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Next-Generation Battery Technologies: Beyond Lithium-Ion

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ABSTRACT

The dominance of lithium-ion batteries (LIBs) in modern energy storage, spanning electric vehicles, consumer electronics, and grid applications, has reached a critical turning point. While LIBs have offered high energy densities and mature supply chains, challenges around resource scarcity, safety risks, cost, and environmental sustainability have sparked global interest in next-generation alternatives. This review explores the evolving landscape of battery innovation beyond lithium-ion technology, including lithium-sulfur, lithium-air, sodium-ion, solid-state, and multivalent ion systems such as magnesium- and aluminum-based batteries. Each emerging technology is assessed for its energy density potential, material availability, commercial viability, and application-specific advantages. Key trends, such as the integration of solid-state electrolytes, advanced cathode architectures, and scalable manufacturing techniques, are analyzed alongside regulatory and safety concerns. Case studies highlight how these innovations are poised to disrupt existing paradigms in energy storage. As battery demand continues to outpace supply and technological ceilings loom for LIBs, next-generation chemistries offer a path toward safer, cheaper, and more sustainable energy solutions.

Keywords: Next-generation batteries, lithium-sulfur, lithium-air, sodium-ion, solid-state battery, battery safety, energy storage, battery manufacturing.

INTRODUCTION

The lithium-ion battery (LIB), which has dominated the market for over three decades, is paramount to the electrification of the transport sector, the decarbonisation of electricity, and the deployment of low-carbon technologies in everyday life. However, challenges such as the cost, availability, and environmental sustainability of lithium feedstocks present risks to the supply chains for current LIBs and thus the industries they have enabled. The monopolistic business landscape forming around LIB production, coupled with automotive industry trends such as the anticipated emergence of electric-only vehicle fleets out to 2035, has spurred discussions of the potential for next-generation or beyond-LIB technologies. This Review investigates the demands placed on next-generation batteries and assesses recent technological advances in this context. While solid-state batteries and lithium-sulfur cells are leading contenders, other chemistries are also humously mentioned. The LIB industry is in a race to produce ever-larger batteries in faster, safer, and more environmentally responsible ways. The demand for batteries from the automotive industry has massively outstripped supply for both commodity supply chains and capital investment, preventing diversification away from the 'low-hanging fruit' graphite-$LiCoO_2$-ft complex. In terms of energy density, existing LIBs have gone about as far as they feasibly can with aqueous manufacturing techniques, commoditised materials, and thermalising alternatives, and will soon be challenged by more innovative systems, albeit with new demand-induced complications in the race for scale and cost-efficiency. Existing chemistries have diversifying and burgeoning industrial supply chains, but will the next-generation chemistries? Furthermore, are new chemistries congruent with the desired combination of improved performance metrics, environmentally responsible manufacture, and eventually low customer purchase costs? [1, 2].

Overview of Lithium-Ion Technology

In commercial lithium-ion batteries, there are anode types of artificial graphite rechargeable batteries with a $LiCoO_2$ cathode and $LiFePO_4$ batteries with a graphitized hard carbon anode, although the predominance of these two compositions does not preclude other chemistries. At present, most of the novel lithium-ion batteries characterized before introduction into research are practical 18650 cell types based on various new scaffolding materials, such as lithium titanium oxides or layered lithium iron magnesium phosphor oxides. The design of battery devices in the laboratory differs from that in industry, leading to differences in chemical composition and possible structural form of the electrodes that may be traded off against one another. Many potential applications have been considered for lithium-ion batteries, including propulsion batteries for electric vehicles, portable electronics, and grid-scale batteries for energy storage. Although all of these applications place different demands on battery chemistry, weight and volume can be traded off against energy density and fabrication cost. Whichever application is considered, improvements are still required for both energy and power density, but still, lithium-ion batteries should still be advantageous for smart grid applications. With increasing global sales of rechargeable batteries and renewable energy generation, this field of research is rapidly growing, and such a specialized area becomes of increasing interest in battery technology safety and modelling. The power densities (energy stored/cycle time) of lithium-ion cells and batteries constructed from commercially available materials are shown. The time scale to charge smartphone batteries is limited by the current-carrying capability of small 1.4 Ah cells made by wrapping equivalent 18650-size metal tubes containing rolled electrodes. New chemistries able to provide 100 times faster reacting particles or 100 times more diffusion in electrolyte should be useful to power dense applications. At the equivalent of 1000 full cycles per day, the energy cost of 20 Wh/L capacity batteries is still significant. New chemistries are required to break the "high safe" voltage cap of Li1.1Ni0.3Co0.3Al0.3O2 and exploit higher lithium concentrations, water co-doping, or stacking structures to significantly reduce Volts per gram/module (design stored energy-weight losses) [3, 4].

