

Material limitations in Achieving High Energy Density for Electric Vehicle (EV)

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Abstract. The transition to electric vehicles (EVs) is a pivotal step towards reducing global carbon emissions, driving a significant focus on advancements in battery technology. As the demand for higher energy density in EV batteries continues to rise, it presents both opportunities and challenges. This paper explores the material limitations that currently hinder the achievement of high energy density in EV batteries, with a particular emphasis on cost, safety, environmental impact, and cycle life. Through a comprehensive analysis, the paper identifies key factors influencing energy density, including electrochemical properties, material selection, and structural design. The discussion extends to innovative solutions such as advanced anode and cathode technologies, solid-state and hybrid electrolytes, and enhanced separator materials. While high energy density batteries hold great promise for the future of EVs, this paper concludes that overcoming the interconnected challenges of cost, safety, and sustainability will require continued research and innovation to achieve widespread adoption.

Keywords: Electric vehicles (EVs), energy density, battery.

1. Introduction

Since electric vehicles (EVs) entered the market in the early 21st century, scientific research institutions and enterprises have focused on advancing battery technology. As EVs can achieve zero emissions, their sales have rapidly increased, particularly after 2010. In 2023, 14 million new EVs were sold worldwide, accounting for 18% of all vehicle sales. The global EV fleet reached 41 million, a fourfold increase from 2019's total of 10 million. A critical area of research in EV development has been improving energy density. The energy density of lithium-ion batteries reached 450 Wh/L in 2020, a significant increase from 195 Wh/kg in 2008 [1], with batteries like the Amprius LISIC currently leading the market with an energy density of 1300 Wh/L. The demand for high energy density batteries in EVs is expected to continue rising over the next decade, as it directly influences the weight and range of EVs.

However, four key factors impact the further increase in energy density: safety, cost, battery life cycles, and environmental conditions. Safety is a fundamental concern, as higher energy density batteries inherently carry greater risks. Cost is another significant challenge, as high energy density batteries require more expensive materials. Additionally, the lifespan of EV batteries may decrease, and environmental factors could limit the potential of these batteries. Metals like cobalt and nickel, which are crucial for thermal stability, are expensive and needed in larger quantities for high energy density cells. Many batteries achieve higher energy density by altering the positive electrode materials. For example, lithium-sulfur (Li-S) cells have a theoretical energy density of up to 2600 Wh/kg, but their electrolytes may degrade at elevated temperatures or during overcharging, producing hazardous gases like hydrogen and carbon monoxide, thereby compromising safety.

To overcome these challenges, scientists and manufacturers are exploring various strategies, including redesigning battery structures, improving thermal management, developing new electrode materials, and researching solid-state batteries. This paper analyzes the primary material limitations in achieving high energy density for EV batteries and proposes solutions to address the challenges associated with increasing energy density.

2. Fundamentals of Energy Density in Batteries

2.1. Definitions and Metrics

Energy density refers to the amount of energy that can be stored in a given container and is typically expressed in two forms: volumetric energy density and gravimetric energy density. Volumetric energy density measures the amount of energy contained per unit volume (Wh/L), while gravimetric energy density refers to the energy per unit mass (Wh/kg). Increasing energy density in EV batteries is a key focus for researchers, as it offers several significant benefits. A battery with higher energy density has less mass and volume, which reduces the overall weight of an EV, thereby extending the vehicle's service life. Additionally, a higher energy density improves the range of EVs, reducing the need for frequent charging and better meeting consumer demands.

Currently, lithium-ion batteries are the most widely used in EVs, accounting for approximately 80% of the market. While other battery types may offer higher theoretical energy densities, their practical performance often falls short due to various limitations. The table 1 below compares the theoretical and practical energy densities of different battery technologies, highlighting that most batteries deliver lower energy densities in practice than their theoretical potential. Notably, technologies like lithium-air batteries and Amprius silicon nanowire batteries show significant gaps between theoretical and practical energy densities, whereas lithium-ion and sodium-ion batteries exhibit closer alignment between theory and practice.

