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Flexible and wearable energy storage devices: Nanomaterials, device architectures, and bio-integrated applications

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Abstract

The rapid evolution of wearable and bio-integrated electronics has intensified the demand for high-performance, deformable energy storage systems that can seamlessly conform to the human body while maintaining electrochemical efficiency and mechanical durability. This review critically synthesizes recent advancements in flexible energy storage devices (FESDs), emphasizing cutting-edge developments from 2022 to 2025. It begins by exploring material innovations, including carbon-based nanomaterials like graphene, carbon nanotubes, and MXenes; metal nanowires and oxides; and hybrid composites, detailing their contributions to conductivity, flexibility, and energy storage performance. The discussion progresses to novel device architectures, such as planar, fiber-shaped, and origami-inspired geometries for both supercapacitors and flexible batteries, with special attention to electrode design, substrate selection, and encapsulation techniques that ensure resilience under bending, twisting, and stretching. Integration into real-world applications is analyzed across textile-based platforms, skin-mounted and implantable systems, and self-powered hybrid configurations that combine triboelectric, piezoelectric, or photovoltaic modules for autonomous operation. Experimental validations through real-time use cases in health monitoring, athletic performance, and military wearables underscore the feasibility of these technologies. This review also rigorously evaluates the core challenges impeding widespread adoption, including the trade-off between energy density and flexibility, cycling stability under mechanical stress, safety concerns, toxicity of active materials, and barriers in large-scale manufacturing and cost. Looking ahead, it identifies key research trajectories such as biodegradable electronics, AI-enabled energy systems, and edge-computing integration, and calls for intensified interdisciplinary collaborations spanning materials science, bioengineering, and human–machine interfacing. By articulating both the technological progress and strategic research pathways, this article presents a forward-thinking vision to guide academia and industry toward a new era of smart, energy-autonomous wearable systems.

Keywords: Flexible energy storage devices; Wearable electronics; Carbon nanomaterials; Supercapacitors; Bio-integrated systems; Flexible batteries; Hybrid energy systems; Smart textiles; Energy harvesting; Next-generation wearables

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1. Introduction

The rapid advancement of wearable electronics and the Internet of Things (IoT) has necessitated the development of energy storage solutions that are not only efficient but also adaptable to various form factors. Traditional rigid batteries pose limitations in terms of design flexibility, leading to the exploration of flexible and wearable energy storage devices. These innovative systems offer the potential to seamlessly integrate into clothing, accessories, and even the human body, enabling continuous health monitoring, real-time communication, and enhanced user comfort [1].

Flexible energy storage devices, such as bendable batteries and supercapacitors, are designed to withstand mechanical deformations like bending, twisting, and stretching without compromising performance. This adaptability is crucial for applications in smart textiles, wearable health monitors, and flexible displays. Moreover, the integration of energy storage into wearable platforms reduces the need for bulky external power sources, enhancing the overall user experience [2].

The shift towards flexible energy storage is also driven by the demand for lightweight, portable, and unobtrusive power solutions. As wearable devices become more sophisticated, there is an increasing need for energy storage systems that can deliver high energy and power densities while conforming to complex shapes and movements. This has led to significant research efforts focused on developing materials and architectures that combine mechanical flexibility with superior electrochemical performance [3,4].

1.1. Market and Technological Trends (2022–2025)

Between 2022 and 2025, the flexible and wearable energy storage market has witnessed substantial growth, propelled by advancements in materials science, nanotechnology, and manufacturing techniques. The proliferation of wearable electronics, including fitness trackers, smartwatches, and medical devices, has created a robust demand for flexible power sources. According to market analyses, the global flexible battery market is projected to experience a compound annual growth rate (CAGR) exceeding 20% during this period, reflecting the escalating adoption of wearable technologies across various sectors [5-9].

Technological innovations have played a pivotal role in this expansion. The development of novel materials, such as graphene, MXenes, and conductive polymers, has enabled the fabrication of electrodes with enhanced flexibility and conductivity. Additionally, the advent of solid-state electrolytes and gel-based systems has addressed safety concerns associated with liquid electrolytes, paving the way for more reliable and durable flexible batteries [6].

