

Innovation And Future Directions in Flexible Energy Storage Systems

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Abstract. In the wake of global energy demands and the urgent need for sustainable solutions, flexible energy storage systems have emerged as a cornerstone for innovation in the electronics industry. These systems are pivotal in addressing the challenges posed by the depletion of fossil fuels and the adverse environmental impacts associated with their consumption. This paper investigates the evolution of flexible energy storage systems, emphasizing the significance of advanced materials, including conductive polymers, flexible carbon nanomaterial electrodes, and metal foil substrates, in developing technologies that promise enhanced electrochemical performance and environmental sustainability. The paper also examines flexible batteries, supercapacitors, and piezoelectric devices, outlining their applications, challenges, and the balance between electrochemical performance and flexibility. The overarching goal is to navigate the dual environmental impact of energy storage systems, striving for solutions that minimize emissions and material disposal issues while enhancing the efficiency and safety of flexible energy storage technologies. This research underscores the pivotal role of flexible energy storage systems in fostering a sustainable electronic landscape, driven by advancements in material science and manufacturing techniques.

Keywords: flexible energy storage system; conductive polymer; flexible battery; flexible supercapacitor; flexible piezoelectric device.

1. Introduction

In recent times, considerable endeavors have been committed to creating sustainable, renewable, and ecological energy storage systems that exhibit superior electrochemical performance. This initiative stems from the pressing issues of depleting fossil fuels, escalating environmental pollution, global warming concerns, and the urgent demand for environmentally friendly alternatives in the contemporary electronics industry. Concurrently, substantial research endeavors have been focused on exploring and advancing flexible energy storage systems. The key objective is to integrate flexible electronics into various devices, including but not limited to portable electronics, flexible displays, electronic sensors, wearable devices, power backup systems, health monitors, laptops, mobile phones, and more [1].

This essay explores the role of advanced materials in shaping flexible energy storage technologies, with a focus on conductive polymers, flexible carbon nanomaterial electrodes, and flexible metal foil substrates. Each material category brings unique properties and applications to the forefront, contributing to the development of versatile and efficient energy storage solutions. Additionally, the essay delves into the types and mechanisms of flexible energy storage systems, encompassing flexible batteries, flexible supercapacitors, and flexible piezoelectric devices. The challenges and future perspectives in the domain underscore the dual environmental impact of energy storage systems and highlight some ongoing quests for enhanced properties and safety in these evolving technologies.

2. Advanced Materials in Flexible Energy Storage

2.1. Conductive Polymers

Recently, conductive polymers, owing to their high degree of flexibility and electrical conductivity, have been found extensively employed in flexible energy storage systems. Polymers have the

property to spontaneously alter conformations in their polymer chains through internal rotations among single bonds. Therefore, conductive polymers demonstrate efficient flexibility for use in flexible energy devices compared to non-polymer-based materials. Also, diverse conducting polymers, including Poly(3,4-ethylenedioxythiophene) (PEDOT) with conductivity of 0.4–400 S/cm and Polyaniline (PANI) with conductivity of 30–200 S/cm have been developed and widely employed.

Conductive PEDOT: PSS shows promise for efficient energy storage systems. Its characteristics can be readily tailored by incorporating or doping appropriate nanofillers. With specific capacity, high electrical conductivity, and an uncomplicated process of fabrication, it serves as an appropriate electrode material for both supercapacitors and batteries. However, in supercapacitors, enhancing PEDOT: PSS's specific capacitance comes with a trade-off – an increase in capacitance compromises the cycling stability during charging and discharging, resulting in a reduced polymer lifespan [2].

Conductive PANI is extensively employed in electrochemical flexible energy storage systems because of its flexibility, high conductivity, cost-effectiveness, ease of synthesis, unique redox properties, and environmental friendliness. However, the pure form of PANI fails to meet the growing need for enhanced molecular structure stability and demonstrates subpar stability as a supercapacitor electrode. To address these limitations, integrating PANI with other active materials like metal compounds, carbon, or other conducting polymers proves effective in compensating for these drawbacks in supercapacitive electrodes. PANI typically functions as a conductive network and layer within diverse composite structures, yielding PANI-based composites characterized by distinctive structures that showcase enhanced electrochemical performance in supercapacitors and rechargeable batteries, because of the synergistic effects [3].

2.2. Flexible Carbon Nanomaterial Electrode

In nanotechnology applications for electrochemical energy storage, the selection of electrode materials is acknowledged as crucial. The properties of electrode materials greatly impact nearly all energy storage applications' performance. Carbon-based functional nanomaterials, in contrast to conventional energy resource materials, exhibit distinctive morphological, electrical, optical, and mechanical properties. These properties hold the potential to significantly enhance energy conversion efficiency in storage systems.

