, and improve efficiency. Collaboration and cross-validation under industry-relevant conditions are critical for identifying promising battery technologies and accelerating their commercialization. These advancements are pivotal for enabling large-scale energy storage solutions and supporting global decarbonization efforts.

3.2 Sodium-ion batteries

3.2.1 Introduction

The transportation sector is undergoing transformative changes driven by the pursuit of environmental sustainability and increasingly stringent emissions regulations. A key aspect of this transition is the need to reduce reliance on scarce raw materials essential for electric vehicle battery production [66]. Sodium-ion batteries have emerged as a promising alternative to traditional LIBs. This shift has been accelerated by significant advancements in overall battery performance, including the development of high-voltage sodium-ion batteries with long cycling lifespans [67] and improved energy densities, reaching 165 to 200 Wh/kg at the laboratory prototype stage [68],[69]. The abundance of sodium, coupled with its relatively less environmentally intrusive extraction process, makes it a promising candidate for battery applications. However, its lower energy density compared to commercial LIBs remains a significant limitation (Table 4). Although the broad global distribution of sodium has the potential to enhance supply chain stability and cost efficiency, its deployment in sectors with high energy demands, such as heavy-duty transportation, requires significant technological advancements to improve efficiency and overall performance. In periods of lithium shortages and price surges, sodium-ion batteries could provide potential cost advantages, reinforcing their role as a complementary energy storage solution [70]. Despite these benefits, recent analyses indicate that, in the short term, sodium-ion batteries struggle to compete with the most affordable lithium-ion variants in terms of cost [71]. Enhancing their energy density to reduce material intensity is one of the most effective strategies for improving their competitiveness. In the following section, we first analyze the electrochemical characteristics of sodium-ion batteries, followed by an examination of key challenges and future prospects, including market dynamics, cost trends, and overall outlook.

Table 4. Overview of sodium-ion and lithium-ion battery technologies.

Criteria	Sodium-Ion Values	Lithium-Ion Values	Notes
Gravimetric energy density (Wh/kg)	100 - 160	180 – 280	Sodium-ion batteries generally have lower gravimetric energy density due to the heavier sodium ions and different electrochemical potential.
Volumetric energy density (Wh/l)	250- 375	300 - 700	Sodium-ion batteries typically have lower volumetric energy density than lithium-ion batteries.
Cycle life	2000 - 4000	1500 - 3000	Sodium-ion batteries tend to have better cycle life in some applications due to lower reactivity with the electrolyte.
Charging time	1 - 2 hours	0.5 - 1.5 hours	Sodium-ion charging is slightly slower due to larger ionic radius and diffusion limitations.
Temperature stability	-20 to 55°C	-20 to 60°C	Similar thermal stability, but sodium-ion may degrade faster at high temperatures.
Material abundance	Very High (abundant)	Moderate to Low	Sodium is significantly more abundant and cheaper than lithium, improving scalability potential.

3.2.2 Electrochemical characteristics

3.2.2.1 Energy density

Sodium-ion batteries face challenges in the field of energy storage primarily due to their substantially lower energy density relative to LIBs. This discrepancy poses issues especially in areas such as long-haul trucking, where a high energy capacity is essential for efficient operations. The inherent limitations of sodium-ion batteries in terms of energy density require the use of larger and heavier batteries to deliver comparable ranges to those of LIBs, which may reduce the overall vehicle efficiency. Consequently, this can diminish the payload capacity and elevate energy consumption, detracting from the main benefits of electric trucks, namely their superior energy efficiency over vehicles powered by fossil fuels. However, there is potential for improvement through ongoing advancements in cathode materials [72]-[74] and electrolyte formulations [75]-[77]. Research into various cathode materials, including layered transition metal oxides (e.g., $NaxMO_2$ where M can be Mn, Co, Ni) [78]-[84], polyanionic compounds (e.g., $Na_3V_2(PO_4)_3$) [62]-[64], and innovative compositions such as sodium-rich Prussian blue analogs [88]-[90], shows promise in enhancing energy density to around 100–160 Wh/kg. However, this is still significantly lower than the energy densities achievable by lithium-ion batteries (LIBs), which range from 250 to 300 Wh/kg.

Enhancements in ionic conductivity of electrolytes [91] and optimization of the electrode/electrolyte interface [92],[93] are also vital for narrowing the energy density disparity with LIBs. In addition, solid electrolytes for sodium-ion batteries offer significant advantages in terms of safety and stability [94]. These solid electrolytes, such as sodium superionic conductors (NASICON-type) and sulfide-based materials, demonstrate high ionic conductivity and excellent thermal stability, which can reduce risks associated with liquid electrolytes, such as leakage and flammability. Moreover, solid electrolytes can form stable SEI that improve the interface contact between the electrolyte and electrode, enhancing the overall cycle stability and lifespan of the battery. The incorporation of SSE in sodium-ion batteries also opens the possibility for ASSB designs, which promise higher energy densities and safer performance under extreme conditions, potentially bringing sodium-ion technology closer to matching or exceeding the capabilities of current lithium-ion systems. In conclusion, despite current limitations in energy density and efficiency, the trajectory of ongoing research offers optimistic strategies for improvement. Enhancing the energy density of sodium-ion batteries is crucial not only for the demanding requirements of long-haul trucking but also for advancing toward sustainable energy systems. Both the academic and industrial sectors must continue to collaborate in pushing the frontiers of material science and electrochemical engineering to realize the full potential of sodium-ion technology.

3.2.3.2 Electrochemical stability

Achieving electrochemical stability [95] in sodium-ion batteries is crucial for their long-term viability and market competitiveness, especially in transportation sectors such as trucking. The stability of cathode materials during extensive electrochemical cycling significantly affects the operational longevity and safety of sodium-ion batteries, which are essential for their commercial practicality. Cathode materials face severe conditions, including repeated charge and discharge cycles that may cause structural degradation, phase transformations, and chemical instabilities, leading to gradual capacity loss and reduced efficiency over time. For example, current sodium-ion technologies may retain about 80% to 90% of their capacity after 1,000 cycles at 2C [96]. In addition, recent advancements have significantly improved cycling stability. For example, an alkaline-type aqueous sodium-ion battery with an Mn-based Prussian blue analogue cathode exhibits a lifespan of 13,000 cycles at 10C [97], demonstrating notable durability improvements. Such advancements are crucial, as sodium-ion batteries must deliver reliable and consistent performance to be viable for commercial applications. Moreover, the interaction between the cathode and the electrolyte plays a pivotal role in determining battery stability. Developing advanced electrolyte formulations and interface engineering strategies is essential to minimize detrimental side reactions that compromise battery integrity and safety over time. Coating technologies that create stable interphases on the cathode are particularly effective in mitigating degradation mechanisms and enhancing battery life. Ongoing advancements in these areas are vital to developing sodium-ion battery systems that not only meet but exceed the rigorous demands of energy density and safety, ensuring the durability needed for broad adoption in trucking and other critical applications.

3.2.2.3 Fast charging capabilities

The development of fast-charging technology is essential for the widespread adoption of EVs, especially in the commercial trucking sector where minimizing downtime is crucial.

Sodium-ion batteries are promising due to their cost and resource availability, but they currently fall short in fast-charging capabilities compared to LIBs. The fast-charging capability of sodium-ion batteries is influenced by both the cathode (positive electrode) and the anode (negative electrode), with both playing crucial roles in determining overall charging performance. The cathode plays a significant role in fast-charging performance due to its ionic diffusion rate and electronic conductivity [98]. Cathode materials with high electronic conductivity and rapid sodium-ion diffusion can facilitate faster absorption and release of sodium ions, leading to improved fast-charging capabilities. For instance, layered transition metal oxides and sodium-rich Prussian blue analogs have open structural frameworks that enable shorter diffusion pathways and higher sodium-ion mobility, which are beneficial for quick charge acceptance. The anode also critically impacts fast-charging performance [99]. Key factors include the specific surface area and the reversible insertion/extraction of sodium ions within the anode material. Nanostructured or porous anodes provide larger surface areas and shorter ion diffusion paths, allowing sodium ions to be inserted and extracted more rapidly. For example, hard carbon and sodium-based alloy anodes are known for their fast-charging properties due to their favorable sodium-ion reversibility and lower polarization during the charging process.

Typically, sodium-ion batteries support charging rates of about 1C to 3C, which is significantly lower than the charging rates of advanced LIBs, often exceeding 5C under optimal conditions. For the trucking industry, where quick turnarounds are essential, this limitation presents considerable operational challenges. Research in this field is directed towards optimizing the structures and compositions of electrode materials to improve ionic conductivity and electron mobility [100],[101]. Strategies include employing nanostructured or porous cathode materials to enable faster ion migration and shorter diffusion paths [102],[103]. Enhancements are also being made to anode materials by incorporating carbon composites or metallic alloys to increase the surface area for ion exchange and enhance overall charge-discharge kinetics [104]-[106]. Advancements in electrolyte technology are equally critical in boosting fast-charging capabilities. The focus is on developing highly conductive, stable electrolytes and integrating additives that create effective SEI [107]-[109]. A notable example is the development of bulk Bi anodes, which overcome the traditional limitations of alloying anodes by undergoing a self-induced transformation into a porous nanostructure during cycling in a glyme-based electrolyte. This enables ultrafast Na-ion diffusion and exceptional cycling stability, as demonstrated in a Na–Bi half-cell, which retains 94% and 93% of its capacity at extremely high charging rates of 80C and 100C, respectively [110]. These findings highlight the potential of bulk alloying anodes to enable fast-charging sodium-ion batteries without relying on costly nanomaterials or surface modifications. These interphases help protect the electrode materials from rapid degradation during fast charging cycles, stabilizing the electrochemical environment within the cell, promoting quicker and more efficient ion transfer, and maintaining electrode structural integrity.