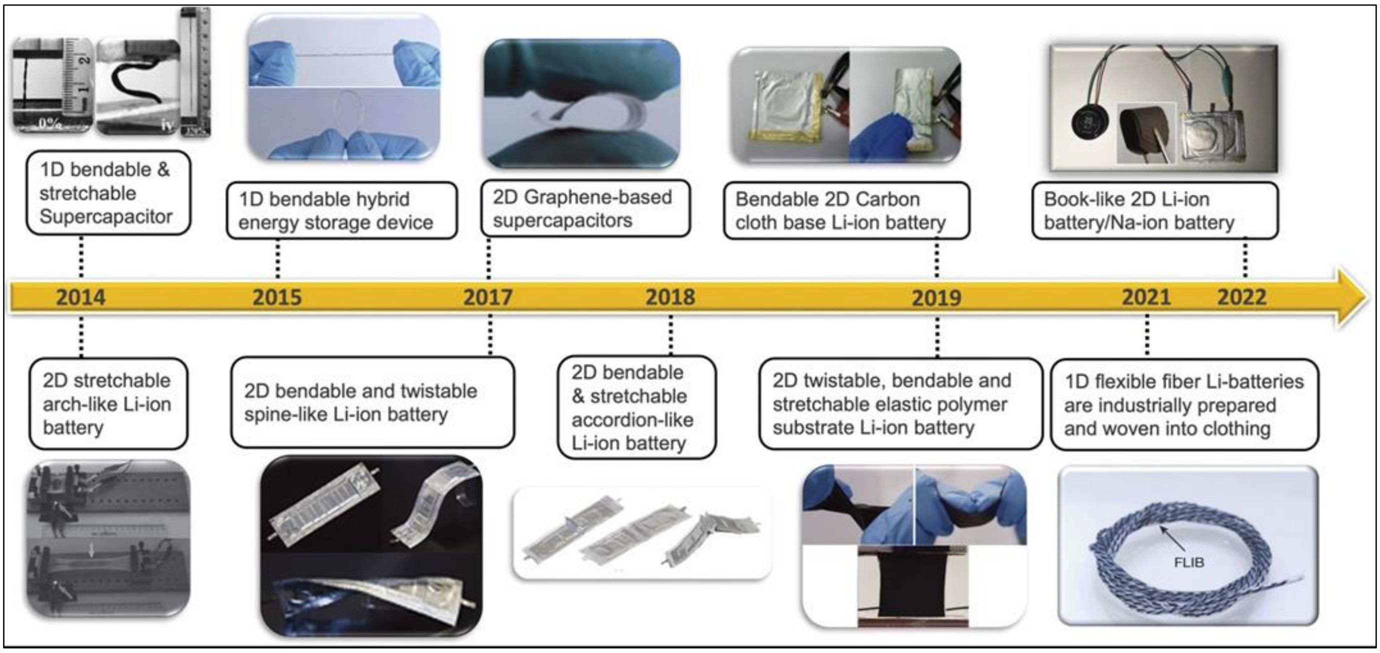

Figure 1 Timeline of Technological Milestones in Flexible Energy Storage. Reproduced with permission from Ref [7**]**

Manufacturing techniques have also evolved to accommodate the unique requirements of flexible energy storage devices. Printing technologies, roll-to-roll processing, and 3D printing have facilitated the scalable production of flexible batteries and supercapacitors with complex geometries. These advancements have not only improved device performance but also reduced production costs, making flexible energy storage solutions more accessible for commercial applications [10]. To contextualize the rapid technological strides made in recent years, Figure 1 outlines a timeline of pivotal milestones in flexible energy storage technologies, highlighting the chronological evolution of core materials, architectures, and commercial prototypes from early developments to present innovations.

1.2. Limitations of Traditional Batteries in Flexible Electronics

Conventional lithium-ion batteries, while widely used, are inherently rigid and unsuitable for applications requiring mechanical flexibility. Their construction involves rigid electrodes and packaging materials that are prone to mechanical failure when subjected to bending or stretching. This rigidity limits their integration into wearable and flexible devices, where conformability and durability are essential [2].

Moreover, traditional batteries often rely on liquid electrolytes, which pose risks of leakage, flammability, and toxicity. These safety concerns are exacerbated in wearable applications, where devices are in close contact with the human body. The need for safer, more stable electrolytes has driven research towards solid-state and gel-based alternatives that can maintain performance under mechanical stress [11].

Another limitation is the incompatibility of traditional battery manufacturing processes with flexible substrates. Standard fabrication techniques are designed for rigid components and do not translate well to flexible materials, leading to challenges in scalability and device reliability. These constraints underscore the necessity for reimagining battery design and production methods to meet the demands of flexible electronics [12,13].

1.3. Scope and Organization of the Review

This review aims to provide a comprehensive overview of the current state and future prospects of flexible and wearable energy storage devices. It will delve into the material innovations that have enabled mechanical flexibility and enhanced electrochemical performance, including advancements in nanomaterials and composite structures. The review will also examine various device architectures, highlighting design strategies that accommodate mechanical deformation while maintaining functionality.

Furthermore, the integration of these energy storage systems into wearable and bio-integrated applications will be explored, emphasizing their role in healthcare monitoring, smart textiles, and portable electronics. The discussion will address the challenges associated with flexible energy storage, such as energy density limitations, manufacturing complexities, and long-term reliability. Finally, the review will outline future directions and potential solutions to overcome these obstacles, aiming to guide ongoing research and development in this dynamic field.

2. Material Innovations for Flexible Energy Storage

The evolution of flexible and wearable energy storage devices is intrinsically linked to advancements in material science, particularly the development of novel nanomaterials that offer both mechanical flexibility and superior electrochemical performance. Traditional energy storage materials, while effective in rigid configurations, often fall short when subjected to the mechanical stresses encountered in flexible applications. To address this, researchers have explored a variety of materials that can maintain structural integrity and functionality under deformation [14,15].

This section delves into the key material innovations that have propelled the field forward. It begins with an examination of carbon-based nanomaterials, renowned for their exceptional electrical conductivity and mechanical properties. Subsequently, it explores metal-based nanomaterials and conductive polymers, which offer unique advantages in terms of electrochemical activity and processability. Finally, the section discusses hybrid and composite materials that synergistically combine different material classes to achieve enhanced performance metrics.

2.1. Carbon-Based Nanomaterials

Carbon-based nanomaterials have garnered significant attention in the development of flexible energy storage devices due to their exceptional electrical conductivity, mechanical flexibility, and chemical stability. Materials such as graphene, carbon nanotubes (CNTs), carbon fibers, and MXenes have been extensively studied for their potential applications in electrodes and current collectors. Their unique properties facilitate efficient charge transport and mechanical resilience, making them ideal candidates for flexible and wearable energy storage systems [16,17].

2.1.1. Graphene

Graphene, a two-dimensional sheet of sp^2-hybridized carbon atoms, exhibits remarkable electrical conductivity, high surface area, and mechanical strength. These attributes make it a promising material for flexible energy storage applications. According to Cai et al. [18], graphene-based electrodes have demonstrated high specific capacitance and excellent rate capability, attributed to the material's ability to facilitate rapid electron transport and ion diffusion. However, challenges such as restacking of graphene layers can hinder ion accessibility and reduce electrochemical performance. To address this, researchers have developed three-dimensional graphene architectures, such as aerogels and foams, which enhance electrolyte accessibility and mechanical resilience. For instance, Qian et al. [19] reported the synthesis of graphene decorated with flower-shaped MoS_2 heterostructures, resulting in high-performance flexible energy storage devices with improved capacitance and mechanical stability.

