Chapter 5

Recent Advances in Supercapacitor Materials:

A Review on Performance Enhancement, Flexibility, and Scalability for Next-Generation Energy Storage

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ABSTRACT

Supercapacitors are attracting attention as high-performance energy storage devices, especially for flexible electronics. They offer high power density, long cycle life, and fast charge/discharge, making them strong alternatives to batteries in applications requiring quick energy delivery. This study reviews recent advances in supercapacitor materials, focusing on enhancing electrode performance through nanostructures and conductive composites. These innovations have significantly improved specific capacitance and electrochemical stability. The development of heat-resistant separators and highly conductive electrolytes has further improved

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performance under harsh conditions. Research is also advancing flexible supercapacitors to meet demand for wearable and portable electronics. Their improved mechanical flexibility and solid-state performance enable new tech integrations. However, large-scale production faces challenges such as high manufacturing costs and complex material synthesis. Continued efforts are needed to reduce costs and enable commercial use across energy storage sectors

1. INTRODUCTION

The rapid growth of electronic technologies and digitalization has led to a continuous increase in worldwide energy consumption. This growth was driven by urbanization, the use of more and more connected devices, developing transportation infrastructures, and rapid industrialization(Mahmood et al. 2024; Reenu et al. 2024a; Wu et al. 2016a). Even with advances within renewable energy development, oil, natural gas, and coal continue to be heavily utilized by society to meet demand for energy. (Komal Zafar et al. 2024; Strielkowski et al. 2021; Wang and Azam 2024). Even worse, the consumption of such resources makes a greater contribution to greenhouse gas emission and global warming(Wang and Azam 2024). Scientifically speaking, moving into a future with no dependence on fossil fuels, the scientific community is in pursuit of greener and cleaner energy solutions. Of these, renewable energy sources, namely, solar, wind, and hydropower, offer a desirable trade-off(Adedoja, Sadiku, and Hamam 2023; Dissanayake and Kularatna-Abeywardana 2024; Olabi et al. 2022). That said, renewables are intermittent by nature and the development of efficient, stable energy storage solutions is crucial to smoothing the intermittency of a renewable system. Energy storage technologies are thus being conceived as the most important factors in smart, sustainable energy grids of the future(Ayorinde et al. 2024; Muralee Gopi et al. 2025a; Olabi et al. 2022).

Among different energy storage technologies, electrochemical devices occupy a special position in this space. These devices refer to batteries, conventional capacitors, and supercapacitors, which exhibit quite distinct characteristics (Muralee Gopi et al. 2025a; Zhang, Gu, and Chen 2023a). Batteries, for instance, offer high energy density (600 Wh/kg) and are suitable for storage with longer durations but come with a shorter life span and a slower charging period than both methods of energy storage, as in the literature (Meena et al. 2023). In contrast, conventional capacitors offer ultra-fast charging and discharging but store very little energy (0.01–0.05 Wh/kg) (Meena et al. 2023). Supercapacitors combine both methods during storage and power density period, showing energy densities ranging from 10-100 Wh/kg, with supercapacitors exhibiting significantly higher power densities than even batteries (Meena et al. 2023; Pandolfo and Hollenkamp 2006). As shown in the Ragone dia-

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