3.2.2.4 Temperature sensitivity

The effectiveness of sodium-ion batteries under varying thermal conditions is crucial for their adoption in diverse climates, especially in the commercial trucking sector. A significant challenge with sodium-ion technology is its pronounced sensitivity to low temperatures, which markedly affects its performance and reliability [111]. At temperatures typically below 0°C, sodium-ion batteries experience reduced ionic conductivity and slower electrochemical kinetics, leading to diminished capacity, increased internal resistance, and extended charging times [112],[113]. This can significantly limit their usefulness in colder regions. The performance drop at low temperatures primarily results from the sluggish mobility of sodium ions within the electrode materials and the increased viscosity of the electrolyte, which impedes efficient ion transfer across the electrode-electrolyte interface. For example, the capacity of a typical sodium-ion battery might decrease by 20% to 40% at temperatures of -20°C compared to its performance at room temperature [114]-[116]. This degradation affects not only the range and efficiency of trucks equipped with sodium-ion batteries but also raises concerns about battery longevity and safety under extreme conditions. In response to these challenges, substantial research efforts are focused on enhancing the low-temperature performance of sodium-ion batteries. Strategies include developing electrolyte formulations with lower freezing points and higher ionic conductivity at colder temperatures [117],[118]. Electrolytes incorporating mixed-salt systems [119]-[121] or organic additives [122],[123] can significantly boost low-temperature performance by reducing viscosity and improving the solvation of sodium ions.

Advancements in electrode material design are also essential. Using nanostructured or highly porous electrodes can create shorter ion diffusion pathways and increase sites for ion exchange, thus partially offsetting the effects of reduced ion mobility at lower temperatures [124]-[126]. Furthermore, incorporating phase change materials within the battery system can help maintain a stable operational temperature, using the latent heat properties of these materials to buffer against temperature fluctuations [127]-[129]. Developing sophisticated thermal management systems is another critical factor. Such systems can actively regulate battery temperature using heating elements or thermal insulators to ensure optimal performance, even in sub-optimal conditions [130]-[132]. These systems must be energy-efficient and compact to preserve the overall energy efficiency and payload capacity of the vehicle. In conclusion, enhancing the temperature resilience of sodium-ion batteries requires a comprehensive approach that includes advanced material science, innovative engineering solutions, and integrated thermal management strategies. By addressing temperature sensitivity issues, sodium-ion technology can expand its applicability, ensuring reliable performance across a broad range of environmental conditions and supporting its adoption in global trucking fleets operating in various climatic zones.

3.2.3 Challenges and outlook

The future of sodium-ion technology in the trucking industry is evolving, with the potential to provide cost-effective and environmentally sustainable energy storage solutions under specific market conditions. As demand for zero-emission commercial vehicles continues to grow, sodium-ion batteries are being explored as a viable alternative. However, their competitiveness depends on several factors, including lithium price fluctuations, supply chain disruptions, and advancements in energy density. While sodium-ion batteries offer advantages such as abundant raw material availability and a lower environmental footprint, their cost efficiency remains uncertain compared to lithium-ion alternatives, particularly LFP batteries, which are already commercially viable at low costs. This section examines the advancements and developments needed to enhance the feasibility of sodium-ion technology in truck transportation, while also addressing the economic and technological challenges that may limit its widespread adoption.

3.2.3.1 Market integration and commercialization

The economic viability of sodium-ion batteries is a key factor in determining their potential for widespread adoption. While sodium is abundantly available and less expensive than lithium, the overall cost competitiveness of sodium-ion batteries remains uncertain. Recent studies indicate that they may become economically favorable primarily in scenarios where lithium prices rise significantly or where supply chain disruptions affect LIBs production [71]. However, the long-term stability of lithium supply and the current cost advantages of LFP batteries challenge the assumption that sodium-ion batteries will consistently maintain a price advantage. Projections suggest that LFP battery prices will decline to approximately $70/kWh by 2025 and could further decrease to $50/kWh by 2030. In contrast, sodium-ion battery prices are expected to be significantly higher in the near term, starting at around $115/kWh in 2025. Although sodium-ion costs are projected to decline rapidly, they are not expected to reach parity with LFP batteries until 2035. The probability of sodium-ion batteries achieving a cost advantage reaches 50% around 2040. Under a hypothetical graphite supply shock scenario, this probability increases to approximately 90% by 2040. These findings highlight the significant influence of critical mineral supply chains—particularly lithium, graphite, and nickel—on the economic competitiveness of sodium-ion batteries. The results suggest that achieving a cost advantage over low-cost alternatives in the near term remains a considerable challenge.

In addition, sodium-ion batteries are recognized for their relatively lower environmental impact, aligning with global efforts to reduce carbon emissions. Sodium mining is generally less invasive and more geographically widespread, potentially easing dependence on specific mining regions and improving supply chain stability. However, comprehensive life cycle assessments indicate that while sodium-ion batteries may have advantages in recyclability and resource extraction, their overall environmental benefits depend on continued improvements in energy density and manufacturing efficiency [135],[136].

Achieving market readiness for sodium-ion batteries depends on substantial technological advancements. While progress has been made, further improvements are necessary to enhance energy density, cycle life, and overall performance. Expanding manufacturing capabilities to improve both the consistency and quality of battery production is critical. Emerging manufacturing techniques, such as roll-to-roll processing [137],[138] and high-throughput electrode fabrication [139],[140], have been adapted for sodium-ion batteries to optimize cost-effectiveness. In addition, integrating automated systems and AI in quality control has significantly increased production efficiency [141],[142]. These developments align with ongoing discussions in academic literature about the role of Industry 4.0 technologies in advancing battery manufacturing processes.

Reliability in real-world applications is essential for market acceptance. Research highlights the necessity of extensive field trials and pilot projects to evaluate sodium-ion battery performance in commercial vehicles under varied operational conditions [143],[144]. Collaboration among battery manufacturers, trucking companies, and government agencies is crucial to supporting these large-scale trials [145],[146]. These initiatives aim to collect performance data across diverse environments and workloads, providing critical insights into durability and efficiency. Such efforts not only validate the technological potential of sodium-ion batteries but also help build confidence among fleet operators and investors, which is crucial for broader adoption.

3.2.3.2 Policy and regulatory support

The impact of policy on the adoption of sodium-ion battery technology is substantial. Government regulations that promote low-emission transportation technologies through subsidies, tax incentives, and direct funding for research play a crucial role in advancing both the development and deployment of sodium-ion batteries [147]-[149]. These policy measures not only stimulate early-stage research and development but also support large-scale implementation and market integration. Furthermore, ensuring a stable and ethically sourced supply chain for battery materials is critical. Policies that promote responsible resource management, including sustainable extraction and effective recycling systems, can minimize environmental harm and enhance battery lifecycle efficiency. Implementing regulations that require the tracking and verification of sodium and other essential minerals can help prevent resource exploitation and uphold environmental and social sustainability standards [150],[151]. One significant regulatory initiative in this regard is the Battery Passport, mandated under the EU Battery Regulation (Regulation (EU) 2023/1542) [152]. This digital system requires industrial and EV batteries to document key information such as material sourcing, carbon footprint, recyclability, and compliance with environmental and social standards. By enforcing transparency in the supply chain, the Battery Passport aims to prevent unethical resource extraction, enhance circular economy practices, and ensure sustainability across the battery lifecycle. Beginning in 2027, batteries sold in the EU must comply with these reporting requirements, reinforcing responsible mineral sourcing and traceability.

In addition, government-led initiatives that foster collaboration between academia, industry, and public agencies can accelerate innovation and scalability in sodium-ion technologies [154],[155]. Such partnerships frequently lead to technological advancements and streamlined pathways to commercialization, leveraging shared expertise and resources. Integrating sodium-ion technology into broader energy and transportation policies can further enhance adoption. For instance, establishing stringent emission reduction targets for the trucking industry could incentivize fleet operators to transition to cleaner energy solutions [156],[157]. In addition, regulatory authorities play an essential role in shaping safety and performance guidelines for sodium-ion batteries. Establishing comprehensive testing criteria and certification processes ensures that these batteries comply with industry requirements before entering the market. Implementing such standards addresses concerns regarding durability, efficiency, and operational safety, fostering trust among manufacturers and consumers alike [158],[159]. Comprehensive policy and regulatory frameworks are essential for creating an enabling environment that facilitates the growth and advancement of sodium-ion battery technology. By aligning policies with the technological advancements and sustainability goals of sodium-ion batteries, governments can enhance the market viability of this technology while reinforcing global sustainability efforts. These measures are essential in steering the transportation sector toward more sustainable, low-emission solutions, solidifying sodium-ion batteries as a key contributor to this transformation.

3.2.3.3 Collaboration and industry partnerships

Collaboration across industries is fundamental to transforming sodium-ion battery technology from research and development to widespread commercial use. Partnerships between battery manufacturers, truck original equipment manufacturers (OEMs), and research institutions are essential for scaling up production and ensuring that sodium-ion batteries meet the rigorous performance and safety requirements of real-world applications [160]-[162]. These collaborations enable the integration of specialized knowledge, resources, and risk management strategies, helping accelerate the transition from early prototypes to commercially viable products. For instance, partnerships with truck OEMs enable battery developers to design sodium-ion technologies tailored to the power and durability demands of commercial vehicles [163],[164]. Integrating battery systems into new truck designs optimizes vehicle performance, enhances environmental efficiency, and improves cost-effectiveness. At the same time, collaborative research efforts drive innovations in battery design, such as the development of modular battery systems that can be scaled or adapted for various vehicle types and applications [165],[166]. Academic and research institutions also play a key role in advancing material science, electrochemistry, and manufacturing techniques [167],[168]. Their contributions have significantly improved battery performance, longevity, and safety, with university-led studies leading to breakthroughs in electrode materials and electrolyte formulations that enhance charging speeds and energy density [169]-[171].