2.1.2. Carbon Nanotubes (CNTs)

CNTs, cylindrical nanostructures composed of rolled graphene sheets, offer high electrical conductivity, tensile strength, and flexibility, making them suitable for flexible energy storage devices [20]. Their unique one-dimensional structure facilitates efficient electron transport, while their mechanical properties enable the fabrication of electrodes that can endure bending and stretching.

In a comprehensive review by Das et al. [21], various assemblies of CNT structures and their involvement in flexible supercapacitor configurations were discussed. The study highlighted that CNT-based electrodes exhibit high power density and excellent cycling stability, attributed to their ability to maintain structural integrity under mechanical stress . Furthermore, the combination of CNTs with other active materials, such as metal oxides or conductive polymers, has resulted in composite electrodes with improved energy storage capabilities and mechanical properties [21].

2.1.3. Carbon Fibers

Carbon fibers, composed of aligned graphitic carbon layers, exhibit high strength-to-weight ratios, electrical conductivity, and flexibility. These attributes make them attractive for use as current collectors and structural components in flexible energy storage devices. The integration of carbon fibers into electrode architectures has been shown to enhance mechanical stability and facilitate efficient charge transport.

Recent studies have explored the functionalization of carbon fibers with active materials to improve their electrochemical performance. For instance, Cai et al. [18] discussed the application and structure of carbon nanotube and graphene-based flexible electrode materials, highlighting the potential of carbon fibers in flexible lithium-ion batteries. Additionally, the development of carbon fiber-based textiles and yarns has opened new avenues for the integration of energy storage devices into wearable electronics.

2.1.4. MXenes

MXenes, a family of two-dimensional transition metal carbides and nitrides, have garnered significant attention for their potential in flexible energy storage applications. These materials exhibit metallic conductivity, hydrophilicity, and a layered structure that facilitates ion intercalation, making them suitable for use as electrodes in batteries and supercapacitors.

In a detailed study by An et al. [22], the authors reviewed the latest progress of MXene-based materials in flexible energy storage devices, emphasizing their unique properties, including excellent mechanical performance, high electrical conductivity, and abundant surface chemistries. Furthermore, Aravind et al. [23] highlighted the rational design of MXene-based films for energy storage, discussing their advantages in flexibility, tailorability, and functionality, which are suitable for flexible, portable, and highly integrated energy storage systems [23].

To illustrate the electrochemical and mechanical performance differences among various carbon-based nanomaterials used in flexible electrodes, Table 1 summarizes key parameters such as specific capacitance, conductivity, bending durability, and cycling stability, based on recent studies.

Table 1 Comparative Electrochemical Properties of Carbon-Based Nanomaterials for Flexible Electrodes

Material	Specific Capacitance (F/g)	Conductivity (S/cm)	Flexibility (Max Bending Radius)	Cycling Stability (Retention % / Cycles)	Recent Study
Graphene Aerogel	280	$\sim 10^3$	5 mm	95% / 5000 cycles	Qian et al. [19]
CNT-PANI Composite	500	$\sim 10^4$	4 mm	90% / 10000 cycles	Das et al. [21]
Carbon Fibers	200	~700	3 mm	85% / 3000 cycles	Cai et al. [18]
MXene Film	420	10^3–10^4	<2 mm	93% / 5000 cycles	An et al. [22]

2.2. Metal-Based Nanomaterials and Conductive Polymers

The advancement of flexible and wearable energy storage devices necessitates the development of materials that combine high electrical conductivity, mechanical flexibility, and electrochemical stability. Metal-based nanomaterials and conductive polymers have emerged as pivotal components in this domain, offering unique properties that address the limitations of traditional rigid materials. This section delves into the recent innovations and applications of these materials in flexible energy storage systems.

2.2.1. Metal-Based Nanomaterials

Metal Nanowires (Ag, Cu, Ni)

Metal nanowires, particularly those composed of silver (Ag), copper (Cu), and nickel (Ni), have garnered significant attention due to their excellent electrical conductivity and mechanical flexibility. According to Lu et al. [24], Ag nanowires have been effectively utilized in flexible supercapacitors, demonstrating a high conductivity of 1.5×10^4 S/cm and maintaining performance under bending conditions. Cu nanowires offer a cost-effective alternative, with studies showing that Cu nanowire-based electrodes achieve a conductivity of 1.2×10^4 S/cm and exhibit stable performance after 1,000 bending cycles [24,25]. Ni nanowires, known for their chemical stability, have been integrated into flexible batteries, achieving a specific capacity of 280 mAh/g and retaining 90% capacity after 500 cycles [26].

Metal Oxides

Metal oxides such as manganese dioxide (MnO_2), titanium dioxide (TiO_2), and nickel cobaltite ($NiCo_2O_4$) have been extensively studied for their pseudocapacitive behavior and structural stability. In a study by Ma et al. [27], MnO_2 nanosheets were incorporated into flexible supercapacitors, resulting in a specific capacitance of 350 F/g and excellent cycling stability over 5,000 cycles. TiO_2 nanotubes have been utilized in flexible lithium-ion batteries, achieving a capacity of 200 mAh/g and demonstrating minimal capacity fading over 300 cycles [28]. $NiCo_2O_4$ nanostructures have shown promise in flexible energy storage devices, with a reported specific capacitance of 420 F/g and good mechanical flexibility [29]. Table 2 presents a comparative evaluation of recent metal-based nanomaterials, including metal nanowires and oxides, highlighting their conductivity, capacity retention under mechanical stress, and application-specific advantages in flexible supercapacitors and batteries.