Graphene and its derivatives, known for their high mechanical flexibility, excellent electrical conductivity, and lightweight nature, are well-suited for flexible electrode materials in various energy storage devices. Ideal flexible battery electrodes require both flexibility to withstand deformations and good electrical conductivity for efficient electrochemical performance. Graphene-based electrodes, including reduced graphene oxide and graphene oxide, meet the criteria, providing outstanding mechanical stability and contributing to effective charge and discharge processes. Constructing graphene-based electrodes without additional components results in advantages such as reduced weight, cost, and improved energy density compared to traditional electrodes. Overall, graphene-based flexible electrodes offer significant benefits, particularly when fabricated without extra components or external heavy metal current collectors [4].

Carbon nanotubes (CNTs), a representative nanocarbon material possessing nanoscaled diameter, can be categorized into single-walled nanotubes (SWCNTs) and multi-walled nanotubes (MWCNTs). The distinctive one-dimensional (1D) nanostructure imparts exceptional physical properties to individual CNTs, including high charge mobility and excellent thermal conductivity. Because of this unique cylindrical shape, individual CNTs are arranged into CNT architectures of various dimensions, encompassing 1D fibers, 2D films, and 3D foams, each exhibiting desirable electrochemical and mechanical characteristics. Moreover, these macroscopic CNTs are manageable and applicable in diverse conditions, rendering them excellent electrode materials for flexible energy storage systems [5].

2.3. Flexible Metal Foil Substrate

In flexible energy storage systems, particularly supercapacitors (SCs), substrates play a crucial role. These substrates are assessed based on parameters like mechanical wettability, flexibility, heat resistance, thinness, cost, and, in some applications, transparency. Metal foils are also frequently employed as flexible substrates for SCs. Nickel (Ni), copper (Cu), aluminum (Al), and gold (Au) are commonly chosen metal foils because of their reasonably good mechanical ductility and elevated electrical conductivity, making them popular choices for SC substrates. Additionally, metal foils can serve dual purposes by acting as current collectors, leveraging their high conductivity.

Metal foils offer advantages in terms of potential stability, compatibility with various active materials, and large-scale Fabrication Potential, allowing them to become a practical choice for flexible electrode substrates in energy storage systems. The stability of the potential of the metal foil is crucial. During charge and discharge processes, metal foils should not undergo chemical or electrochemical reactions that could compromise their structural integrity. This stability helps to improve the performance and durability of flexible energy devices. Also, metal foils, such as Ti, Cu, or stainless steel, serve as substrates for flexible electrode materials by allowing the casting of active materials onto them. This compatibility is essential for constructing efficient and functional flexible energy storage devices. Additionally, metal foils are suitable for fabrication on a large scale using industrial manufacturing techniques like electro-deposition, roll-to-roll processing, and spray coating. This characteristic enhances the scalability and feasibility of producing flexible electrodes for widespread applications [6].

3. Types and Mechanisms of Flexible Energy Storage System

3.1. Flexible Batteries

The exploration of flexible batteries has gained attention due to their potential to enhance the flexibility, adaptability, and comfort of electronic products. These versatile characteristics drive advancements in wearable electronics, implantable medical robots, and the Internet of Things (IoT). Most high-performing rigid and brittle batteries are not directly suitable for flexible devices exposed to challenging operating conditions, including stretching, flexing, twisting, folding, and bending. Consequently, there is a need for flexibility-focused material and system designs, prompting the exploration of soft features in carbon, metal, and polymer materials, along with innovative manufacturing methods for complete cell fabrication.

The lithium-ion battery (LIB) is recognized for its prolonged cycle life, cost-effectiveness, and high energy density, making it a promising solution for energy storage and conversion. Recent advancements involve the creation of flexible LIBs (FLIBs) tailored for portable and wearable electronic devices, necessitating foldable, lightweight, stretchable, and implantable features. FLIBs necessitate the preservation of superior mechanical and electrochemical characteristics throughout repeated mechanical deformations. Achieving FLIBs typically involves ensuring flexibility across all battery components, with particular emphasis on electrodes. Polymers can be introduced into the electrode due to its high degree of flexibility. For instance, certain flexible polymers are suitable for use as active materials for FLIBs, because they experience redox reactions with lithium ions in a reversible manner. Wei et al. developed sulfur-linked carbonyl-based poly (2,5-dihydroxyl-1,4-benzoquinonyl sulfide) (PDHBQS) compounds shown in Figure 1. The resulting cathode exhibited a discharge capacity of 182 mAhg^{-1} at $50 \text{ mA} \cdot \text{g}^{-1}$ within a potential in the range of 1.5 V to 3.5 V. Furthermore, it demonstrated a capacity of 75 mAhg^{-1} under $5000 \text{ mA} \cdot \text{g}^{-1}$. Moreover, flexible batteries utilizing lithium foil anode and the PDHBQS-SWCNTs cathode demonstrated robust electrochemical performance even under constant bending [7].