Limitations of Lithium-Ion Batteries

The Li-ion battery currently represents the forefront of battery technology, excelling in both energy and power density. Lithium's lightweight nature allows a 1+ charge carrier to hold significant capacity. Sodium, while next to lithium, is less suitable due to its larger size, and although magnesium is similar in weight, its stable 2+ charge reduces energy density. Lithium-ion batteries have benefited from advancements in intercalation materials like graphite and metal oxides for anodes and cathodes, respectively. Despite extensive research and development since their introduction, Li-ion batteries face challenges, such as dendrite formation with metallic lithium. Commercial models typically use graphite anodes, raising concerns about resource sustainability. Next-generation solid-state batteries aim to integrate lithium metal, promising increased energy density. However, Li-ion technology does have drawbacks for applications like electric vehicles (EVs) and grid storage, primarily due to high costs, which heavily influence EV prices and highlight the importance of resilient supply chains. Lithium and graphite, essential components of these batteries, have established supply chains that are under strain from demand. While alternatives exist, they often result in more toxic byproducts. Furthermore, the pace of improvement in Li-ion technology is slowing, indicating the need for new cathode materials as current options reach capacity limits. This limitation necessitates larger cell sizes, which introduces safety concerns, including increased internal resistance and the risk of thermal runaway. Proper cell design is crucial, as larger cell sizes heighten risks of short circuits and overheating, emphasizing the need for designs that mitigate these dangers [5, 6].

Emerging Battery Technologies

Numerous chemistries have been explored as Next-Generation Batteries, primarily focusing on high energy density and non-flammable systems. These "beyond Li-ion" technologies are at various stages of research and commercial readiness, with lithium-sulfur (Li-S) and lithium-air (Li-O2) being the most advanced, having been studied for over a decade. Although recent breakthroughs exist in sodium-ion, potassium-ion, lithium-titanate, magnesium-based, calcium-ion, and aluminum-ion batteries, they are further from commercialization. Significant technical hurdles must be addressed to enhance their performance beyond Li-ion standards, with this research examining techniques for organic cathodes, oxygen cathodes, and redox flow chemistries. Li-S technology, in particular, shows potential to surpass Li-ion performance. Current research aims to manage polysulfide dissolution, develop solid-state electrolytes, and innovate cathode materials, though Li-S batteries are hindered by limited cycle life and lower power density. A review of ongoing studies and proposed solutions is included. Novel materials such as lithium polysulfide and iron sulfide, along with new solid-state Li-S cell designs featuring ionic liquids and polymers, are presented. These materials also allow broader operational temperature ranges. Enhancing power density while aligning with conventional Li-ion production processes will be achieved with smaller, conductive carbon microfibers to boost ionic conduction and cathode conductivity [7, 8].

Comparative Analysis of Next-Generation Batteries

Comparative analysis highlights next-generation batteries likely to be commercially viable based on energy density and development prospects. These technologies, compared to lithium-ion, include lithium-sulfur (Li-S), lithium-metal with Li alloy, sodium-ion, potassium-ion, calcium-ion, all-solid-state, and unconventional systems like redox flow and supercapacitors. Their pros and cons are mapped on energy density versus development stages, identifying Li-S, lithium-metal, and lithium-oxidation batteries as the most promising. Achieving dendrite-free lithium metal for lithium-metal batteries remains challenging. Lithium foil serves as excessive lithium, while breakthroughs in Li oxidation are possible; Li-ion batteries are used in plug-in hybrids, with solid-state and sodium-ion technologies expected to yield commercial products within 5-10 years. For post-lithium anodes, development focuses on thin intercalation-type anodes and layered NMC and manganese oxides for sodium and potassium-ion batteries, though more progress is needed for potassium-ion options. This analysis offers an objective assessment of next-generation technologies, evaluating energy density and development prospects to guide future R&D. Technologies are reviewed for energy density and development status, considering the time needed for products and advancements in materials. Trade-offs exist in performance, balancing maximum energy density with material supply, safety, cost, and thermodynamics. Addressing environmental challenges requires high energy density and material availability, while safety and affordability are crucial for widespread use [9, 10].