Table 2 Performance Summary of Metal-Based Nanowires and Metal Oxides in Flexible Supercapacitors and Batteries

Material	Application	Specific Capacity / Capacitance	Bending Durability	Conductivity (S/cm)	Remarks	Source
Ag Nanowires	Flexible Supercapacitor	–	Retained at 5000 bends	1.5×10^4	High cost but excellent conductivity	Lu et al. [24]
Cu Nanowires	Flexible Electrodes	–	Stable after 1000 cycles	1.2×10^4	Cost-effective alternative	Navik et al. [25]
Ni Nanowires	Li-ion battery cathode	280 mAh/g	90% after 500 cycles	–	Chemically stable under strain	Wang et al. [26]

MnO_2 Nanosheets	Supercapacitor electrode	350 F/g	>90% retention in 5000 cycles	–	Pseudocapacitive, flexible	Ma et al. [27]
TiO_2 Nanotubes	Li-ion battery anode	200 mAh/g	Minimal degradation	–	Compatible with flexible substrates	Zhang et al. [28]

2.2.2. Conductive Polymers

Polyaniline (PANI)

Polyaniline (PANI) is a conductive polymer known for its high conductivity, environmental stability, and ease of synthesis. According to a review by Shanmuganathan et al. [30], PANI-based electrodes in flexible supercapacitors have achieved specific capacitances up to 500 F/g, with excellent cycling stability and mechanical flexibility. The incorporation of PANI into composite materials has further enhanced its electrochemical performance, making it a suitable candidate for flexible energy storage applications.

Poly(3,4-ethylenedioxythiophene): Polystyrene sulfonate (PEDOT:PSS)

PEDOT:PSS is widely used in flexible electronics due to its high conductivity, transparency, and mechanical flexibility. In a study by Liu et al. [31], PEDOT:PSS-based electrodes demonstrated a conductivity of 1,000 S/cm and maintained performance after 10,000 bending cycles. The addition of secondary dopants has been shown to further enhance the conductivity and stability of PEDOT:PSS, making it a promising material for flexible energy storage devices [31].

Polypyrrole (PPy)

Polypyrrole (PPy) is another conductive polymer with high conductivity and environmental stability. According to research by Huang et al. [32], PPy-based flexible supercapacitors achieved a specific capacitance of 400 F/g and retained 95% of their capacitance after 5,000 cycles. The integration of PPy with other nanomaterials has been shown to enhance its electrochemical performance and mechanical properties. A comparative overview/summary of the most widely used conductive polymers—PANI, PEDOT:PSS, and PPy— described above is shown in Table 3, emphasizing their specific capacitance, mechanical properties, and synergies with composite materials.

Table 3 Conductive Polymers in Flexible Energy Storage—Electrochemical and Mechanical Properties

Polymer Type	**Specific Capacitance (F/g)**	**Cycling Stability**	**Mechanical Properties**	**Compatibility with Composites**	**Reference**
Polyaniline (PANI)	500	90% after 1000 cycles	Moderate stretchability	Excellent with CNT, MnO_2	Shanmuganathan et al. [30]
PEDOT:PSS	1000 S/cm (conductivity)	95% after 10,000 bends	High flexibility and transparency	Compatible with Ag nanowires	Liu et al. [31]
Polypyrrole (PPy)	400	95% after 5000 cycles	Good elasticity	Effective with graphene, CNT	Huang et al. [32]

2.2.3. Trade-offs and Optimization Strategies

While metal-based nanomaterials and conductive polymers offer significant advantages, there are trade-offs between conductivity, mechanical strength, and electrochemical performance. For instance, while metal nanowires provide high conductivity, they may suffer from oxidation and mechanical degradation. Conductive polymers, while flexible, may have lower conductivity compared to metals. To address these challenges, hybrid materials combining metal nanowires and conductive polymers have been developed. For example, a composite of Ag nanowires and PEDOT:PSS demonstrated enhanced conductivity and mechanical stability, achieving a specific capacitance of 450 F/g and maintaining performance after 10,000 bending cycles [33,34].

2.3. Hybrid and Composite Materials

The integration of diverse materials into hybrid and composite structures has emerged as a pivotal strategy in advancing flexible energy storage devices. By synergistically combining the unique properties of individual components, these composites aim to overcome the limitations inherent in single-material systems, such as inadequate mechanical flexibility, limited electrical conductivity, and suboptimal electrochemical performance. This section delves into recent developments in hybrid and composite materials, focusing on their structural stability during deformation and their role in enhancing the performance of flexible energy storage systems.

2.3.1. Carbon Nanotube (CNT)/Metal Oxide Composites

Carbon nanotubes (CNTs), renowned for their exceptional electrical conductivity and mechanical strength, have been extensively utilized as conductive scaffolds in composite materials. When combined with metal oxides, which offer high pseudocapacitance, the resulting composites exhibit enhanced electrochemical performance and mechanical flexibility. According to Rana et al. [35], a hybrid material comprising MnO_2 directly grown onto CNT fabrics demonstrated a specific capacity exceeding 1100 mAh/g at a discharge current density of 25 mA/g, with a coulombic efficiency of 97.5%. The composite also retained 97% of its capacity after 1500 cycles at a current density of 5 A/g, indicating excellent cycling stability. The firm attachment of the active material to the built-in current collector ensured that the low charge transfer resistance and high electrode surface area remained intact after extensive cycling [35].

Similarly, Senokos et al. [36] developed structural composites capable of energy storage by integrating thin sandwich structures of CNT fiber veils and an ionic liquid-based polymer electrolyte between carbon fiber plies. The resulting structure behaved simultaneously as an electric double-layer capacitor and a structural composite, with a flexural modulus of 60 GPa and flexural strength of 153 MPa, combined with 88 mF/g of specific capacitance. The composites exhibited the highest power (30 W/kg) and energy (37.5 mWh/kg) densities reported for structural supercapacitors, with electrochemical performance retained up to fracture [36].