Establishing partnerships with recycling firms is equally critical for implementing an effective lifecycle management strategy for sodium-ion batteries [172],[173]. Efficient recycling processes allow for the recovery and reuse of battery materials, reducing reliance on newly extracted raw materials and minimizing environmental impact. However, given the low intrinsic value of sodium and other abundant elements in Na-ion batteries, the economic feasibility of collecting, transporting, and processing end-of-life (EOL) sodium-ion batteries remains a challenge. Furthermore, industry-wide collaborations are vital in setting international standards and best practices for the manufacturing, testing, and deployment of sodium-ion batteries [174],[175]. Through cooperative initiatives, stakeholders across the battery supply chain can establish and uphold stringent quality benchmarks, ensuring that sodium-ion batteries meet reliability and performance expectations. Ultimately, fostering strategic partnerships among manufacturers, OEMs, researchers, and recyclers is fundamental to the successful commercialization of sodium-ion batteries. By leveraging collective expertise, sharing risks, and aligning objectives, stakeholders can drive the widespread adoption of this promising technology, positioning it as a central component in the shift toward sustainable transportation solutions.

3.2.3.4 Long-term prospects

The potential of sodium-ion batteries in the trucking industry and grid storage is being explored, particularly in cost-sensitive markets where economic and environmental considerations are paramount [176],[177]. These batteries offer a viable energy storage solution due to their reliance on widely available raw materials and a manufacturing process with a lower environmental impact than LIBs. One of their most promising applications in trucking is integration into battery swapping systems [178],[179], which address a key challenge in electric transportation: prolonged vehicle downtime due to charging. By enabling rapid battery replacements, swapping systems significantly reduce idle time, improving fleet efficiency and operational productivity for heavy-duty trucks [180], while mitigating the relatively lower driving range of sodium-ion-powered vehicles. With their cost advantages and compatibility with swapping systems, sodium-ion batteries are well-positioned to support the evolving logistics landscape.

The widespread availability of sodium helps lower production costs and reduces risks associated with supply chain disruptions that frequently affect lithium-based alternatives. As the technology matures and production scales, sodium-ion batteries are expected to offer even greater economic benefits, facilitating broader adoption in commercial trucking and other transport applications. Continued advancements in research and development will further enhance the performance and durability of sodium-ion batteries, strengthening their position as a credible alternative to conventional technologies. Improvements in energy density, cycle life, and efficiency will be critical in expanding their practical applications and market competitiveness. Their economic viability, potential for innovation—particularly in battery swapping systems—and alignment with global sustainability goals position them as a key player in the transition toward more efficient and environmentally responsible transportation. As industry stakeholders continue investing in sodium-ion technology, its role in shaping the future of transportation is expected to become increasingly significant.

3.3 Safety considerations

Advanced batteries have the potential to transform energy storage, but their safety challenges (Table 5) require targeted and comprehensive solutions. Beyond those advanced machine learning-based digital diagnostic solutions [181],[182], addressing these challenges requires advancements in materials science, system design, and operational protocols to ensure safe and efficient performance. Real-world testing under diverse environmental and operating conditions is essential to validate their reliability and safety, enabling seamless integration into applications such as EVs.

Table 5. Safety challenges and mitigation strategies for advanced battery technologies.

Battery Technology	Temperature Stability Range	Thermal Runaway Trigger	Safety Challenges	Mitigation Strategies
Ternary Lithium-Ion Batteries	20°C to 60°C	150°C to 200°C	Thermal runaway at high temperatures, flammable liquid electrolytes	Non-flammable electrolytes, protective electrode coatings
Lithium Iron Phosphate Batteries	20°C to 70°C	200°C to 250°C	Limited low-temperature performance, electrolyte degradation under abuse conditions	Stable phosphate-based cathodes, robust manufacturing quality control, non-flammable electrolyte additives
Lithium Titanate Oxide Batteries	30°C to 55°C	300°C +	High-temperature stability but potential gas formation under overcharge conditions	High-voltage electrolyte formulations, gas-suppressing additives
Lithium-Metal Batteries	0°C to 45°C	120°C to 150°C	Dendrite growth causing short circuits, high thermal runaway risk	Advanced separators, solid-state electrolytes, electrolyte additives to suppress dendrites
Solid-State Batteries	20°C to 100°C (with optimized designs)	250°C to 300°C	Poor interfacial contact, mechanical stress, limited ionic conductivity	Optimized solid electrolyte compositions, stable interfaces, enhanced mechanical designs
Silicon-Containing Batteries	0°C to 50°C	180°C to 220°C	Volumetric expansion causing stress and degradation, loss of electrode integrity	Silicon-composite materials, flexible binders to accommodate expansion
Lithium-Sulfur Batteries	-20°C to 50°C	140°C to 180°C	Polysulfide shuttle effect leading to capacity fade, low cycle life, flammable electrolytes	Polysulfide-trapping materials, protective cathode coatings, solid-state electrolytes
Lithium-Air Batteries	15°C to 50°C	120°C to 150°C	Reactive intermediates during cycling, thermal instability, potential decomposition of discharge products	Selective oxygen-permeable membranes, stable electrolyte systems, catalyst stabilization
Sodium-Ion Batteries	10°C to 60°C	180°C to 220°C	Electrode degradation, long-term cycling instability	Improved electrode materials, advanced electrolytes for better stability

3.3.1 Ternary lithium-ion battery

Ternary LIBs, which employ NCM or NCA cathodes, are widely recognized for their exceptional energy density, making them indispensable in applications such as EVs. However, their widespread use is accompanied by persistent safety challenges, primarily stemming from the risk of thermal runaway [183]. This phenomenon, which can lead to catastrophic battery failure, is triggered by a combination of factors, including the instability of high-nickel cathode materials, the flammability of organic electrolytes, and the susceptibility of separators to mechanical or thermal damage. Nickel-rich cathodes, such as NCM811, while offering higher energy densities, are prone to oxygen release and exothermic reactions under high temperatures, further intensifying safety risks.

Liquid electrolytes, commonly composed of organic solvents such as ethylene carbonate and dimethyl carbonate contribute significantly to the thermal instability of ternary LIBs. Under elevated temperatures or abusive conditions, these solvents decompose, releasing flammable gases such as hydrogen and carbon monoxide, which exacerbate the thermal runaway process. In addition, separators, which are critical for preventing short circuits, can shrink or melt under high heat, allowing direct contact between the cathode and anode, further accelerating thermal events. Mechanical damage or overcharging adds to these risks by promoting dendrite growth, internal short circuits, and localized heating, all of which compromise battery integrity.

Coating cathodes with materials such as aluminum oxide, lithium niobate, or boron-based compounds has proven effective in improving safety by reducing the reactivity between cathodes and electrolytes [184],[185]. These coatings act as barriers, preventing side reactions and mitigating oxygen release at high temperatures. Similarly, advanced separators with ceramic coatings or thermal shutdown mechanisms have been developed to maintain structural integrity at elevated temperatures, blocking ion flow and preventing further reactions during thermal events [186],[187]. Electrolyte additives, such as lithium bis(fluorosulfonyl)imide and flame-retardant compounds such as triphenyl phosphate, enhance the stability of the SEI and suppress the formation of flammable gases, further reducing the risk of thermal runaway [188],[189].

Innovative approaches in nanotechnology have also played a role in enhancing the safety of ternary LIBs. Nanostructured cathode and anode materials offer better thermal dissipation and reduced reactivity, minimizing the formation of hotspots that can trigger thermal events. Moreover, advanced battery management systems equipped with real-time monitoring and smart algorithms can detect early signs of abnormal behavior, such as overcharging or overheating, and take preventive actions, including voltage balancing or current cutoff, to safeguard the battery system.

3.3.2 Lithium iron phosphate batteries

LFP batteries exhibit high thermal stability and lower susceptibility to thermal runaway. Unlike ternary LIBs with NCM or NCA cathodes, the phosphate-based cathode in LFP batteries is inherently more stable, even at elevated temperatures. This stability is attributed to the strong covalent bonding in the phosphate group, which resists decomposition and oxygen release under abuse conditions, significantly lowering the risk of exothermic reactions. Consequently, LFP batteries exhibit superior thermal and chemical stability, making them particularly well-suited for large-scale energy storage systems, electric buses, and other applications where safety is a critical requirement.

Despite their lower energy density compared to ternary LIBs, LFP batteries provide notable advantages in terms of longer cycle life, enhanced operational safety, and reduced sensitivity to overcharging. The absence of cobalt, a material prone to instability, further contributes to their reliability under high-stress scenarios. The development of advanced electrolytes has further improved the performance and safety of LFP batteries. SSE, which eliminate the flammability concerns associated with liquid electrolytes, have shown promise in maintaining the thermal and chemical stability of the system. Gel-polymer electrolytes are another innovation, offering a balance between the safety of solid-state systems and the ionic conductivity of liquid electrolytes. These electrolyte advancements are critical for maintaining the safety profile of LFP batteries while supporting higher energy densities and faster charging capabilities.

