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A Review of Research Progress in Energy Storage Materials

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Abstract. The substances utilized within energy storage are vital components of modern energy systems, and their performance significantly influences the efficacy, security, steadiness, and durability of these frameworks. As global society shifts toward renewable power integration and carbon neutrality, superior-quality and sustainable energy storage materials have attracted extensive attention. This overview provides a comprehensive summary of recent scientific breakthroughs in primary energy storage material categories including electrochemical energy storage, thermal energy storage, mechanical energy storage, and hydrogen energy storage. The properties, uses, benefits, and drawbacks of various materials are critically examined, and the issues of high production costs, lack of long-term stability, resource use, and environmental effects are highlighted. Moreover, new approaches such as solid-state batteries, new electrode materials, low-carbon material design, recycling technologies, and smart monitoring systems are addressed. This review offers a detailed understanding of the state-of-the-art and the future trends of energy storage materials to guide the development of efficient, safe, and sustainable energy storage technologies.

Keywords: energy storage materials, electrochemical energy storage, thermal energy storage, hydrogen energy storage, cycle life

1. Introduction

The growing adoption of renewable energy sources has posed an immediate need to have effective energy storage technologies. The materials used in energy storage define the important performance parameters such as energy density, cycle life, safety and operational stability of storage systems [1]. Thus, it is crucial to develop sophisticated materials to store energy to attain carbon neutrality and decrease reliance on fossil fuels [2].

Despite the considerable advances in lithium-ion batteries, thermal storage materials, mechanical storage systems and hydrogen storage technologies, there are still a number of challenges. The current materials continue to be constrained by high production costs, short life, safety issues, and environmental effects during manufacturing and recycling [3]. Past research has largely concentrated on single storage technologies or materials, with overall comparisons based on performance, economic, and environmental impact being lacking.

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Thus, this review is a summary of the latest developments in electrochemical, thermal, mechanical and hydrogen energy storage materials. The benefits, constraints, areas of application, and future development plans of various systems are presented to give a guideline on sustainable technologies of energy storage.

2. Literature review

The emergence of renewable energy technologies and the growing demand of sustainable energy systems in the world have brought to the fore the significance of advanced energy storage technologies. The basic elements of these systems are energy storage materials, whose characteristics, such as energy density, cycle life, thermal stability, and safety directly affect the overall performance and reliability of energy storage devices.

Despite the impressive advances made in lithium-ion batteries, thermal storage materials, mechanical storage systems and hydrogen storage technologies, there are still a number of challenges. Current materials continue to be plagued by such drawbacks as low energy density, high preparation cost, lack of long-term stability, resource use, and environmental concerns in production and recycling. Past research has primarily concentrated on single storage technologies or particular materials but no thorough comparisons between various energy storage materials based on performance, economic and environmental impact have been conducted [3].

Thus, the purpose of this review is to summarize in a systematic manner recent developments in electrochemical, thermal, mechanical and hydrogen energy storage materials. The benefits, constraints, areas of application, and future development plans of various systems are compared to offer a detailed source of information on how to develop sustainable and high-performance energy storage technologies.

3. Methodology

This paper collects and analyzes domestic and foreign literature on electrochemical energy storage, thermal energy storage and hydrogen energy storage, and evaluates their performance and application prospects. In electrochemical energy storage, breakthroughs in key materials of lithium-ion batteries and other systems have greatly promoted portable electronic devices, electric vehicles and grid energy storage [2, 4]. Electrochemical technologies have the advantages of fast response and high efficiency, mainly including lithium batteries, lead-acid batteries, flow batteries and supercapacitors [5]. Although widely commercialized, high cost restricts large-scale promotion [6]. Therefore, cost reduction and efficiency improvement through new materials, optimized processes and innovative mechanisms are urgently needed. Meanwhile, the environmental problems of battery materials need to be solved.

Thermal energy storage has completed basic research and is gradually applied. Although low in cost, its efficiency and safety are limited, and it is still in the demonstration stage [6]. Mechanical energy storage such as flywheels, pumped storage and compressed air storage relies on inertia and gravity, but its efficiency and energy density need to be improved [7]. Hydrogen energy storage is efficient and eco-friendly with broad prospects, but its high investment cost hinders large-scale application [6]. To address these problems, researchers are developing new materials and routes to lower cost and enhance performance.

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Table 1. Comparison of different energy storage technologies and materials

Technology	Main Materials	Advantages	Limitations	Applications
Lithium-ion battery	Lithium cathodes, graphite anodes, electrolytes	High efficiency and energy density	Cost, safety, recycling issues	EVs, electronics, grids
Sodium-ion battery	Sodium cathodes and carbon anodes	Low cost and abundant resources	Lower energy density	Large-scale storage
Thermal storage	Phase-change materials, molten salts	Low cost and long cycle life	Heat loss and conductivity problems	Industrial heat storage
Hydrogen storage	Hydrogen carriers, catalysts	High energy density and clean	High cost and safety challenges	Long-duration storage

4. Results

This section systematically evaluates the global research status of energy storage materials, focusing on performance, economic benefits and environmental impacts of electrochemical, thermal and hydrogen storage systems. Key materials are analyzed from energy density, power density and cost.