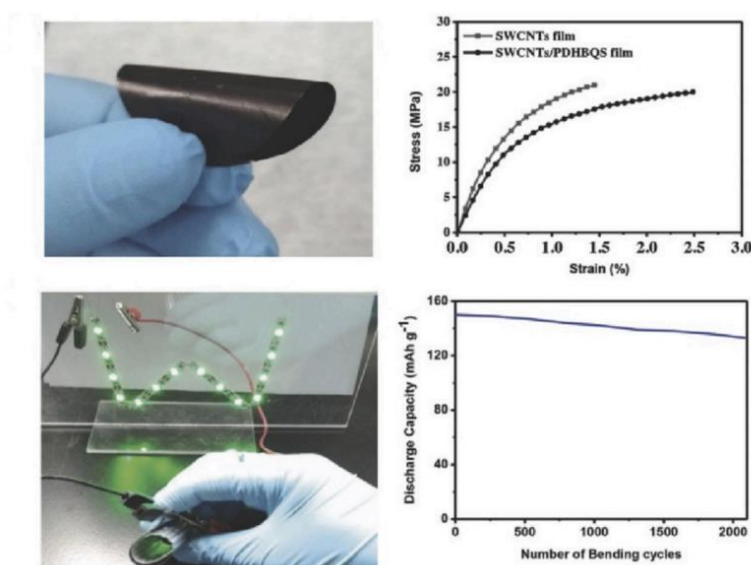


Fig. 1 Image of a PDHBQS/SWCNTs film alongside its stress-strain curve, a visual representation capturing a rolling battery, along with discharge capacities recorded over 2000 bending cycles [7].

Printed batteries are becoming popular due to their customization, lightweight design, and potential eco-friendliness. They find applications in sensors, medical and wearable devices, and smart cards. For a battery to be considered printed, at least one element (electrodes, current collectors, or electrolyte/separator) has to be manufactured using printing technologies. For printed batteries, inks are typically formulated for separators/electrolytes and electrodes, while the distinct current collectors are often not produced through printing. These inks consist of a solvent, a polymer binder, and appropriate fillers tailored for specific functional characteristics. However, a key challenge in developing printed batteries lies in creating functional inks for different components. Unlike traditional batteries, printed batteries offer advantages like precise electrode tuning, intricate architectures, easy device integration, and extensive impregnability of materials. Formulating functional inks requires customization for specific printing techniques to achieve high energy density and crack-free mechanical flexibility. Properties like surface tension of the ink and viscosity significantly impact the printing process and determine successful patterns [8].

3.2. Flexible Supercapacitors

Supercapacitors have attracted research interest owing to their enhanced cyclic stability and rapid charge-storage capability, and are considered as a promising substitute for traditional energy storage systems. Recent literature reports aim to boost supercapacitor energy density to levels comparable to lithium batteries (100–150 Wh/kg vs. 120–170 Wh/kg). The performance of supercapacitors depends on factors like electrode material electrochemical behavior, electrolyte choice, and electrode potential window. Considerable amount of research work has been invested in the evolution of advanced electrode materials designed for flexible supercapacitors, aiming to facilitate efficient ionic diffusion and electron transport [9].

Polymer supercapacitors possess unique characteristics like viscoelasticity, toughness, and glass transition point. Modifying polymer chains, either through altering functional groups or combing with various materials, enables the creation of new composites or polymers with specific functions such as improved self-healing, electrical conductivity, and mechanical properties. It is important to develop specific polymer materials for constructing flexible supercapacitors with specific functions. However, many conducting polymers exist in powder form, they often lack the ability to stand freely or possess sufficient robustness for subsequent processing. Challenges facing conducting polymers in supercapacitors include stability and composite fabrication. Anticipated improvements encompass

enhancing stability and creating well-defined interfaces in composites to achieve superior supercapacitor performance [10].

Carbon nanomaterials, comprising CNTs, graphene, and their derivatives, are extensively researched for flexible supercapacitors owing to their exceptional physicochemical properties. Their customizable structure allows the formation of materials in various forms, comprising 1D fibers, 2D films, and 3D structures, demonstrating impressive mechanical strength and flexibility. These characteristics make carbon nanomaterials well-suited for various flexible supercapacitor configurations, such as fibers, films, micro-supercapacitors, stretchable devices, and arbitrarily shaped capacitors. These resulting supercapacitors show promise for integration into electronic devices to supply energy. Nevertheless, current carbon nanomaterials face challenges related to limited capacitance and energy density, necessitating further optimization of their structure and exploration of new energy storage mechanisms. Understanding the intricate relationships between specific surface area, pore structure, energy density, and the specific capacitance of carbon nanomaterials requires further in-depth research. Additionally, the large-scale production of uniform macroscopic carbon nanomaterials with controlled morphology is still a challenge, requiring innovative methods and equipment for continuous, stable, and efficient manufacturing [11].