Table 1. Theoretical and practical energy density of batteries (Wh/kg)

Battery	Theoretical	Practical
Lithium-ion	250-300	150-250
Sodium-ion	150-300	100-200
Lithium-air	3500	100-300
Lithium-sulfur	2600	300-600
Silicon nanowire	4200	300-500
Silver oxide	1000	200-400

2.2. Factors Influencing Energy Density

The factors influencing energy density can be categorized into three main areas: electrochemical, material, and structural. Electrochemical factors are paramount, as the specific capacity of the active materials (anode and cathode) and the voltage system directly determine the energy storage capacity of the battery. Additionally, the choice of electrolyte impacts ionic conductivity and stability, thereby affecting overall performance and energy density. Material selection is also critical; properties such as electrical conductivity, thermal stability, and safety must be balanced to optimize usable energy density and ensure efficient ion and electron transport. The type of materials used in the anode (e.g., graphite, silicon) and cathode (e.g., lithium cobalt oxide, lithium iron phosphate) significantly influence these outcomes. Structurally, considerations such as electrode design, cell configuration, and separator properties are essential. These factors highlight the challenges associated with increasing energy density, including cost, safety, lifespan, and environmental impact, making it difficult to balance these competing demands effectively.

3. Material Limitations in Current EV Battery Technology

3.1. Cost

The cost of batteries is a critical factor in determining the price of EVs, making affordability and cost-effectiveness essential for widespread adoption. Lithium, a key element in lithium-ion battery cathodes, is abundant but presents challenges in scaling production to meet the growing demand as EV adoption increases. Cobalt, valued for its ability to provide thermal stability in batteries, is the

most expensive component in EV batteries due to limited mining regions. Recently, cobalt prices have surged to \$26,500 per ton, compared to \$10,700 per ton for lithium. Nickel, which offers higher energy density and greater storage capacity at a lower cost (\$16,400 per ton), faces issues of scarcity, potentially leading to supply shortages. These raw material costs significantly impact overall production expenses.

Moreover, the production process for high energy density batteries is more complex than that of conventional batteries. Manufacturers must employ advanced technologies, including optimized battery designs and more efficient manufacturing processes, which further drive-up costs. Additionally, high energy density batteries require specialized cathode and anode materials, such as high-nickel ternary compounds or silicon-based materials, which are more expensive. While reducing cobalt content is one approach to lowering costs, it introduces other challenges, such as potential safety concerns and reduced cycle life [2].

3.2. Safety

Safety is the most critical consideration for high energy density EV batteries, as any advantages are rendered moot if the batteries are too dangerous to use. While eliminating cobalt can reduce costs, this often results in decreased thermal stability and shorter cycle life, increasing the risk of fires and explosions. To mitigate these risks, manufacturers incorporate safety measures such as fuses and current interrupt devices, which are both costly and time-consuming to implement. Additionally, designing safe batteries requires extensive experimentation and research, often involving numerous failures, making it challenging to reduce costs while maintaining safety.

Another significant safety concern is the growth of lithium dendrites, caused by uneven lithium-ion deposition and other complex factors. Dendrites can lead to short circuits and reduce battery capacity. Research from Xi'an Jiaotong University highlights that dendrite formation in all-solid-state batteries forces the solid electrolyte to operate at low current densities. Furthermore, dendrites negatively impact the battery's cycle life, meaning the battery undergoes fewer charge-discharge cycles before its capacity declines. Thus, improving energy density is contingent upon resolving the dendrite issue. Although the hybrid Zn-Fe flow cell avoids dendrite formation and offers a longer lifespan, its energy density remains relatively low [3].

3.3. Environmental Impact

Temperature is a significant environmental factor that affects battery performance, particularly in terms of energy density, endurance, and charging rates. Temperature variations have a marked impact on the range of EVs. For instance, when forty-one EVs were evaluated under different temperature conditions, their average range at high temperatures (50°C) was approximately 66%, compared to 47% in winter and 74% in normal weather [4]. Additionally, temperature influences the charging and discharging speeds, especially in cooler conditions. For example, at 10°C, the charging current in each cell is only 2Ah, whereas at 20°C, this value doubles. These temperature effects reduce the effective charge and discharge capacity of the battery, thereby affecting the normal operation of EVs.