Although LFP batteries do not achieve the same energy density as ternary lithium-ion batteries, their superior safety, long cycle life, and continuous performance improvements make them a reliable and versatile choice across various applications. Innovations in phosphate-based chemistries, such as LFMP ($LiFeMnPO_4$) and LFVP ($LiFeVPO_4$), aim to enhance energy density while preserving the intrinsic safety of phosphate materials. LFMP offers a higher operating voltage (~4.1V), improving energy output, but requires careful management to mitigate structural stress and side reactions. LFVP, on the other hand, delivers both increased energy density and better thermal stability, ensuring safer operation at higher voltages with reduced electrolyte degradation. Ongoing advancements in material engineering, battery architecture, and system optimization will continue to strengthen the role of LFP and its derivatives in electric buses, grid storage, and emerging sectors like electric aviation and heavy-duty transport, where both safety and efficiency are critical.

3.3.3 Lithium titanate oxide batteries

LTO batteries are prized for their outstanding safety profile, thanks to the high stability of their anode material and a low risk of dendrite formation. However, several safety concerns and challenges still need addressing to ensure their reliable and broad application. One major safety issue with LTO batteries is their vulnerability to thermal and chemical degradation under specific operational stresses [190]. Although the temperature threshold for thermal runaway in LTO batteries is much higher than in traditional graphite-based LIBs, extreme conditions such as overcharging or rapid discharging can still jeopardize their safety. These conditions can cause the electrolyte to decompose, generate gases, and possibly cause the battery cell to swell, compromising both the structural integrity and safety of the battery. In addition, the high operating voltage of the

LTO anode presents compatibility challenges with conventional liquid electrolytes. Maintaining electrolyte stability at high voltages is crucial to avoid harmful side reactions that could degrade the performance and safety of the battery. Developing advanced electrolyte formulations capable of operating effectively across the broad electrochemical window of LTO is therefore a critical area of research. Moreover, the durability of the LTO anode during extensive cycling is a concern [191]. While the anode material boasts a long cycle life due to minimal volume expansion during lithium insertion and extraction, continuous use can cause a build-up of interfacial resistance and the potential development of localized hotspots. These issues can intensify thermal management challenges and reduce the safety margin of the battery.

Efforts to overcome these challenges focus on enhancing the thermal and chemical stability of LTO batteries through material engineering and systemic optimizations. Innovations in electrolyte additives, improved cell designs, and the incorporation of sophisticated monitoring systems are being explored to mitigate safety risks and enhance the performance of LTO-based energy storage solutions. As these improvements progress, LTO batteries are expected to become increasingly vital in applications where safety and durability are critical.

3.3.4 Lithium-metal batteries

LMBs are gaining attention for their exceptional energy density, which significantly exceeds that of conventional LIBs [192]. This makes them a promising technology for applications demanding compact and lightweight energy storage, such as EVs, drones, and aerospace systems. However, the adoption of LMBs is hindered by substantial safety challenges, with dendrite growth being the most critical [193]. During repeated charging cycles, lithium metal tends to deposit unevenly on the anode surface, forming needle-like structures known as dendrites. These dendrites can grow through the separator, leading to internal short circuits, thermal runaway, and, in extreme cases, catastrophic battery failure. This issue is exacerbated by the high reactivity of lithium metal, which interacts with electrolytes to generate heat and flammable byproducts.

To address the safety challenges associated with LMBs, significant progress has been made in the development of materials and technologies that target dendrite suppression and overall battery stability. One promising direction involves the adoption of SSE, which offer a safer alternative to traditional liquid electrolytes [194],[195]. These electrolytes act as physical barriers that prevent dendrite penetration while maintaining the necessary ionic conductivity for efficient battery operation. Various solid-state electrolyte materials, such as oxide ceramics, sulfide-based systems, and polymer composites, have been explored for their unique properties. Among these, garnet-type oxides such as $Li_7La_3Zr_2O_{12}$ (LLZO) have shown particular promise due to their high ionic conductivity and dense structure, which effectively inhibit dendrite growth [196]. Efforts to enhance the usability of these materials have led to the development of hybrid electrolytes that combine ceramics with polymers, improving flexibility, interfacial contact, and mechanical robustness while addressing the brittleness commonly observed in ceramic materials. These advancements contribute to creating safer and more reliable LMBs. Another critical area of research involves the design of advanced separators with dendrite-blocking capabilities [197]. Modified separators with ceramic coatings or multilayer structures provide enhanced mechanical resistance, effectively preventing dendrites from piercing through the cell structure. These separators are often combined with ion-selective membranes, which regulate lithium-ion transport while blocking impurities and undesired reactions that could accelerate dendrite growth. In addition, separators with thermal shutdown mechanisms, which interrupt ion flow at elevated temperatures, add another layer of safety by mitigating the risk of thermal runaway [198].

Electrolyte additives have also emerged as an effective strategy to control lithium deposition and suppress dendrite formation [199]. Additives such as lithium bis(fluorosulfonyl)imide (LiFSI), lithium nitrate ($LiNO_3$), and ionic liquids have been shown to stabilize the SEI on the anode surface. A stable SEI layer not only prevents direct contact between lithium and the electrolyte but also promotes uniform lithium deposition, reducing the likelihood of dendrite growth. Recent studies have also explored fluorinated solvents [200] and flame-retardant additives [201], which improve electrolyte stability while enhancing the safety profile of the battery.

Nanostructured anodes represent another promising solution to mitigate dendrite-related risks [202],[203]. By replacing traditional lithium metal foil with nanostructured or 3D porous hosts, researchers have achieved more uniform lithium plating and stripping. These advanced anode designs provide increased surface area, which lowers current density and minimizes the formation of high-energy regions where dendrites typically nucleate. For instance, carbon-based scaffolds with lithiophilic coatings have demonstrated the ability to guide lithium-ion deposition into well-defined patterns, effectively suppressing dendrite formation and enhancing cycle life [204].

3.3.5 Silicon-containing batteries

Silicon-containing batteries hold immense potential for advancing energy storage technologies due to the exceptionally high theoretical capacity of silicon—approximately ten times that of conventional graphite anodes [205]. However, their practical application is hindered by significant safety and performance challenges associated with the inherent properties of silicon. The primary issue is the substantial volumetric expansion of silicon, which can exceed 300% during lithiation. This repeated expansion and contraction during charge and discharge cycles induces severe mechanical stress, leading to electrode pulverization, loss of electrical contact with the current collector, and instability of the SEI. These effects result in rapid capacity fading, reduced calendar life, and increased risks of short circuits and thermal instability. To mitigate these challenges, researchers have developed various strategies to improve the structural integrity and safety of silicon-containing batteries. One of the most promising approaches is the use of silicon-based composites, which combine silicon with more stable materials to accommodate its volumetric changes. For example, silicon-carbon composites have gained significant attention due to their ability to buffer mechanical stress and maintain electrical conductivity [206]. In such designs, the carbon matrix acts as a flexible scaffold that absorbs expansion and prevents electrode fracture. Recent advancements include hierarchical structures, such as core-shell designs [207], where silicon is encapsulated within a carbon shell, and porous silicon-carbon hybrids that provide additional space to accommodate expansion.

Nanostructuring silicon has also proven to be an effective strategy for mitigating volumetric expansion [208]. Nanoscale silicon particles, nanowires, and hollow silicon nanospheres have been shown to minimize stress accumulation and improve mechanical resilience by shortening ion diffusion pathways and providing sufficient space for expansion. In addition, coating silicon nanoparticles with stabilizing materials, such as oxides or conducting polymers, has been demonstrated to enhance SEI stability and suppress undesired side reactions [209]. The development of advanced binders is another critical area of research for addressing the mechanical degradation of silicon-based anodes [210]. Traditional polymeric binders, such as polyvinylidene fluoride, lack the elasticity required to accommodate the volumetric changes of silicon. Novel binders with high elasticity and adhesion, such as those based on carboxymethyl cellulose, styrene-butadiene rubber, and alginate, have been formulated to maintain electrode cohesion during cycling. Conductive binders that integrate ionic or electronic conductivity, such as polyaniline [211] or polydopamine [212], further enhance electrode performance by facilitating charge transport while accommodating mechanical stress. Improving the electrolyte composition is also essential to enhancing the safety and performance of silicon-containing batteries. The high reactivity of silicon with standard liquid electrolytes can result in unstable SEI formation and continuous electrolyte consumption, leading to increased resistance and compromised safety. Fluorinated electrolytes and electrolyte additives, such as fluoroethylene carbonate and lithium bis(fluorosulfonyl)imide, have shown promise in stabilizing the SEI layer and reducing electrolyte decomposition [213],[214]. SSE are another area of exploration, offering the potential to eliminate leakage risks and improve compatibility with silicon-based anodes [215]. Advances in gel-polymer electrolytes, which combine the flexibility of liquid electrolytes with the stability of solids, have also shown potential for enhancing safety and longevity [216].

Despite these advancements, achieving the widespread commercial deployment of silicon-containing batteries requires continued progress in scaling up manufacturing techniques and improving cost efficiency [217]. High-performance silicon-based electrodes often rely on complex fabrication processes, such as chemical vapor deposition or precision nano structuring, which must be adapted for large-scale production. Collaborative efforts in materials science, engineering, and computational modeling are essential to overcoming these barriers and unlocking the full potential of silicon-containing batteries. Silicon-containing batteries represent a significant step forward in energy storage innovation, combining high energy capacity with emerging safety solutions. By addressing the challenges of volumetric expansion, SEI instability, and thermal management, these batteries have the potential to transform applications ranging from consumer electronics to EVs and grid-scale storage systems. Continued interdisciplinary research and real-world validation will play a critical role in advancing this promising technology.