3.3. Flexible Piezoelectric Devices

Piezoelectric energy harvesting, known for efficiently converting mechanical energy into electricity, outperforms alternatives such as triboelectric and electromagnetic methods. This superiority stems from the stability in humid or changing environments and the high electromechanical coefficient. To overcome piezoceramics' brittleness and cater to flexible electronics, there's a growing focus on researching Flexible Piezoelectric Energy Harvesters (FPEHs). This involves exploring materials like ceramic oxides, polymers, and biomaterials, along with diverse device designs to enhance performance and adaptability for various applications. The development of self-powered sensors using FPEHs for wireless data transmission, environmental remediation, and biomedical sensing adds significant appeal to this research area.

Piezoelectric materials, known for their suitability in wearable electronics, stand out for their flexibility, lightweight, high-voltage electrical properties, and biocompatibility. In the realm of flexible electronic sensors, inorganic semiconductors like ZnO and ZnS show promise due to their exceptional piezoelectric properties. RMIT's research group has introduced a printable and highly efficient piezoelectric material using liquid metal printing, which is extremely thinner than a single hair. This material demonstrates an 800% improvement in efficiency compared to other non-toxic piezoelectric materials, making it valuable for industrial applications. Piezoelectric biomaterials, known for their biocompatibility and porous structure, find applications in energy storage and harvesting. Yuan et al. discuss biomaterials' design and application, focusing on polypeptide bio-piezoelectric materials. The M13 phage, with its robust piezoelectric response, is highlighted for its functional versatility and hierarchical structure in viral piezoelectric devices [12].

Because of their scalability, piezoelectric materials are extensively employed in energy harvesting. Various processing methods, including additive manufacturing, printed electronics, and near-field electrospinning, have been employed for piezoelectric material preparation. Printed electronics, known for excellent stretchability, large-scale production on flexible substrates, minimal environmental impact, and low cost, outperforms traditional photolithography [13]. Near-field electrospinning offers precise fiber deposition control, adjustable diameters from tens of nanometers to micrometers, and unique properties suitable for micro-nanotechnology and biomedicine applications [14].

4. Challenges and Future Perspectives

Energy storage systems possess a dual aspect, as their environmental effects can be both beneficial and detrimental. The environmental impact includes both positive contributions to decarbonization

and potential negative effects on emissions and material disposal. Efficient storage systems and strategic deployment are crucial for minimizing environmental harm and realizing the full potential of electrical energy storage in reducing greenhouse gas emissions [15].

Despite the progress made, several challenges remain in flexible energy storage systems. One of the primary challenges is achieving a balance between flexibility and electrochemical performance, particularly in the design of flexible batteries and supercapacitors. While flexible materials enable energy storage systems to be integrated into wearable electronics and other flexible devices, maintaining high energy density and cycle stability under mechanical deformation poses significant engineering hurdles. Furthermore, the scalability and cost-effectiveness of flexible energy storage technologies are critical factors for widespread adoption. Manufacturing techniques must be optimized to enable large-scale production of flexible electrodes and substrates while minimizing production costs. Additionally, ensuring the environmental sustainability of materials and manufacturing processes is essential to align with the goals of eco-friendly energy solutions.

The future trajectory of flexible energy storage systems involves achieving concurrent high flexibility, efficiency, stability, and safety. Moreover, these devices are anticipated to seamlessly integrate with diverse application technologies, driven by ongoing innovations in both application needs and manufacturing methods.

5. Conclusion

The pursuit of flexible energy storage systems is a response to depleting fossil fuels and environmental concerns in the electronics industry. Advanced materials like conductive polymers, flexible carbon nanomaterial electrodes, and metal foil substrates are pivotal in shaping these technologies. Conductive polymers, exemplified by PEDOT:PSS and PANI, offer high conductivity and flexibility but face challenges in cycling stability and specific capacitance. Flexible carbon nanomaterial electrodes, including graphene and carbon nanotubes, show promise for lightweight, cost-effective energy storage. Metal foil substrates, crucial for supercapacitors, provide mechanical flexibility and large-scale fabrication feasibility. Exploring flexible batteries, supercapacitors, and piezoelectric devices reveals diverse applications and challenges. Lithium-ion batteries are promising for portable devices, but challenges include novel electrode materials. Supercapacitors show potential for high cyclic stability but need advancements in energy density. Piezoelectric devices offer energy harvesting for various applications. Balancing the dual environmental impact of energy storage systems is crucial. Efficient storage systems and strategic deployment are necessary for realizing their potential in reducing greenhouse gas emissions. The future entails achieving high flexibility, efficiency, and integration with evolving technologies, marking a pivotal role for flexible energy storage in a sustainable electronic landscape.

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