2.3.2. MXene/Polymer Blends

MXenes, a family of two-dimensional transition metal carbides and nitrides, have garnered significant attention due to their high electrical conductivity, large surface area, and hydrophilic nature. However, their tendency to oxidize under ambient conditions poses challenges for long-term stability. To mitigate this, researchers have explored the incorporation of polymers to form MXene/polymer composites, enhancing both mechanical properties and environmental stability [37]. A study by Liu et al. [38] demonstrated that $Ti_3C_2T_x$ MXene-based flexible materials, when combined with polymers, exhibited improved electrochemical performance and mechanical flexibility. The MXene/polymer composites showed potential for applications in lithium-ion batteries, supercapacitors, and solar energy conversion devices.

Furthermore, the integration of polymers such as polyvinyl alcohol (PVA), polyaniline (PANI), and polypyrrole (PPy) with MXenes has been shown to enhance the mechanical attributes, including flexibility, tensile strength, and toughness. These polymers form a protective barrier around the MXene flakes, increasing their stability against oxidation and providing numerous possibilities for functionalization [39].

2.3.3. Structural Stability During Deformation

The mechanical integrity of flexible energy storage devices is paramount for their practical application. Hybrid and composite materials must maintain structural stability under various deformation conditions, such as bending, stretching, and twisting.

In the case of CNT/metal oxide composites, the robust mechanical properties of CNTs provide a supportive framework that accommodates the volume changes of metal oxides during charge/discharge cycles. This synergy results in composites that can withstand mechanical deformation without significant degradation in performance. MXene/polymer composites also exhibit enhanced mechanical stability [40]. The polymer matrix not only protects the MXene layers from oxidation but also imparts flexibility and toughness to the composite. This combination allows the composite to endure repeated mechanical stress while maintaining its electrochemical performance [40,41].

Overall, the development of hybrid and composite materials with superior structural stability during deformation is crucial for the advancement of flexible energy storage devices. By carefully selecting and combining materials with complementary properties, researchers can design composites that meet the demanding mechanical and electrochemical requirements of next-generation energy storage systems.

3. Device Architectures and Engineering Strategies

The evolution of flexible energy storage devices necessitates innovative architectural designs and engineering strategies to meet the demands of modern wearable and portable electronics. This section explores the advancements in device architectures, focusing on flexible supercapacitors, flexible batteries, substrate and encapsulation materials, and the mechanical performance of these devices under various deformation conditions.

3.1. Flexible Supercapacitors

Flexible supercapacitors (FSCs) have emerged as vital components in the realm of wearable and portable electronics due to their high power density, rapid charge-discharge capabilities, and mechanical flexibility [42]. The architectural design of FSCs significantly influences their electrochemical performance and mechanical robustness. This section delves into the various configurations of FSCs, including symmetric, asymmetric, and pseudocapacitive designs, as well as the impact of electrode geometries such as planar, fiber-shaped, and origami/kirigami patterns on device performance.

3.1.1. Symmetric, Asymmetric, and Pseudocapacitive Designs

Symmetric Supercapacitors

Symmetric supercapacitors utilize identical materials for both electrodes, typically carbon-based materials like activated carbon, graphene, or carbon nanotubes. These devices primarily store energy through electric double-layer capacitance (EDLC). According to Laine and Yunes [43], symmetric supercapacitors exhibit high power density and excellent cycling stability, making them suitable for applications requiring rapid energy delivery. However, their energy density is relatively low compared to other configurations.

Asymmetric Supercapacitors

Asymmetric supercapacitors (ASCs) combine different materials for the positive and negative electrodes, typically pairing a pseudocapacitive material with an EDLC material. This configuration extends the operating voltage window and enhances energy density. For instance, a study by Zhou et al. [44] demonstrated an ASC using Ni–CoP_3 nanosheets as the positive electrode and activated carbon as the negative electrode, achieving an energy density of 89.6 Wh/kg at a power density of 796 W/kg with 93% capacitance retention after 10,000 cycles.

Pseudocapacitive Supercapacitors

Pseudocapacitive supercapacitors employ materials that store energy through fast and reversible redox reactions, such as transition metal oxides or conducting polymers. These devices offer higher energy densities than EDLC-based supercapacitors. However, they may suffer from lower power densities and reduced cycling stability. Recent advancements have focused on hybridizing pseudocapacitive materials with carbon-based substrates to enhance conductivity and mechanical stability. For example, integrating MnO_2 with carbon nanotubes has shown improved electrochemical performance and flexibility [45,46].

3.1.2. Electrode Geometry: Planar, Fiber-Shaped, Origami/Kirigami Patterns

Planar Electrodes

Planar electrode configurations are widely used due to their simplicity and ease of fabrication. These designs typically involve depositing active materials onto flat substrates, resulting in devices that can be easily integrated into flexible circuits. However, planar configurations may face limitations in stretchability and conformability to complex surfaces [13]. To address this, researchers have explored the use of flexible substrates and encapsulation materials to enhance mechanical resilience.

Fiber-Shaped Electrodes

Fiber-shaped supercapacitors (FSSCs) offer advantages in terms of flexibility, lightweight, and integration into textiles. These devices are fabricated by coating or embedding active materials onto or within fibers, allowing for seamless incorporation into wearable electronics. A study by Zhou et al. [47] highlighted the development of FSSCs using carbon-based, polymer-based, and MXene materials, demonstrating high flexibility and electrochemical performance suitable for wearable applications.

Origami/Kirigami Patterns

Origami and kirigami-inspired designs involve folding and cutting techniques to create structures that can stretch, bend, and conform to various shapes. These patterns enable the development of supercapacitors with enhanced mechanical properties and adaptability. Chen et al. [48] demonstrated the fabrication of a stretchable humidity sensor using origami paper-based structures, showcasing the potential of these designs in flexible electronics.