3.3.6 Solid-state batteries

SSBs offer a transformative approach to energy storage by addressing many of the inherent safety concerns associated with conventional liquid-electrolyte systems [218]. The absence of flammable liquid electrolytes significantly reduces the risk of leakage, thermal runaway, and combustion, making these batteries particularly attractive for applications requiring enhanced safety, such as EVs. However, the transition from liquid to SSE introduces its own set of challenges [219],[220], including interfacial instability, mechanical stress, and limited ionic conductivity, all of which must be resolved to unlock the full potential of this technology.

One of the primary challenges in SSBs is the interfacial contact between the solid electrolyte and the electrodes [221]. Unlike liquid electrolytes, which conform to the surface of electrodes and facilitate ion transport, solid electrolytes often exhibit poor interfacial contact due to their rigid nature. This issue is particularly problematic with lithium metal anodes, where interfacial voids can form during cycling, leading to increased resistance and uneven lithium deposition. Recent advancements have focused on developing interface-engineering techniques to mitigate these issues. For example, structural approaches, such as cathode-supported solid electrolyte membrane frameworks [222], and interface modifications [223], have shown promise in reducing impedance and facilitating uniform ion transport. Another significant hurdle is the mechanical stress that arises during battery operation [224]. Solid electrolytes must endure the expansion and contraction of electrodes during repeated charge and discharge cycles. This mechanical strain can lead to the formation of cracks in the electrolyte or delamination at the interfaces, compromising both safety and performance. To address this, researchers are exploring the use of composite electrolytes that combine the mechanical flexibility of polymers with the high ionic conductivity of ceramics [225]. These hybrid electrolytes not only improve mechanical robustness but also enhance ionic transport properties. Furthermore, advancements in solid electrolyte processing, such as sintering under optimized conditions [226], have led to materials with fewer grain boundaries and improved structural integrity, which are better equipped to withstand mechanical stress.

3.3.7 Lithium-sulfur batteries

The safety of Li–S batteries is a critical consideration in their development and commercialization. While Li–S batteries offer high theoretical energy density, their safety challenges stem from multiple factors, including polysulfide shuttle effects, lithium metal dendrite formation, and thermal stability concerns. The dissolution and migration of lithium polysulfides (LiPS) can lead to self-discharge, capacity fading, and potential internal short circuits. In addition, the use of lithium metal as the anode introduces risks associated with dendritic growth, which may penetrate the separator and cause catastrophic failure, including thermal runaway.

Recent advancements have sought to mitigate these risks through various material and electrolyte modifications. A promising approach involves the incorporation of a flame-retardant polyphosphazene interlayer, which chemically interacts with LiPS to inhibit their shuttling effect, thereby enhancing cycling stability [227]. This multifunctional interlayer also acts as a secondary current collector, improving sulfur utilization while significantly reducing the flammability of the sulfur cathode and electrolyte, thereby enhancing the overall safety of Li–S batteries. Another key strategy to improve safety involves the use of gel polymer electrolytes, which provide a safer alternative to conventional liquid electrolytes [228]. A poly(ethylene oxide)-polyacrylonitrile copolymer membrane electrolyte has demonstrated enhanced ionic conductivity and mechanical strength, effectively blocking lithium dendrite growth. In addition, the crosslinked structure of this polymer electrolyte strongly adsorbs LiPS, thereby mitigating shuttle effects and improving cycling stability and rate capability. Flexible batteries utilizing this electrolyte have also demonstrated robust performance, maintaining over 96% capacity retention after 1,000 bending cycles, highlighting its potential for safer and more durable Li–S battery applications. Furthermore, all-solid-state Li–S batteries represent an emerging approach to enhancing safety by eliminating flammable liquid electrolytes altogether [229]. A deeper understanding of the sulfur redox mechanisms in the solid state has revealed unique electrochemical characteristics that distinguish them from their liquid-phase counterparts. Mass transport and reaction kinetics limitations are critical factors in solid-state Li–S battery design, with advanced characterization techniques such as cryogenic electron microscopy providing valuable insights into their behavior. These solid-state systems offer promising pathways for addressing safety concerns while maintaining the high energy potential of Li–S batteries. Addressing these concerns requires continued advancements in material design, electrolyte engineering, and cell architecture. By integrating flame-retardant interlayers, polymer-based electrolytes, and all-solid-state battery designs, researchers are actively working toward improving the intrinsic safety of Li–S batteries, ensuring their viability for next-generation energy storage applications.

3.3.8 Lithium-air batteries

Lithium-air batteries hold significant promise due to their exceptionally high theoretical energy density, which approaches the energy content of fossil fuels. However, their practical implementation is hampered by unique safety challenges stemming from their reliance on oxygen from the environment. The open-cell architecture of lithium-air batteries, designed to intake oxygen as a reactant at the cathode, exposes the system to contaminants such as moisture and CO_2. These contaminants can trigger parasitic reactions, leading to the formation of lithium hydroxide, lithium carbonate, and other undesirable byproducts, which degrade the cell performance and reduce its cycle life. In addition, the high reactivity of lithium metal at the anode introduces further complications, including the risk of thermal runaway under certain conditions.

A key safety issue in lithium-air batteries is the formation and breakdown of lithium peroxide [230], a critical byproduct generated during the discharge and charge processes. These reactions often produce highly reactive oxygen species, such as superoxide and peroxide ions, which can react with the electrolyte and other battery components. This reactivity can lead to chemical degradation, reduced efficiency, and the release of heat, which may pose safety risks. To address this challenge, research has focused on designing more stable electrolytes capable of withstanding these reactive conditions. For instance, electrolytes formulated with ionic liquids have demonstrated reduced side reactions and enhanced redox stability, enabling improved performance in challenging systems such as lithium-air batteries [231]. SSE are also being explored as a safer alternative, as they provide a robust barrier against reactive intermediates and eliminate the flammability risks associated with liquid systems, offering improved thermal and chemical stability for lithium-air batteries [232]. Advancements in cathode design also play a crucial role in addressing safety challenges in lithium-air batteries. Porous carbon-based cathodes, while commonly used due to their high surface area and conductivity, are prone to clogging and degradation from discharge products such as lithium peroxide. Recent innovations include the development of catalytic cathodes incorporating transition metals, such as manganese or ruthenium oxides, which facilitate the efficient decomposition of lithium peroxide during charging and minimize the accumulation of discharge byproducts [233],[234]. In addition, hybrid cathodes combining carbon materials with nanostructured catalysts have demonstrated improved oxygen reduction and evolution reaction kinetics, which enhance both safety and efficiency [235].

3.3.8 Sodium-ion batteries

The development and implementation of solidum ion batteries pose significant safety considerations and challenges that require meticulous examination. Solidum ion batteries, as advanced energy storage devices, rely on SSE that offer several advantages, such as reduced flammability and enhanced thermal stability compared to conventional liquid electrolytes. However, these advantages do not entirely eliminate the safety risks associated with their operation, particularly under extreme or unforeseen conditions. One of the primary safety concerns arises from dendritic growth, a phenomenon where metal dendrites penetrate the solid electrolyte interface during repeated charge-discharge cycles [236]. This occurrence can result in internal short circuits, potentially leading to thermal runaway and catastrophic failure. Although solid electrolytes are designed to mitigate dendrite formation, their mechanical robustness and resistance to such intrusions are not yet fully optimized, necessitating further material innovation. Another challenge is the compatibility of solid electrolytes with active electrode materials [237]. Issues such as interface instability and the formation of interfacial resistance layers can compromise the cell performance and safety. Chemical and electrochemical reactions at the interfaces may produce byproducts that deteriorate the structural integrity of the battery over time, increasing the risk of leakage or failure. Furthermore, the manufacturing process for solidum ion batteries introduces additional safety considerations. Achieving uniformity and defect-free interfaces between solid electrolytes and electrodes is crucial, as microscopic imperfections can exacerbate stress concentrations and lead to mechanical failure. Scaling up production without compromising these critical parameters remains a formidable challenge for industrial adoption.

To address these challenges, ongoing research is focused on the development of novel solid electrolyte materials with enhanced ionic conductivity, mechanical strength, and compatibility with a wide range of electrode chemistries. Simultaneously, advancements in computational modeling and diagnostic tools are enabling a deeper understanding of failure mechanisms, paving the way for more robust and safer designs.

4. MODELING ADVANCED BATTERY PERFORMANCE

4.1 Modeling of lithium advanced batteries

The battery technologies analyzed and modeled (Table 6) include: (1) lithium metal with a solid-state electrolyte and lithium chloride (LiM/SSE/Li-Cl); (2) lithium metal with a solid-state electrolyte and a lithium oxide cathode (Lithium-Air Battery) (LiM/SSE/L_2O); (3) lithium metal with a solid-state electrolyte and a lithium-sulfur cathode (LiM/SSE/LiS); (4) graphite with a polymer electrolyte and a nickel cobalt manganese cathode in liquid electrolyte (Graphite/Polymer/NCM (liquid)); (5) silicon-carbon with a solid-state electrolyte and a nickel cobalt manganese cathode in liquid electrolyte (SiC/SSE/NCM (liquid)); (6) lithium-silicon with a solid-state electrolyte and a nickel cobalt manganese cathode in liquid electrolyte (LiSi/SSE/NCM (liquid)); (7) lithium-silicon with a solid-state electrolyte and a nickel cobalt manganese cathode in a solid-state electrolyte (LiSi/SSE/NCM (solid-state)); (8) Sodium-ion Cell #1, which is designed for higher energy density by optimizing cathode and anode capacity, reducing overall mass, and improving volumetric efficiency; and (9) Sodium-ion Cell #2, which features a larger electrode area and a higher cathode mass, prioritizes low cost. Among these, the two sodium-ion battery models use liquid organic electrolytes, whereas all others employ either semi-solid-state or completely solid-state technologies. Cell performance is determined by its design parameters, which include electrode composition, thickness, density, porosity, electrolyte distribution, and current collector properties. Key equations are used to estimate the gravimetric energy density (Wh/kg) and volumetric energy density (Wh/L) of a cell based on its structural and electrochemical characteristics.