Although higher temperatures generally provide a greater range and faster charging rates, they also accelerate the growth of the Solid Electrolyte Interphase (SEI), which can lead to thermal runaway and decrease the lifespan of EV batteries. While most batteries are not highly sensitive to changes in ambient humidity, high-nickel cathode materials can readily absorb moisture, leading to the formation of lithium carbonate and lithium hydroxide layers on the particle surfaces. This process consumes lithium within the material, adversely affecting battery performance and capacity. Beyond temperature and moisture, chemical pollutants in the air can also degrade battery performance and longevity. For example, the aluminum current collector in lithium-ion batteries is prone to corrosion, which can cause the positive electrode material to lose electrical and mechanical contact with the aluminum foil, thereby reducing capacity and power [5].

3.4. Cycle

High energy density in batteries often results in a lower cycle life. For example, while lithium-ion batteries can achieve 1,000 to 2,000 cycles under ideal conditions, the Amprius LISIC battery, which boasts one of the highest energy densities on the market at 500 Wh/kg, only reaches 320 cycles, making it impractical for many applications. Several factors contribute to this phenomenon, with one of the primary causes being the formation of by-products during electrochemical reactions. High energy density materials can generate by-products during charging and discharging, which may form films on the electrode surface, increasing resistance and thereby reducing battery performance. Additionally, these materials undergo significant volume changes, potentially leading to the degradation of the electrode structure and impairing the battery's ability to be reused.

The cycle life of a battery is critical because it directly affects the battery's lifespan; a low cycle life necessitates more frequent replacements, which is undesirable in applications like electric vehicles. Thus, the production of EV batteries must consider not only energy density but also durability. Finding the right balance between energy density and cycle life remains a significant challenge in battery development.

4. Emerging Solutions to Overcome Material Limitations

4.1. Advanced Anode Technologies

Thermal stability is a critical factor in ensuring battery safety, and recent developments in materials have aimed to address this issue. One approach involves the use of silicon-carbon composites, which combine silicon with carbon through a gel matrix. This method offers a viable alternative to pure silicon as an anode material. Although silicon has a high theoretical specific capacity (approximately 4200 mAh/g), it undergoes volume changes of up to 300% during charge and discharge cycles, leading to structural damage and reduced cycle performance [6]. Silicon-carbon composites help mitigate these issues by restricting the thermal expansion of silicon, with the carbon matrix providing structural stability and effectively supporting the silicon particles.

Another promising approach is the development of nanostructured anodes, where the anode material is reduced to the nanoscale to enhance battery performance. Nanomaterials can better accommodate volume changes during charge and discharge due to their small size, reducing mechanical stress and extending the battery's cycle life. Additionally, using lithium anodes with protective coatings is a feasible strategy, as lithium anodes offer high theoretical capacity and low potential. Protective coatings, such as PVA and PMMA, can minimize direct contact between lithium and the electrolyte, thereby reducing the occurrence of side reactions. Furthermore, metals like copper and nickel can be used to coat the lithium anode, providing mechanical strength, electrical conductivity, and inhibiting the growth of lithium dendrites. This method effectively addresses environmental impacts and enhances the cycle life of batteries [7].

4.2. Next-Generation Cathode Materials

High-voltage cathode materials are crucial in lithium-ion batteries for increasing energy density, a key requirement for EVs. To enhance the thermal stability of these cathodes, which are prone to thermal runaway, coatings are often applied. In addition to traditional cathodes, alternative chemistries are being explored, such as lithium-sulfur (Li-S) batteries, which are a focus of research due to their potential for high energy density in EVs. Despite challenges related to safety and cycle life, scientists have developed strategies to improve the electrochemical performance of Li-S batteries, including using metal nitrides as cathode host materials.