Applications of Next-Generation Batteries

For true mobility applications, the next-generation replacement for the lithium-ion battery is likely to depend on the choice of key elements of the technology and cell-level design to maintain, at a minimum, the charge densities, at higher voltages than in lithium-ion, existing manufacturing ecosystems and supply chains, and a good balance of cost and safety. For e-mobility, an all-solid-state battery will be required, containing at least 3/4 of the energy in the cell. The key concept innovations required are a highly porous cathode architecture, an all-solid-state composite cathode with an inorganic solid-state electrolyte and other inorganics for the support structure, and a gelled polymer electrolyte for the anode, conventionally comprising conductive carbon. For load-leveling applications in the energy transition, technologies are required to be zero-stratified and capable of use at scale manufacturing. The technologies identified by their key components, followed by thoughts on the use of next-gen batteries that may be either drop-in replacements or additional battery technology options in 2030, are covered. In the 2030s, there will be a clear choice of operation and mass/volume/size for the gross battery technologies available to be put into different applications. Both lithium-ion and the new next-gen batteries will be available using similar approaches in terms of historical investments and established supply chains, with both liquid and solid-state battery variants possible for use in e-mobility applications. Solid-state batteries are preferable for energy storage systems, large-scale deployment, electric aviation, and consumer electronics. Beyond lithium chemistries are the options that are likely to be used in expendable backup storage applications in connection with energy-intensive IoT devices [11, 12].

Manufacturing Challenges

The manufacture of battery cells has progressed rapidly in recent years. Nevertheless, gaps remain regarding the technology and knowledge needed to ensure the high quality of battery cells. Given the material diversity and complexity of processes, there is an inherent difficulty involved in ensuring the battery quality in a wider context beyond battery cells. Looking to the future, battery manufacturers will face the challenge of scaling up the production of batteries, which demands a more universal and methodical approach to the assurance of battery quality. A detailed description is given of aspects of the quality of lithium-ion battery cells, including some of the indicators and methods that are currently being applied to ensure the quality of battery cells. Challenges and ideas for enhancing capability in quality assurance are highlighted. A first look at battery quality assurance beyond battery cells is also provided. It is concluded that battery quality assurance is a long-term and complex effort that needs to leverage knowledge and experience accumulated in related areas and take a systems view of battery quality. It is a necessary effort for the success of electrification. Battery production processes are increasingly optimized to achieve even higher speeds and lower costs. This rapid growth, however, poses a challenge: current production is becoming complex, making it hard to maintain quality assurance across all steps of the production process. As production goes through tighter tolerances to fit ever-increasing demand, this challenge becomes even bigger. This topic of quality at scale discusses the processes involved in producing batteries, as well as potential quality criteria and methodology. The rising global demand for energy storage and the electrification of transportation is increasing the need for batteries. Consequently, battery production has increased dramatically, especially in Asia, but also in Europe and North America. In this race, quality is already a competitive advantage, as any downtime of operations can result in losses of millions of dollars an hour. With the rise of battery production, further steps need to be taken to ensure quality at scale [13, 14].

Future Trends in Battery Technology

A variety of promising battery chemistries are under investigation, yet remain years away from commercialization. These alternatives hold potential to excel beyond lithium-ion technology in specific energy, energy density, sustainability, cost, and safety. Recent research focuses on batteries utilizing lithium anodes paired with lithium or sodium cathodes. Notable technologies include lithium metal batteries (LMBs), lithium-sulfur (Li–S), lithium-oxygen (Li–O2), sodium-ion batteries (SIBs), and sodium-sulfur (Na–S). Additionally, conventional alkaline battery chemistries such as zinc-manganese dioxide are reimagined as next-generation devices with innovative designs and electrolytes for enhanced energy and solid-state compositions. Concepts like zinc-air and zinc-bromine have promising properties that could address renewable energy storage and electric aviation challenges after extensive research. Non-aqueous electrolytes also contribute to advancements in lithium-ion capacitors, asymmetric supercapacitors, and ultracapacitor systems. Various energy storage systems are being actively researched, falling into five categories based on their energy-storage mechanisms, including molten salt electrolyte phase and lithium redox systems. All can be produced at low cost using abundant elements, offering greater volumetric energy density than lithium-ion batteries. The PhoPencil marks a significant advance in battery technology, lacking any assigned intellectual property rights. If cost-effective production methods for lithium-sulfur batteries are developed, they could overshadow the pea-pod battery. Future generations will start with PAN (poly-acrylonitrile), a low-cost polymer, aiming for simple, low-cost post-production [15, 16].