(1) Cathode parameters

The cathode contributes significantly to the total capacity and mass of the battery cell.

Volumetric capacity (Ah/cm^3):

$$Ah/cm^3 = (\frac{Ah}{g}) \times density \times (1 - porosity) \tag{1}$$

where Ah/g represents the specific capacity of the cathode material, density (g/cm^3) refers to the mass per unit volume of the cathode material, and porosity denotes the fraction of the cathode volume occupied by the electrolyte.

Areal capacity (Ah/cm^2):

$$Ah/cm^2 = (Ah/cm^3) \times thickness \tag{2}$$

where thickness is the thickness of the cathode layer (cm).

Cathode area (cm^2):

$$Cell\ cm^2 = \frac{Ah\ cell}{Ah/\ cm^2} \tag{3}$$

where Ah cell is the total cell capacity (Ah).

Cathode mass (g):

$$Gathode\ g = (cell\ cm^2) \times thickness \times density \times (1 - porosity) \tag{4}$$

(2) Anode parameters

The anode typically has excess capacity to accommodate lithium or sodium intercalation.

Total anode capacity (Ah anode):

$$Ah\ anode = Ah\ cell \times anode\ oversize\ factor \tag{5}$$

where anode oversize factor is the ratio of anode capacity to cathode capacity.

Effective density (g/cm^3):

$$Effective\ density = density \times (1 - porosity) \tag{6}$$

Anode mass (g):

$$Anode\ g = \frac{Ah\ anode}{Ah/g} \tag{7}$$

Areal capacity (Ah/cm^2):

$$Ah/cm^2 = \frac{Ah\ anode}{cell\ cm^2} \tag{8}$$

Volumetric capacity (Ah/cm^3):

$$Ah/cm^3 = (\frac{Ah}{g}) \times density \times (1 - porosity) \tag{9}$$

Anode thickness (cm):

$$Thickness\ anode = \frac{Ah/cm^2}{Ah/cm^3} \tag{10}$$

(3) Solid-state electrolyte separator

Separator mass (g):

$$SSB\ separator\ g = (cell\ cm^2) \times (thickness \times 10^{-4}) \times separator\ dendity \tag{11}$$

SSE resistance (Ω-cm^2):

$$SEE\ Ohm - cm^2 = (\Omega - cm) \times (thickness \times 10^{-4}) \tag{12}$$

Total resistance (Ω):

$$SSE\ Ohm = \frac{SSE\ Ohm - cm^2}{cell\ cm^2} \tag{13}$$

(4) Liquid electrolyte separator

Separator mass (g):

$$Liquid\ separator\ g = (cell\ cm^2) \times (thickness\ \times 10^{-4}) \times separator\ density \tag{14}$$

Liquid electrolyte mass in separator (g):

$$Liquid\ in\ separator\ g = (cell\ cm^2) \times (thickness\ \times 10^{-4}) \times liquid\ electrolyte\ density\ \times porosity \tag{15}$$

Areal resistance (Ω-cm^2):

$$LEB\ separator\ Ohm - cm^2 = (\Omega - cm)_{LEB\ separator} \times (thickness\ \times 10^{-4}) \tag{16}$$

(5) Electrolyte within electrode porosity

Electrolyte mass in electrodes (g):

$$Electrolyte\ mass\ in\ electordes = (cell\ cm^2) \times electrolyte\ density \times (total\ electrode\ thickness) \times porosity \tag{17}$$

Electrolyte resistance (Ω-cm2):

$$Electrolyte\ resistance\ in\ electrodes = \frac{(Ohm - cm)_{liq\ electrolyte}}{porosity^{1.5}} \times (total\ electrode\ thickness) \times (cell\ cm^2) \tag{18}$$

(6) Current collectors (CC)

Resistance of CC (Ω):

$$Resistance\ of\ CC = \frac{resistivity \times CC\ length}{CC\ thickness \times CC\ width} \tag{19}$$

Mass of CC (g):

$$CC\ g = density \times cell\ cm^2 \times CC\ thickness\ (cm) \tag{20}$$

(7) Energy Estimation

Cell energy (Wh):

$$Wh\ cell = Ah\ cell\ \times V_{avg} \tag{21}$$

Gravimetric energy density (Wh/kg):

$$Cell\ Wh/kg\ = (\frac{Wh\ cell}{\sum g\ weights\ of\ cell}) \times 1000 \tag{22}$$

Volumetric energy density (Wh/L):

$$Cell\ Wh/L\ = (\frac{Wh\ cell}{\sum thickness\ of\ cell \times cell\ cm^2}) \times 1000 \tag{23}$$

Table 6. Parameters and metrics for the modeling of advanced battery technologies.

Parameter	LiM/SSE /LiCl	LiM/SSE /Li2O	LiM/SSE /LiS	Graphite /Polymer /NCM	SiC/SSE/ NCM	LiSi/SSE/ NCM (Liquid)	LiSi/SSE/ NCM (solid-state)	Sodium-ion cell #1	Sodium-ion cell #2
Cathode Thickness (μm)	50	50	50	250	150	150	150	200	200
Cathode Capacity (Ah/g, Area)	0.55	3.00	0.91	0.17	0.22	0.22	0.19	0.16	0.12
Cathode Density (g/cm^3)	1.86	2.15	1.86	1.60	1.86	2.10	2.15	2.15	2.15
Cathode Capacity (Ah/cm^3)	1.01	3.01	1.69	0.27	0.41	0.46	0.40	0.25	0.18
Cathode Capacity (Ah/cm^2)	0.005	0.015	0.009	0.007	0.006	0.007	0.006	0.007	0.007
Cathode Mass (g)	37	24	22	120	92	101	108	122	169
Cathode Additional Material Ratio	0.10	29.86	0.10	0.20	0.10	0.10	0.30	0.10	0.10
Cathode Material Capacity (Ah/g)	0.60	1.80	1.00	0.20	0.24	0.24	0.24	0.18	0.13
Anode Capacity (Ah)	22	22	22	22	22	22	22	22	22
Anode Density (g/cm^3)	0.53	0.53	2.33	1.70	0.53	2.33	2.33	1.30	1.30
Anode Capacity (Ah/cm^3)	1.53	1.34	5.24	0.50	1.53	2.10	2.10	0.46	0.27
Anode Mass (g)	8	9	10	74	8	10	10	62	105
Anode Capacity (Ah/cm^2)	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Separator Density (g/cm^3)	1.80	1.80	1.80	1.35	1.80	1.80	1.80	1.17	1.17
SSE Thickness (μm)	25	25	25	25	25	25	25	25	25
SSE Mass (g)	18	6	11	10	15	13	15	6	8
SSE Interface Resistance (Ω·cm^2)	3.75	5.00	3.75	0.40	3.75	5.00	5.00	0.50	0.50
SSE Resistance (mΩ)	0.95	3.80	1.59	0.13	1.14	52.00	1.50	1.00	1.00
Cu Conductivity (μΩ·cm)	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
Al Conductivity (μΩ·cm)	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80
Current Collector Thickness (μm)	10	10	10	15	10	10	10	15	15
Cu Density (g/cm^3)	8.23	8.23	8.23	8.23	8.23	8.23	8.23	8.23	8.23

Parameter	LiM/SSE /LiCl	LiM/SSE /Li2O	LiM/SSE /LiS	Graphite /Polymer /NCM	SiC/SSE/ NCM	LiSi/SSE/ NCM (Liquid)	LiSi/SSE/ NCM (solid-state)	Sodium-ion cell #1	Sodium-ion cell #2
Al Mass (g)	11	4	6	12	9	8	9	10	11
Cu Resistance (μΩ·cm^2)	0.11	0.11	0.08	0.14	0.10	0.10	0.10	0.11	0.11
Al Resistance (μΩ·cm^2)	0.18	0.18	0.14	0.23	0.16	0.16	0.15	0.18	0.19
Cu Resistance (pΩ)	27.10	27.00	35.00	35.00	29.70	29.00	28.00	30.00	30.00
Al Resistance (pΩ)	44.60	44.00	57.60	55.00	48.80	49.00	47.00	50.00	51.00
Cell Area (cm^2)	3943	1327	2366	3000	3286	2910	3359	4061	5622
Total Mass (g)	105	83	66	254	152	155	169	340	506
Volume (cm^3)	52	49	37	135	68	67	76	151	224
Mass Density (g/cm^3)	2.03	1.703	1.79	1.87	2.23	2.303	2.226	2.25	2.25
Cell Energy (Wh)	56	56	50	72	72	72	72	9	6
Energy Density (Wh/kg)	532	671	755	283	473	465	426	188	127
Energy Density (Wh/l)	1079	1143	1355	532	1055	1071	947	423	285

The cell performance for each of the future technologies are summarized in Table 7. The energy density values calculated from the models for the different future technologies are reasonably close to the energy densities shown in Section 2 for the corresponding battery technologies being developed. The calculations of the cell resistances are very difficult and hence, the values of the pulse power shown in Table 6 are not reliable. Unfortunately, there is very little test data available for the resistances of the advanced batteries.

Table 7. The model results for the performance of the advanced battery technologies.