Recently, researchers at the University of California, San Diego, developed a new cathode material—a crystal composed of sulfur and iodine [8]. This innovation enhances the electrical conductivity of batteries and offers new possibilities for the commercialization of Li-S batteries.

Notably, the crystal's low melting point (65 °C) grants it structural repairability, thereby extending the lifespan of Li-S batteries.

Another promising technology is the lithium-air battery, which utilizes lithium as the anode and oxygen from the air as the cathode reactant. With a theoretical energy density even higher than that of Li-S batteries (3500 Wh/kg), lithium-air batteries face challenges related to by-product formation and the impact of carbon dioxide, which diminish conductivity and cycle stability. Researchers at the University of Cambridge have addressed these issues by replacing lithium peroxide with lithium hydroxide and incorporating lithium iodide as an intermediate compound [9]. These advancements reduce adverse chemical reactions and bring lithium-air batteries closer to commercialization.

4.3. Solid-State and Hybrid Electrolytes

Electrolytes serve as the medium for ion transport within batteries. However, as battery designs strive for higher energy density by using thinner membranes and less electrolyte, the accelerated consumption of electrolytes can lead to performance degradation. Two main categories of innovative materials for solid-state electrolytes have emerged: inorganic solid electrolytes (ISEs) and polymer solid electrolytes (SPEs). Inorganic solid electrolytes, such as lithium fluoride and lithium oxide, offer high ionic conductivity and excellent thermal stability; for instance, the ionic conductivity of LGPS at room temperature can reach 1.2×10^{-2} S/cm. While polymer solid electrolytes generally exhibit lower ionic conductivity than ISEs, they provide superior flexibility and machinability, enabling close contact between battery components and reducing internal resistance. Additionally, polymer materials are typically low-cost and easy to mass-produce, which can help lower the overall cost of batteries.

Despite these advancements, the interface between the electrode and electrolyte remains a significant challenge for solid-state electrolytes, necessitating further optimization to improve contact and performance [10]. A promising approach to addressing these challenges is the development of hybrid electrolytes, which combine the benefits of both ISEs and SPEs. However, creating hybrid electrolytes requires precise control over the proportion and distribution of solid and liquid components, increasing the complexity and cost of manufacturing [11].

4.4. Enhanced Separator Materials

The separator is a critical component in batteries, serving as a channel for ion transport within the electrolyte and preventing short circuits. As energy density increases, concerns about the separator's thermal stability and safety become more pronounced. High-temperature-resistant separators offer a viable solution; for instance, incorporating inorganic ceramic nanoparticles into polyolefin separators enhances thermal stability and reduces the risk of thermal runaway under high-temperature conditions. Another approach is the development of multifunctional separators, which not only provide ionic conductivity and mechanical strength but also offer additional features such as anti-pollution and self-cleaning functions. By introducing a porous structure or specific surface modifications—such as solid polymer electrolytes modified with ferroelectric ceramic nanofibers—into the separator, the affinity between the separator and the electrolyte can be improved, thereby increasing ion transport efficiency.

5. Conclusion

Increasing the energy density of EV batteries continues to face significant challenges, including total cost, safety, environmental impact, and cycle life. Thermal stability is crucial for ensuring safety, while manufacturing costs are a primary concern affecting the overall expense of batteries. These limitations are interconnected; for instance, enhancing battery safety often requires increasing the amount of cobalt used, which, due to its high cost, drives up production expenses. Addressing these four issues simultaneously is complex, and achieving high energy density in EV batteries will require extensive research and development over time.

Nevertheless, researchers and scientists have made progress by exploring alternative materials for cathodes, anodes, and electrolytes, as well as improving separators. Moving forward, companies should focus on developing cost-effective methods to prevent thermal runaway and continue advancing research on new electrode materials and electrolyte optimization. Although high energy density batteries hold great promise for EV applications, overcoming these challenges is essential for their widespread adoption. With sustained research and innovation, it is anticipated that batteries with higher energy density and longer cycle life will be realized in the future.

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