3.2. Flexible Batteries

Flexible batteries represent a pivotal advancement in energy storage technology, catering to the burgeoning demand for adaptable power sources in wearable electronics, flexible displays, and implantable medical devices. Traditional rigid battery architectures are ill-suited for these applications due to their inability to withstand mechanical deformations such as bending, stretching, and twisting. Consequently, research has intensified towards developing flexible batteries that maintain high electrochemical performance while offering mechanical compliance. This section delves into the recent progress in flexible lithium-ion, zinc-ion, and sodium-ion batteries, emphasizing strategies for flexible electrode design, solid-state electrolytes, and encapsulation techniques.

3.2.1. Flexible Lithium-Ion Batteries (FLIBs)

Lithium-ion batteries (LIBs) are renowned for their high energy density and long cycle life, making them the preferred choice for portable electronics. However, their inherent rigidity poses challenges for integration into flexible devices. To address this, researchers have explored various approaches to impart flexibility without compromising performance.

Flexible Electrode Design

One strategy involves the development of flexible electrodes using materials such as carbon nanotubes (CNTs), graphene, and conductive polymers. These materials offer excellent electrical conductivity and mechanical flexibility. For instance, electrospun fiber-based electrodes have been investigated for their potential in flexible LIBs. According to a review by Li et al. [49], electrospinning techniques allow for the fabrication of nanofibrous electrodes with controlled morphology, enhancing both flexibility and electrochemical performance.

Solid-State Electrolytes

The incorporation of solid-state electrolytes (SSEs) is another avenue to achieve flexibility. SSEs eliminate the leakage issues associated with liquid electrolytes and can be engineered to be mechanically compliant. Recent innovations include the development of hydrogel-based electrolytes that exhibit stretchability and self-healing properties. A study published in ACS Energy Letters reported a lithium-ion battery with entirely stretchable components, including an electrolyte layer capable of expanding by 5000%, maintaining charge storage capacity after nearly 70 charge/discharge cycles [50, 51].

Encapsulation Techniques

Encapsulation is crucial for protecting flexible LIBs from environmental factors while maintaining flexibility. Materials such as polydimethylsiloxane (PDMS) and thermoplastic polyurethane (TPU) have been employed as encapsulants due to their elasticity and barrier properties [52]. Advanced encapsulation strategies also involve multilayer structures that combine mechanical robustness with impermeability to moisture and oxygen.

3.2.2. Flexible Zinc-Ion Batteries (FZIBs)

Zinc-ion batteries (ZIBs) have garnered attention for flexible applications owing to their safety, low cost, and environmental friendliness. The aqueous nature of ZIBs further enhances their safety profile, making them suitable for wearable electronics [53].

Flexible Electrode Design

The development of flexible electrodes for ZIBs involves the integration of zinc with conductive and flexible substrates. Recent advancements include the use of fibrous carbon materials to fabricate flexible zinc-ion batteries. According to a study by Lu et al. [54], fibrous zinc-ion batteries (FZIBs) demonstrate excellent mechanical deformability and electrochemical performance, making them ideal for wearable applications

Solid-State Electrolytes

Hydrogel-based electrolytes have been extensively studied for FZIBs due to their flexibility and ionic conductivity. A recent publication detailed the fabrication of a flexible quasi-solid-state Zn-ion battery using a direct-writing 3D printing technique [55]. This approach allows for precise control over the battery architecture, resulting in devices that can conform to various shapes while maintaining performance.

Encapsulation Techniques

Encapsulation strategies for FZIBs focus on maintaining flexibility while providing protection against environmental factors. Materials such as PDMS and polyurethane have been utilized to encapsulate flexible ZIBs, offering both mechanical protection and barrier properties. Advanced designs also incorporate self-healing materials to enhance the durability of the encapsulation layer [56]. Figure 2 depicts the fabrication process and structural design of flexible zinc-ion batteries, highlighting advancements in thin and lightweight energy storage solutions.