Parameter	Gravimetric Energy Density (Wh/kg)	Volumetric Energy Density (Wh/l)	Resistance (mΩ)	Pulse Power (W/$kg_{95\%}$)
LiM/SSE/LiCl	532	1079	4.3	1353
LiM/SSE/L_2O	671	1143	6.0	1400
LiM/SSE/LiS	755	1355	5.9	1565
Grapht/Polymer/NCM	283	532	5.9	408
SiC/SSE/NCM	473	1055	4.3	879
LiSi/SSE/NCM (liquid)	465	1071	5.0	1200
LiSi/SSE/NCM (solid-state)	426	947	5.5	1100
Hard Carbon/Organic El./Na Nickelate	188	423	4.3	576
Hard Carbon/Organic El./Na Nickelate	127	285	3.1	533

*95% efficiency (P = EF(1-EF) V^2/R) [238].

4.2 Costs of the advanced lithium batteries

During the early stages of battery development, the primary cost consideration ($/kWh) is the cell itself, which includes raw material and processing costs, as well as expenses associated with assembly and electrode integration. Among these factors, raw material cost is the most straightforward to estimate when the battery design is known or assumed. However, the costs of raw materials ($/g) and their processing for battery applications remain uncertain and are often challenging to obtain. Table 8 provides details on various advanced battery designs. If reliable data on raw material and processing costs were available, the corresponding material costs ($/kWh) could be determined with greater accuracy.

Numerous cost studies have been conducted on conventional lithium batteries (CLBs) [71],[239], along with several cost analyses for SSBs [240]-[244]. A key point of interest is the comparison of the cost ($/kWh) between CLBs and the projected cost ($/kWh) of SSBs. For SSBs, cost projections can be estimated based on the raw material costs of SSBs and the inferred processing and assembly costs of CLBs, which are currently being produced at large volumes. Table 8 provides a summary of available cost projections for SSBs. These projections assume large-scale production and different cell designs, with most cases incorporating lithium metal anodes. The amount of excess lithium used in the anode can significantly impact both cost and cycle life. The cost estimates presented in Table 8 indicate that, at the same production volume, CLBs will have a lower cost ($/kWh) than SSBs. The reasons for this cost difference are discussed in [240]. As of 2025, the cost of SSBs remains high, ranging between $400–800/kWh, but it is expected to decline rapidly between 2025 and 2030 as new SSB production plants come online. Most automobile and truck manufacturers, as well as large battery companies, are actively developing SSBs, as evidenced by numerous industry reports and news releases. Many of these companies are targeting 2030 for the high-volume production of SSBs.

Table 8. Summary of solid-state battery cost projections in the literature.

SSB Technology	Raw Material cost ($/kWh)	Cell cost ($/kWh)	Pack cost ($/kWh)	Source
General SSB (No Specific Details)	N/a	75-65	N/a	[241]
General SSB (No Specific Details)	N/a	N/a	280-140	[242]
Conventional Lithium Batteries	N/a	N/a	139	[242]
Li-Metal Anode (500 Wh/kg)	91	N/a	158	[243]
Conventional Lithium Batteries (270 Wh/kg)	68	N/a	126	
Li-Metal Anode (Varying Li Excess)	N/a	N/a	70-127	[244]
Conventional Lithium Batteries	N/a	N/a	120	[244]

4.3 Testing of the advanced technology lithium batteries

In Section 2, the development of advanced high-energy-density batteries and cells was discussed, including test data from various companies working on these technologies. However, there is essentially no third-party test data available in the literature for any of the advanced lithium-based technologies. The initial plan for this Caltrans project was to test prototype batteries being developed in the battery laboratory at the University of California, Davis. Due to contractual constraints, the project duration was reduced from 12 months to 6 months, which did not provide sufficient time to procure cells for testing. Efforts were made to obtain test cells from Amprius (US), as well as Molicel and ProLogium in Taiwan, but no cells were acquired. Battery manufacturers appear reluctant to provide prototype cells for laboratory evaluation unless the recipient is a potential customer. While our research group has made significant progress in obtaining cells and supercapacitors for testing in the past [238],[245],[246], acquiring test prototype cells has become increasingly challenging due to stricter manufacturer regulations and limited access to cutting-edge cell technologies.

The following tests were planned for the cells: (1) charging tests ranging from 1 hour to 10 minutes, (2) constant current discharge tests from 1C to 10C, (3) constant power tests from 100 W/kg to 1000 W/kg, (4) high-current 10-second pulse tests to determine cell resistance, and (5) life cycle tests. The data generated from these tests would have been used to develop the Ragone curve (Wh/kg vs. W/kg) for the cells and to assess their pulse power characteristics (resistance vs. W/kg). In addition, the life cycle tests would have indicated the number of charge cycles achievable under specific charge current and temperature conditions. The series of tests outlined above is essential for characterizing the performance of each advanced cell technology.

5. ADVANCED BATTERY SOLUTIONS FOR SPECIALIZED TRANSPORTATION

This section of the report examines the application of advanced batteries in heavy-duty vocational trucks, buses, and construction machinery. As of 2024, all of these vehicle types are undergoing electrification using conventional LIBs. In some cases, vehicle range or the operating time of construction machinery remains below market expectations or optimal user requirements. In addition, in almost all cases, the size, weight, and volume of the batteries pose challenges for vehicle and machinery design. Furthermore, the cost of batteries, measured in dollars per kilowatt-hour ($/kWh), continues to make electrified vehicles and construction machinery significantly more expensive than their diesel-powered counterparts.

5.1 Advanced batteries in buses and vocational trucks

The role of advanced batteries in addressing the challenges of electrifying buses and vocational trucks will be analyzed. The size and cost of the battery are primarily determined by the energy required (kWh) for daily vehicle operation, including considerations for convenient charging as needed. For vocational trucks and buses, the daily range (miles) can be estimated based on energy consumption (kWh/mi) under appropriate driving cycles. Table 9 presents available data on battery sizing for buses and vocational trucks, including the driving cycles used to calculate energy consumption in Wh/mi. For specialized vehicles such as refuse trucks and cement mixers, distinct driving cycles are necessary. However, among these, a dedicated driving cycle was only available for cement mixer trucks [247]. Additional details regarding the input parameters and ADVISOR modeling can be found in [248],[249].

Table 9. Battery energy requirements for various HD truck applications.

Truck battery requirements	Driving cycles	Energy consumption kWh/mi*	Range miles	Energy needed kWh
Transit buses	New York Cycle	1.8	150	270
Inter-city buses	65mph const.	1.33	300	400
Long-haul truck	65 mph const.	2.0	500	1000
Dump-truck	NEDC	2.8	150	420
Refuse truck	NEDC (part)	3.75	100	375
Cement mixer truck	Spec. cycle	4.04	147	594

*based on Advisor simulations.

The battery size and cost for each application listed in Table 9 can be determined based on the assumed battery characteristics provided in Table 10 for both current (2024) and advanced (2030) LIBs. The year 2030 is considered the earliest timeframe for the commercial availability of advanced high-energy-density batteries, even in limited quantities and at a high cost. Widespread commercialization of these advanced batteries at prices below $100/kWh is unlikely to occur before 2035 or later. Battery size, including both weight and volume, is expected to decrease as a result of increases in the energy density of advanced cells and improvements in cell packaging within battery packs for onboard vehicle applications [250]-[252]. These advancements could lead to a 10% reduction in weight and a 20% reduction in battery volume. In addition, battery costs, measured in dollars per kilowatt-hour ($/kWh), could decline by approximately 15% due to packaging improvements. The projected battery sizes and costs for 2024 and 2030 are summarized in Table 10. By 2030 or 2035, the size of advanced batteries, in terms of both weight and volume, is expected to be 2.0 to 2.5 times smaller than that of batteries available in 2024. While the timeline for these performance improvements remains uncertain, the findings in this report strongly suggest that such advancements are achievable. In addition, the cost of batteries in 2030–2035 is projected to be approximately 28% lower than in 2024. The maximum power capability required for most applications remains relatively low (<300 W/kg) and well within the expected performance range of advanced batteries (Table 7). These batteries are also anticipated to provide significant improvements in safety.

Table 10. Battery improvements between 2025 and 2030*

Battery Type	Gravimetric Energy Density (Wh/kg)	Volumetric Energy Density (Wh/l)	Cell Cost ($/kWh)*	Gravimetric Efficiency Ratio (Wh/kg cell / Wh/kg pack)	Volumetric Efficiency Ratio (Wh/l cell / Wk/L pack)	Cost Factor ($/kWh pack / $/kWh cell)
Current (2024)	270	550	110	1.3	1.7	1.41
Advance (2030)*	500	1150	90	1.2	1.4	1.23

*2030 is the earliest time at which it is likely advanced batteries will be available for use in trucks.

5.2 Advanced batteries in transit and intercity buses

The application of advanced batteries in city transit and inter-city buses is presented in Table 11. Range is a critical consideration for inter-city buses but is of lesser importance for city buses. The range of an inter-city bus could be extended to 500 miles using an advanced battery, which would be smaller (1,666 kg, 800 L) than the conventional battery used in a 300-mile inter-city bus. In addition, SSBs are expected to offer significantly improved safety compared to conventional LIBs. As shown in Table 11, the weight and volume of the battery in a city transit bus can be substantially reduced with the use of advanced batteries. Moreover, the enhanced safety and significantly faster charging capabilities of advanced batteries are expected to provide strong incentives for their adoption in transit buses.

The cost of advanced batteries, measured in dollars per kilowatt-hour ($/kWh), will remain significantly higher than that of conventional LIBs until commercial-scale, high-volume production is achieved. By 2030 and beyond, if large-scale production plans announced by advanced battery developers in 2025 are successfully implemented, the cost of advanced batteries is projected to approach or even fall below that of conventional LIBs. In such a scenario, the cost of both conventional and advanced lithium battery cells would decline to below $100/kWh. This reduction would significantly lower the overall cost of batteries for buses, making electric buses more affordable without the need for substantial financial incentives.

