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Review of Performance Analysis of Lithium-Sulfur Batteries for Electric Vehicles: Challenges and Future Prospects

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Abstract
The automotive sector has witnessed rapid technological advancements, particularly in developing electric vehicles (EVs), which rely heavily on batteries for energy supply. While lithium-ion batteries are the predominant choice, they face significant challenges, including low energy density and usage limitations. As a result, researchers are exploring alternative battery technologies such as lithium-air, lithium-sulfur, and all-solid-state batteries to potentially replace conventional lithium-ion batteries in electric vehicles. This review aims to compare the performance of these alternative battery types, focusing specifically on lithium-sulfur (Li-S) batteries, which have demonstrated an energy density of 2,500 Wh/kg. This surpasses the energy densities of lithium-air batteries (250-1200 Wh/kg), all-solid-state batteries (500 Wh/kg), and lithium-ion batteries (890 Wh/kg), highlighting their significance in energy storage capacity. Given their impressive energy density and increasing attention, Li-S batteries are rapidly advancing toward mass commercialization than their lithium-ion and all-solid-state counterparts. However, several challenges remain to be addressed, particularly in enhancing battery development to ensure timely integration into the market.

Keywords: *Lithium-air Battery, lithium-sulfur battery, all-solid-state battery*

1. Introduction

The transition to renewable energy has emerged as an urgent global priority, presenting both opportunities and challenges for contemporary society. As climate change and greenhouse gas emissions become increasingly pressing issues, there is a critical need to rethink our transportation methods and energy systems (Robert et al., 2024). The transportation sector is a significant contributor to emissions, with a growing number of vehicles relying on fossil fuels. One potential solution to this issue is the adoption of electric vehicles (Fitrianto et al., 2023).

Lithium-ion batteries (LIBs) play a crucial role as a power source for various electric transportation applications, including electric vehicles, unmanned aerial vehicles (UAVs), and aerospace equipment. However, concerns regarding safety, particularly related to LIB failures during impacts and collisions, pose significant barriers to their widespread adoption in electric transportation (Honggang Li et al., 2024). Thus, understanding the strain rate-dependent mechanical behavior and failure mechanisms of lithium-ion battery components is vital for designing batteries that are not only safe but also structurally optimized for electrical transportation.

In this regard, lithium-sulfur (Li-S) batteries have emerged as a promising alternative to traditional lithium-ion batteries, primarily because of their potential to deliver significantly higher capacity and energy density (Forde et al., 2024). The increasing demand for electronic consumer goods and electric vehicles has led to growing interest in lithium batteries with high energy densities (Yi et al., 2024). Modern society relies heavily on efficient and dependable energy storage systems. Although lithium-ion batteries have shown excellent performance in portable electronics and electric vehicles, safety concerns such as the risk of fires and explosions have restricted their widespread adoption (Chen et al., 2021).

Li-S batteries stand out as strong candidates to replace conventional LIBs, mainly due to their advantages in terms of environmental impact, resource availability, and high energy capacity. Despite these benefits, their practical use is hindered by inherent issues, such as instability of lithium metal anodes, poor conductivity, and rapid capacity degradation (Tiwari et al., 2024). Developing robust protective layers for lithium metal anodes is crucial to improving their practical application. However, ensuring the optimal isolation of reactants within the electrolyte, while enabling efficient and uniform ion transport, continues to be a major challenge for high-energy-density batteries, especially for Li-S systems (Liu et al., 2023).

As nations strive to shift towards renewable energy, the development of effective energy storage solutions is essential to maintaining a balance between supply and demand, particularly due to the variable nature of renewable energy sources (Ruzzenenti et al., 2024). The swift advancement of electrochemical energy storage technologies, driven by clean and renewable energy, aims to combat fossil fuel depletion and lower CO_2 emissions (Sun et al., 2024). Although lithium-ion batteries are increasingly utilized across multiple sectors, including portable devices, electric vehicles, and renewable energy systems, the occurrence of thermal runaway incidents remains a significant safety concern (Kumar et al., 2024).

The demand for electrical devices places higher requirements on power supply systems. It is essential to reduce the mass and volume of batteries while simultaneously increasing their capacity to enhance the operating duration of electrical equipment, all while preventing combustion, explosion, or battery failure (Niu et al., 2024).

Li-S batteries are regarded as promising candidates for next-generation energy storage solutions, primarily due to their high energy density, affordability, and eco-friendly nature. However, their path to commercialization is obstructed by several challenges, including the poor electrical conductivity of sulfur and its reduction products, low utilization of active materials, limited sulfur loading, and the pronounced displacement effects of lithium polysulfide (LiPS) (Sultanov et al., 2023). Despite offering high theoretical energy capacity, environmental benefits, and abundant sulfur resources, Li-S batteries encounter fundamental issues—such as polysulfide shuttling, sulfur isolation, the formation of lithium dendrites, and volume expansion—that severely hinder their commercial viability (He et al., 2024).

Therefore, it is crucial to advance the development of lithium batteries to meet the growing energy needs of a sustainable future, particularly through Li-S battery technology. Ongoing research and innovation are essential for addressing these challenges and presenting viable solutions to mitigate greenhouse gas emissions and combat global warming. The primary focus of this study is to develop lithium batteries with enhanced energy capacity, improved thermal stability, and cost-effectiveness.