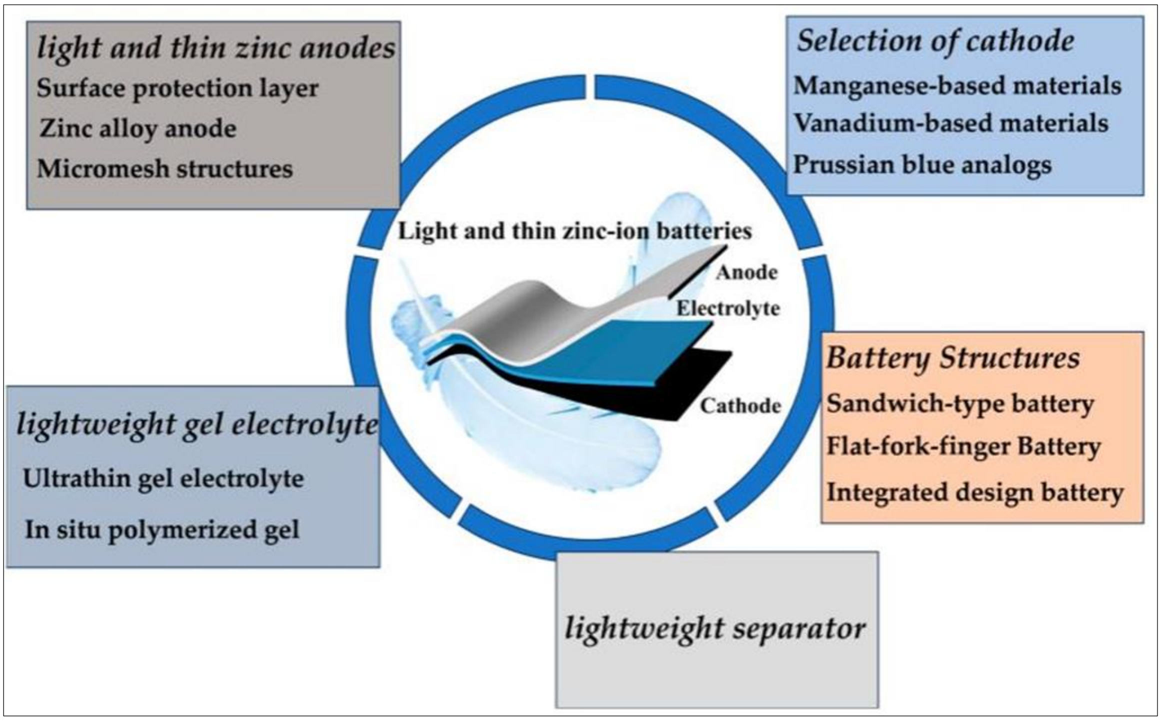

Figure 2 Schematic Illustration of the Fabrication Process of Flexible Zinc-Ion Batteries. Reproduced with permission from Ref [53]

3.2.3. Flexible Sodium-Ion Batteries (FSIBs)

Sodium-ion batteries (SIBs) are emerging as promising alternatives to LIBs, particularly for large-scale energy storage, due to the abundance and low cost of sodium. Recent research has focused on adapting SIBs for flexible applications [57].

Flexible Electrode Design

The development of flexible electrodes for SIBs involves the use of materials such as hard carbon and MXenes, which offer good electrochemical performance and mechanical flexibility. A review by Lu et al. [58] highlighted the progress in carbon nanomaterials for highly flexible fibrous SIBs, emphasizing their potential in wearable electronics.

Solid-State Electrolytes

Flexible aqueous rechargeable sodium-ion batteries (ARSIBs) have been explored using hydrogel-based electrolytes. These electrolytes provide safety, eco-friendliness, and flexibility. A study published in the Journal of Materials Chemistry A discussed optimization strategies for ARSIBs, focusing on enhancing ionic conductivity and mechanical properties [53].

Encapsulation Techniques

Encapsulation of FSIBs involves materials that can accommodate mechanical deformation while protecting the battery components. Biodegradable polymers and elastomers have been investigated for this purpose, aligning with the sustainability goals associated with sodium-ion technology. Advanced encapsulation designs also aim to integrate self-healing properties to extend the battery lifespan [54].

Table 4 provides a consolidated summary of major flexible battery types, including lithium-ion, zinc-ion, and sodium-ion variants, focusing on their energy densities, electrode and electrolyte configurations, bending performance, and application areas.

Table 4 Summary of Flexible Battery Types and Their Key Properties

Battery Type	Electrode Material	Electrolyte Type	Energy Density (Wh/kg)	Bending Durability	Applications	Reference
Flexible LIB	CNT/Graphene/Polymer composite	Solid-state / Gel polymer	~150	Retains 80% capacity after 70 bends	Smart wearables, displays	Li et al. [49]
Flexible ZIB	Zn@carbon fibers	Hydrogel electrolyte	80–100	>90% after 1000 bending cycles	Wearable health devices	Lu et al. [54]
Flexible SIB	Hard carbon / MXene	Aqueous hydrogel	70	Moderate, eco-friendly	Eco-flexible devices	Lu et al. [54], El Foujji et al. [66]

3.3. Substrate and Encapsulation Materials

The mechanical adaptability, biocompatibility, and environmental stability of flexible energy storage devices are fundamentally influenced by the choice of substrate and encapsulation materials. Substrates serve as the foundational layers upon which active materials are deposited, dictating the device's mechanical properties, conformability, and sometimes even its electrochemical behavior. On the other hand, encapsulation materials act as protective barriers, shielding the device from environmental stressors such as moisture, oxygen, and mechanical abrasion, while simultaneously preserving its flexibility and user comfort. For applications in wearable and epidermal electronics, the selection of substrates and encapsulants must strike a delicate balance between flexibility, skin compatibility, thermal and chemical stability, and, increasingly, sustainability [59-61]. This section explores the use of various materials such as textiles, PDMS, PET, paper, and biodegradable polymers, and examines the engineering strategies for achieving waterproofing, breathability, and skin conformity in flexible devices.

3.3.1. Role of Substrate Materials

Textiles

Textile-based substrates offer a unique combination of mechanical strength, flexibility, porosity, and comfort, making them ideal for wearable electronics. The integration of energy storage components onto fabrics enables seamless incorporation into clothing, transforming garments into power sources. According to a study by Islam et al. [62], cotton and polyester textiles were successfully coated with conductive inks containing carbon nanotubes and silver nanowires to fabricate flexible supercapacitors with good mechanical endurance and washability. The inherent weave structure of textiles allows for improved breathability and sweat permeability, critical for prolonged skin contact. Furthermore, the stretchability and multidirectional deformability of knitted and woven fabrics enhance the resilience of the embedded devices under dynamic body movements [62].

PDMS (Polydimethylsiloxane)

PDMS is a silicone-based elastomer extensively used as both a substrate and encapsulation material in flexible electronics due to its optical transparency, biocompatibility, and excellent flexibility. Its low modulus of elasticity allows PDMS-based devices to conform well to skin and curved surfaces without causing discomfort. PDMS also provides significant thermal stability and chemical inertness, which protect active materials from external degradation. In a research work reviewed by Khurram Tufail et al. [63], a flexible lithium-ion battery encapsulated in PDMS demonstrated excellent cycling stability and mechanical robustness even after 1,000 cycles of bending at a 5 mm radius. Moreover, its compatibility with microfabrication techniques such as soft lithography enables the design of complex micro-patterns for electrodes or integrated circuits.