Table 11. Summary of the battery pack characteristics in 2024 and 2030.

Truck battery requirements	Battery Weight (kg)	Battery Volume (L)	Battery Cost ($)	Battery Power (W/kg)
		Transit buses		
Current 2024	1298	833	41850	192
Advanced 2030	647	329	29970	386
		Inter-city buses		
Current 2024	1923	1235	62000	130
Advanced 2030	983	487	44400	254
		Long-haul truck		
Current 2024	4807	3086	155000	73
Advanced 2030	2450	1218	111000	143
		Dump-truck		
Current 2024	2048	1296	65100	146
Advanced 2030	1029	512	46620	292
		Refuse truck		
Current 2024	1803	1157	58125	194
Advanced 2030	919	457	41625	381
		Cement mixer truck		
Current 2024	2855	1833	92020	123
Advanced 2030	1424	645	64152	246

5.3 Advanced batteries in construction machinery

The use of the advanced batteries in construction machinery is discussed this section. Construction machinery is typically not categorized as on-road vehicles, as most operations occur at construction sites. The power (kW) and energy storage (kWh) requirements of these machines depend on their power profile (kW vs. time) during operation. The most reliable indicators of power and battery storage requirements are the characteristics of various machines available on the market, as documented in the literature [251] and in manufacturer news releases available online. These requirements vary significantly because the size (gross weight) of machines of the same type can differ substantially. The battery requirements for construction machinery are summarized in Table 12. Key parameters include the energy storage capacity of the battery (kWh) and the peak power of the electric motors (kW). Notably, some machines have an operating time of only four hours before requiring a recharge. Ideally, the operating time before recharging would match a full workday, allowing batteries to be recharged overnight. This goal could be achieved using advanced batteries with higher energy densities, enabling longer operating times without increasing battery weight or volume. While this approach would raise the cost of the machines, it would also enhance their utility. In addition, the weight of the battery in construction machinery serves as a counterweight to balance the machine during loaded operations. Therefore, increasing battery weight does not negatively impact the overall weight of the machine but rather reduces the need for additional counterweights.

The specification sheets of construction machinery [252] (Figure 10) indicate that the electric versions of these machines appear identical to their diesel-engine counterparts and have the same weight. This suggests that manufacturers have successfully replaced the engines and fuel tanks with electric motors and batteries without altering the external design of the equipment. With the adoption of smaller, advanced batteries, this design approach is expected to remain feasible. Volvo, based in Sweden and one of the largest global manufacturers of construction machinery, also produces heavy-duty trucks and light-duty vehicles. The company has developed electrified versions of nearly all the engine-powered construction machines in its product lineup. In addition, Volvo markets electric cars and electric trucks. Many of the new electric components required for electrified construction equipment are shared with those used in electric cars and trucks, demonstrating significant overlap in technology development and application.

As with on-road vehicles used in construction projects, battery charging is a critical consideration for construction machinery [253]. For larger machines with batteries exceeding 200 kWh, the equipment is often connected to the electrical grid during operation and utilizes an onboard battery charger. For smaller machines or less extensive projects, the machines operate independently of the grid, and their batteries are charged during periods of low usage, similar to electric passenger cars. When charging occurs during work breaks, fast charging is required, necessitating a charging time of 60 minutes or less. Alternatively, overnight charging can take place over a period of 2–8 hours. For smaller machines equipped with batteries under 100 kWh, charging can be accomplished using a Level 2 charger with a power output of 20 kW. However, larger machines with batteries exceeding 200 kWh require higher power charging solutions.

While a 50 kW DC charger is sufficient for overnight charging of large batteries, work-break fast charging requires a 300 kW DC charger to fully charge the batteries in one hour or less. The chargers necessary for construction sites are readily available and relatively affordable due to their alignment with the existing light-duty electric vehicle charging infrastructure [254]. However, some construction sites are located in remote areas, where providing access to high-rate chargers may be challenging. In addition, the widespread adoption of battery charging for construction machinery is expected to significantly increase overall power demands at construction sites, necessitating careful planning of grid infrastructure and energy management solutions.

Table 12. Summary of the characteristics of electric construction machines.

Construction machine type	Gross weight (kg)	Energy storage kWh	Electric motor kW	Operating Time (hr/charge)
Excavators	2675	20	18	4
	23000	264	160	5
Front loaders	5450	40	30	4
	20000	282	180	5
Compactors	2800	20	33	Up to 4
Cranes (wheeled)	60,000	226	200	Up to 7

Figure 10. Selected construction machinery trucks that have been electrified.

6. OUTLOOK

Based on both academic and market literature and publicly available news releases, it is evident that the electrification of construction trucks, machinery, transit buses, and inter-city buses is progressing, primarily utilizing conventional LIBs and electric drive components originally developed for passenger cars, SUVs, and medium- and heavy-duty trucks. In the case of buses, electric models are commercially available and gaining traction in an expanding global market [255]. For construction trucks and machinery, there have been successful demonstrations and implementations of various types of electrified equipment in real-world construction projects in the United States, China, and Europe [256]. Electrified construction machinery offers several advantages beyond near-zero emissions, including the elimination of CO_2 and other pollutants typically associated with diesel engines. These machines are also more energy-efficient, significantly quieter during operation, and have lower operating costs, with reduced energy expenses and less frequent maintenance compared to diesel-powered equipment [257],[258]. These benefits provide compelling reasons, beyond the reduction of CO_2 emissions, for advancing the electrification of construction equipment.

The electrification of HDVs, including buses, vocational trucks, and construction equipment, is still in its early stages, with varying degrees of progress across different sectors. Buses have seen more widespread adoption due to well-defined operational routes and charging infrastructure, whereas construction equipment remains in the nascent stages of electrification, facing unique challenges such as variable duty cycles and high-power demands. As a result, the cost of electrified products remains significantly higher than that of their diesel-powered counterparts, though continued technological advancements are expected to enhance performance and cost-effectiveness over time.

Market trends indicate a growing shift toward electrification, driven by regulatory policies and industry-led innovation. Federal and state subsidies, along with increasingly stringent emissions regulations, are accelerating adoption. However, the pace of market expansion will depend on advancements in battery technology, economies of scale, and infrastructure development. Manufacturers recognize the potential benefits of electrification and are investing in research and development to address existing limitations.

A key enabler of widespread electrification is the development of next-generation lithium-based batteries with higher energy density without compromising other critical performance metrics, such as cycle life and fast-charging capability. However, battery health remains a significant challenge, as aging and capacity fade are inevitable over time. Despite advancements in material design and battery management strategies, capacity degradation continues to impact long-term usability and the economic viability of EVs. Significant progress has been made in both mechanistic studies and AI-driven battery diagnostics to bridge the gap between laboratory research and real-world performance

[259],[260], but further understanding of battery cycle life [261] and calendar life[262], as well as improvements in cell-level performance from material sciences, are necessary to enhance the longevity and reliability of advanced battery systems.

Battery safety, on the other hand, is not an inevitable issue but remains a critical concern due to the potential for catastrophic failures such as thermal runaway. Unlike gradual capacity fade, safety incidents can occur suddenly and have severe consequences. Advances in mechanistic investigations [263] and early fault detection using specialized deep learning methods [264] are helping mitigate these risks, but safety failures still pose a major barrier to widespread adoption. Beyond increasing energy density, ensuring the highest levels of safety is essential for the viability of advanced batteries in high-power applications, such as construction machinery. If these advancements are realized, electrified heavy-duty vehicles could achieve or surpass the operational performance of conventional diesel-powered models while offering lower long-term operating costs. In addition, the inherent benefits of electrification—such as reduced noise pollution and improved air quality in work environments—could further incentivize adoption.

SSB developers have set ambitious targets for commercial production by 2030 [265], a milestone that could significantly enhance the competitiveness of electrified construction equipment and other industrial vehicles. However, the scalability and cost trajectory of SSB technology remain uncertain. Its successful integration into mainstream applications will require overcoming challenges related to manufacturing efficiency, material availability, and cost reduction.

From an operational perspective, the findings of this study suggest that Caltrans could begin incorporating electrified versions of trucks and construction machinery within its fleet, leveraging technologies that are already available from established manufacturers. The initial deployment of electrified equipment will likely rely on conventional LIBs, similar to those used in battery-electric passenger and commercial vehicles currently operating in California. The necessary charging infrastructure is expected to be accessible, given the ongoing expansion of the electric vehicle charging network. Although the upfront cost of electrified construction machinery remains relatively high, long-term cost projections are difficult to determine due to multiple influencing factors, including raw material prices, regulatory policies, and advancements in battery production efficiency. Early adoption by Caltrans could provide valuable operational insights, informing broader electrification strategies and helping identify the most effective pathways for transitioning to advanced battery technologies as they become commercially viable. This knowledge could also be of strategic interest to other state agencies, such as the CARB and the CEC, in shaping future policies for zero-emission HDVs and equipment.

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DATA SUMMARY

Products of Research

The researchers did not collect any new experimental data as part of the research. They summarized data that were available in the literature in the report and generated numerical results from our modeling of advanced batteries. Those results are given in the report.

Data Format and Content

All the data discussed in the report are summarized in the report in the proper format.

Data Access and Sharing

All the data discussed in the report are given in the report with the source of the data given in the reference list at the end of the report.

Reuse and Redistribution

All data cited in the report can be reused and redistributed by the general public if it is properly cited and referenced.