2. Literature Review Analysis Performance Battery Lithium-Sulfur

As greenhouse gas emissions regulations become more stringent, the development of sustainable transportation systems has become a global imperative. In this context, the study of transportation systems utilizing electric vehicles (EVs) has garnered increased research attention (Kim et al., 2023). EVs are essential for reaching climate and energy goals, as well as for reducing carbon emissions in road transport—a sector heavily reliant on fossil fuels and accounting for 20.2% of global CO_2 emissions. To lessen the environmental impact of transportation, numerous policies have been introduced globally to support the adoption of EVs and achieve net-zero emission targets. For example, the European Union has implemented regulations to lower fleet emissions, while simultaneously encouraging the production and sale of zero- and low-emission vehicles (Zaidi et al., 2023).

In recent years, the push towards electric vehicles has led to significant advancements in various aspects, with energy storage being a key focus of development. The advancement of electric vehicles is closely related to the progress in battery technology (Dwipayana et al., 2023). Electric vehicles rely on electricity stored in batteries as their energy source. The advantages of electric vehicles over conventional vehicles include high energy conversion efficiency and reduced fossil fuel consumption, which directly decreases greenhouse gas emissions into the atmosphere (Dyartanti et al., 2021). However, the lithium-ion batteries (LIBs) currently employed in electric vehicles still have several drawbacks, such as limited lifespan, low energy capacity, risks of overcharging, overheating, and high costs. Therefore, there is a need for batteries that have greater energy capacity, longer lifespans, are less prone to overheating, and are more affordable.

Li-S batteries are seen as a promising alternative to lithium-ion batteries due to their significantly higher practical energy density (Chen et al., 2023). These batteries utilize lithium as the anode and sulfur as the cathode, where lithium ions migrate between electrodes during charge and discharge cycles, generating capacity through redox reactions between lithium and sulfur (Wang et al., 2021). The incorporation of redox mediators has been identified as an effective approach to improve redox reactions involving deep sulfur species in Li-S batteries. Recent research on these mediators has provided insights into their reaction mechanisms and classifications, offering valuable direction for the future development of high-performance redox mediators in Li-S systems (Zhou & Sun, 2024).

The appeal of Li-S batteries lies in their high specific capacity, superior energy density, eco-friendliness, and cost-effectiveness, positioning them as one of the most promising electrochemical energy storage solutions (Li et al., 2021). Their high theoretical energy density has led to their recognition as a potential breakthrough in energy storage technology. Nonetheless, practical challenges remain, such as the high reaction resistance of lithium polysulfides, which impedes the broader application of Li-S batteries. Addressing these issues requires the development of strategies to improve the kinetics of lithium polysulfide formation and transformation from sulfur or Li_2S. Recently, redox mediators have gained attention as catalytic agents that enhance sulfur redox reactions, pushing forward the progress of Li-S battery technology (Zhou & Sun, 2024).

Studies on the performance analysis of Li-S batteries play a crucial role in advancing energy storage and battery technology. Boasting a theoretical energy density of around 2,500 Wh/kg, Li-S batteries present a far higher potential compared to traditional lithium-ion batteries, which achieve only about 890 Wh/kg. The contribution of this research extends beyond merely improving energy storage capacity; it also encompasses a deeper understanding of the challenges faced by Li-S batteries, such as cycle life and stability, which are crucial for developing more efficient and sustainable battery technologies.

The research methods employed in this analysis include sulfur purification techniques via dissolution-recrystallization to obtain high-quality sulfur for use as a cathode material. Analytical techniques such as X-ray diffraction (XRD), energy-dispersive spectroscopy (EDS), and X-ray fluorescence spectroscopy (XRF) were utilized to evaluate the purity, particle size, and crystallinity of the purified sulfur. The results indicated that the purified sulfur achieved a purity of 91.159% and a crystallinity degree of 75.620%, which is a significant step in enhancing battery performance (Typical et al., 2021).

The results of this study reveal that Li-S batteries have the potential to achieve higher energy densities than other battery technologies, along with enhanced cycle stability through the use of refined sulfur. The research underscores the need for advancements in materials and electrode design to improve the efficiency and longevity of Li-S batteries, thus accelerating their adoption in the marketplace (Typical et al., 2021).

The findings are valuable to a range of stakeholders, including the automotive industry, battery manufacturers, and researchers in energy technology. As demand for electric vehicles and efficient energy storage solutions continues to rise, this study lays a foundation for the development of new, innovative products. Furthermore, the insights gained may assist policymakers in crafting strategies for a more sustainable and efficient energy transition.

Conclusions

This review highlights the significant potential of lithium-sulfur (Li-S) batteries as a next-generation energy storage solution for electric vehicles (EVs). With a theoretical energy density of approximately 2,500 Wh/kg, Li-S batteries far exceed the capacities of traditional lithium-ion and other alternative battery technologies. Despite their advantages, Li-S batteries face intrinsic challenges such as low conductivity, polysulfide dissolution, and issues with lithium dendrite formation, which hinder their commercialization. Ongoing research and development are crucial for addressing these challenges, particularly through the enhancement of materials and electrode designs. By overcoming these barriers, lithium-sulfur batteries could play a pivotal role in the transition to sustainable transportation, offering environmentally friendly and efficient energy storage options. Stakeholders in the automotive and energy sectors can leverage these insights to foster innovations and implement strategies that align with the growing demand for cleaner energy solutions in the face of climate change.

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