In electrochemical systems, lithium-ion and sodium-ion batteries present high power density (hundreds to thousands of W/kg) and moderate energy density (tens to hundreds of Wh/kg). Most lithium-based batteries last 1000–5000 cycles, and sodium-based batteries can reach thousands of cycles. They are widely used in consumer electronics and electric vehicles, but limited by cycle life.

Thermal energy storage has a wide range of energy density. Sensible heat systems are relatively low, and phase-change materials are at a medium level. With low power density but long cycle life (more than 10,000 cycles) and low cost, thermal storage is suitable for industrial waste heat recovery and seasonal heat storage. Current improvements focus on enhancing density, extending hardware life and reducing energy loss.

Hydrogen storage has ultra-high energy density (thousands of Wh/kg), ideal for long-term large-scale energy storage. Its power density is restricted by supporting devices such as electrolyzers and fuel cells. Cycle life varies from hundreds to more than ten thousand cycles. However, high transportation cost and safety risks in storage remain to be solved.

5. Discussion

Based on the above results, this section deeply analyzes key problems and clarifies future development directions [1]. Electrochemical energy storage features fast response and high stability, supporting frequency regulation and peak shaving for power grids [8]. Compressed air energy storage can use abandoned mines for large-scale and long-term storage, helping grid load fluctuation and seasonal adjustment [2, 7]. Flywheel energy storage provides millisecond response and performs well in transient stability control [6]. Hydrogen energy storage realizes long-term and cross-seasonal clean energy storage via water electrolysis and fuel cells [7].

Nevertheless, challenges remain. The rotor and magnetic bearing of large flywheels need optimization for safety [6]. Electrochemical systems with high-density materials face environmental

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and maintenance problems, which require recycling and life extension [7]. Driven by new energy vehicles, demand for long-life and high-safety materials promotes research on solid-state batteries and sodium-ion batteries [9].

Future research should develop new electrolytes and stable electrodes, and apply interface engineering to improve battery performance. Solid-state batteries are expected to fundamentally solve safety hazards and low energy density of liquid electrolytes [1]. Sulfide or polymer solid electrolytes combined with high-capacity electrodes can further enhance performance. In addition, AI and big data can monitor battery status, predict life and improve safety. In general, future energy storage materials should pursue higher efficiency and stability via material and technology innovation, emphasize low-carbon environmental protection and balance economy for large-scale commercial application.

Although various composite modified energy storage materials obtain excellent performance in laboratory environment, there are multiple obstacles restricting large-scale industrial popularization. Firstly, the high-precision composite synthesis process requires expensive precursor raw materials and precision sintering, coating equipment, bringing huge cost pressure to small and medium-sized energy storage enterprises. Secondly, the batch performance consistency of new composite materials is poor due to immature large-scale preparation technology, which cannot meet the strict operation standards of grid energy storage. Thirdly, the disassembly and recovery process of waste composite energy storage materials is complex. There is no mature low-cost recovery route for silicon-carbon negative electrodes and composite solid electrolyte, resulting in resource waste and heavy metal pollution risk.

From the policy level, China has issued a series of supporting policies for new energy storage industry, including tax incentives for composite electrode manufacturers, special industrial pilot funds for all-solid-state batteries, and standardized recycling system for power batteries. The EU and the United States have put forward carbon tariff restrictions on battery raw materials, which further promotes the research and development of low-carbon recyclable composite energy storage materials. Future material research needs to balance laboratory performance and industrial manufacturability, develop green low-cost synthesis routes to realize large-scale commercial application.

6. Conclusion

In conclusion, energy storage materials are experiencing rapid development. Emerging materials and technologies lay a foundation for an efficient and sustainable energy future [1, 10]. Facing increasing energy demand and environmental pressure, optimization of material processing, raw material acquisition and next-generation technologies should focus on performance and eco-friendliness. From the short-term perspective of 1–5 years, the research focus is to optimize the existing composite modification process, popularize carbon-coated lithium iron phosphate electrodes and ceramic composite phase change heat storage materials, and improve the echelon utilization and recycling system of power batteries to meet the incremental demand of new energy grid connection and vehicle energy storage. In the medium and long term of 5–15 years, the industrialization of all-solid-state composite electrolyte lithium batteries, low-cost sodium-ion batteries and room-temperature magnesium-based composite hydrogen storage alloys will be comprehensively promoted. A multi-energy complementary coupling energy storage system integrating electrochemistry, heat storage and hydrogen storage will be built to realize deep decarbonization of the whole energy industry chain.

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Future research can focus on stability under transient shocks to solve problems such as spontaneous combustion and short service life. Hydrogen energy storage is important for deep peak shaving and flexible grid operation, but high cost and safety risks in storage and transportation restrict its application [1]. Therefore, future efforts should develop low-cost and high-efficiency hydrogen storage materials, optimize catalysts and hydrogen storage schemes, and improve system safety and economy. For thermal energy storage, on the basis of mature technology, improvements should be made in environmental protection, energy density enhancement, loss reduction and new systems such as chloride molten salt and ceramic solid heat storage.

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