Regulatory and Safety Standards

In addition to technical parameters, the battery innovation landscape needs to be assessed about regulatory aspects and safety standards. Regulations and standards for one formal sector often do not exist, or if they do exist, they often do not reach all actors in the sector. Therefore, the regulation and safety standards overview was not aimed at new chemistries, components, and materials being developed, but on existing regulations and standards for the older seen battery technologies. This approach provides a knowledge base to discuss safety and regulatory development and introduction at the sector level. With the crucial impact on public health and the environment, and the likelihood that industrial battery technologies will be used and produced at a staggering scale, existing regulations and standards focus on waste management and safety. Safety standards mainly refer to the safety of new types of batteries to humans and animals. With the usage of safety standards, it can be assured that whole battery systems are safe: Will not explode or catch fire, will not leak, etc. Over the years, safety standards have been developed and extended as new battery management systems and new components and materials have been added to batteries. Users can access safety standards, and there is an overview of standards within the battery sector. This is in contrast to regulations. Environmental and waste-related regulations focus on sustainable innovations (environmental protection) and advanced recycling (protection of natural resources), but with the public health and safety aspects taken into account. It is crucial to develop needle filters/environmental protection development regulations accordingly, and in that regard, check the grade of data-availability against existing regulations with time frames for research investments offered afterwards or other consequences [17, 18].

Case Studies of Next-Generation Batteries

Battery technology has advanced since the invention of batteries in the 1770s. The once-used wet-cell lead-acid battery was replaced by the more efficient sealed lead-acid, which then gave way to nickel-based batteries. Each was later replaced by lithium-ion. Falling prices of lithium-ion batteries, on a cost-per-kilowatt-hour of storage basis, are causing a boom in the construction of utility-scale batteries for electricity grid applications, including network-frequency regulation and smoothing of intermittent renewable generation from wind and solar photovoltaics. Inexpensive lithium-ion cells, which pack more electrical energy into a smaller volume or weight compared to past types, are also being applied to other fields from high-capacity batteries in electric cars, laptops, and cameras, to energy-dense batteries powering small devices such as smartwatches, drones, and even satellites. High-capacity batteries necessarily use more reactive materials to store higher amounts of electric energy. Several potential chemistries could facilitate the development of high-capacity batteries with safer configurations. New battery breakthrough chemistries will rely on components including doped graphite, solid-state electrolyte interphase or lithium protective layers, thin lithium source layers, silicon during discharge reaction, and magnesium salts. Despite the rise of alternative battery chemistries, high-capacity batteries most likely to achieve levels of commercialization in the next 15 years are hybrid lithium-ion/sodium-ion batteries using silicon electrodes and/or lithium anode/manganese cathodes. There are already small-scale commercial production lines for silicon anodes for cell assembly with relatively simple designs. Products with lithium anodes are also in pilot production but with many redesign issues in a novel component, i.e., solid polymer rather than liquid organic electrolytes to avoid dendrites [19-24].

CONCLUSION

The global push toward electrification and carbon neutrality demands battery technologies that outperform the current lithium-ion standard in energy density, safety, cost, and environmental impact. While lithium-ion batteries remain central to the market, their limitations in raw material availability, safety, and performance ceiling necessitate the exploration of new chemistries. Emerging technologies such as lithium-sulfur, lithium-air, and solid-state systems offer promising solutions, albeit with technical and manufacturing challenges still to overcome. Sodium-, potassium-, magnesium-, and calcium-ion batteries also present viable paths, particularly where material abundance and lower cost are priorities. For these alternatives to succeed at scale, significant advancements in cathode and anode materials, electrolytes, and regulatory frameworks are essential. The transition from laboratory prototypes to commercial deployment will require global collaboration, robust investment, and systemic quality assurance in manufacturing. Ultimately, the evolution beyond lithium-ion marks not the end of a technology but the beginning of a broader energy storage revolution tailored for a cleaner, safer, and more resilient energy future.

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