PET (Polyethylene Terephthalate)

PET films, commonly used in food packaging, have become popular substrates for flexible electronics due to their lightweight, transparency, and high tensile strength. They are chemically stable and exhibit low moisture permeability, which makes them suitable for printed and roll-to-roll fabricated energy storage devices. Researchers have leveraged

PET's smooth surface and thermal resistance to fabricate multi-layered thin-film batteries and supercapacitors. A study by Fu et al. [64] showed that roll-to-roll processing of pseudocapacitive devices on PET substrates resulted in devices with consistent electrical performance and minimal mechanical degradation under repeated bending. However, PET's relatively lower stretchability compared to elastomers limits its application in highly deformable or stretchable devices.

Paper

Paper substrates have emerged as a sustainable and low-cost option for flexible electronics. Their natural porosity, biodegradability, and mechanical compliance make them suitable for disposable or short-term applications. Cellulose fibers in paper can facilitate the adhesion of electrode inks and electrolytes, and can even serve as passive components in the device. Belaineh et al. [65] demonstrated a paper-based supercapacitor fabricated by screen-printing carbon-based inks onto cellulose sheets, which exhibited a specific capacitance of 86 F/g and retained 92% capacity after 5,000 cycles. Challenges with paper substrates include sensitivity to moisture and limited thermal durability, which can be mitigated using hydrophobic coatings or multilayer encapsulation.

Biodegradable Substrates

With the growing emphasis on green electronics, biodegradable polymers such as polylactic acid (PLA), polycaprolactone (PCL), and gelatin-based films are gaining traction. These materials degrade naturally in the environment or within the human body, making them suitable for transient electronics and implantable devices. In a recent study, El Foujji et al. [66] developed a sodium-ion battery using a PLA-based substrate and biodegradable gel electrolyte, achieving both environmental safety and mechanical resilience [66]. Such materials often require reinforcement or hybridization with conductive or robust layers to enhance their structural integrity and device lifetime. The key characteristics of commonly used substrate and encapsulation materials in flexible energy devices as described in this section—including their flexibility, barrier performance, and biocompatibility—are summarized in Table 5 to support material selection in device design.

Table 5 Comparison of Substrate and Encapsulation Materials for Flexible Devices

Material	Function	Flexibility	Barrier Property	Biocompatibility	Typical Use Case	References
PDMS	Substrate/Encapsulation	Excellent	Moderate	High	On-skin flexible devices	Khurram Tufail et al. [63]
PET	Substrate	Good	High	Low	Printed flexible batteries	Fu et al. [64]
Textile Cotton	Substrate	Excellent	Poor without coating	High	Wearable smart textiles	Islam et al. [62]
Paper	Substrate	Moderate	Low	Biodegradable	Disposable devices	Belaineh et al. [65]
PLA	Substrate	Moderate	Low	Biodegradable	Transient implantable devices	El Foujji et al. [66]

3.3.2. Engineering Strategies for Encapsulation

Waterproofing

Waterproofing is essential for ensuring the long-term operational stability of flexible energy devices, especially when exposed to humid environments, sweat, or even immersion in water. Effective waterproofing strategies involve the use of multilayer coatings composed of elastomers, barrier films, and sealants. A notable approach involves the use of bilayer structures, where a hydrophobic outer PDMS layer is combined with an inner oxygen/moisture barrier such as parylene or ethylene-vinyl alcohol (EVOH). According to Chong et al. [67], supercapacitors encapsulated with a PDMS/parylene combination retained 90% of their capacitance after 10 days of water immersion, compared to less than 50% for devices with PDMS alone. Advanced waterproofing also leverages self-healing materials that autonomously repair microcracks that may form during mechanical deformation [67].

Breathability

While waterproofing is crucial, maintaining breathability—particularly for on-skin or wearable applications—is equally important to prevent skin irritation and discomfort. Breathable encapsulation materials allow for the passage of air and water vapor while excluding liquid water. This is typically achieved using porous elastomers, microperforated films, or nanofibrous membranes. One innovative approach involved the development of a breathable yet waterproof e-skin battery using a polyurethane nanomesh that achieved a water vapor transmission rate (WVTR) of over 2,000 $g/m^2/day$ while maintaining mechanical integrity and device protection [68]. Such dual-functional materials are crucial for continuous, real-time monitoring systems worn directly on the skin.

Skin Conformity

Skin-conformable devices must be able to stretch, bend, and twist with the natural motion of the body without delaminating or causing discomfort. This requires encapsulation materials with low Young's modulus and high stretchability. PDMS, polyurethane (PU), and thermoplastic elastomers (TPEs) have been widely used for this purpose. Moreover, surface microstructuring or wrinkling of encapsulation layers can enhance adhesion and skin compatibility. A recent study by Xia et al. [69] used an origami-inspired kirigami pattern in a PU-encapsulated supercapacitor, which improved skin adherence and reduced strain-induced damage by 45% compared to flat devices. Incorporating bioadhesive layers or sweat-resistant interfaces further enhances conformability and comfort during prolonged use [69].

4. Integration into Wearable and Bio-Integrated Systems

The convergence of flexible energy storage technologies with wearable and bio-integrated systems represents a transformative frontier in electronics. This integration facilitates the development of devices that are not only portable but also seamlessly conform to the human body, enabling continuous health monitoring, on-the-go communication, and enhanced user interaction. Flexible energy storage devices, such as supercapacitors and batteries, are pivotal in powering these systems, offering the necessary adaptability and resilience required for dynamic environments. This section delves into the various strategies employed to integrate energy storage solutions into textiles, on-skin applications, and hybrid systems, emphasizing their design considerations, fabrication techniques, and practical applications.

4.1. Textile-Based Energy Storage Devices

Textile-based energy storage devices have emerged as a promising solution for powering wearable electronics, owing to their inherent flexibility, breathability, and compatibility with conventional garment manufacturing processes. By embedding energy storage functionalities directly into fabrics, these devices enable the creation of smart textiles capable of powering sensors, displays, and communication modules without compromising comfort or aesthetics. This subsection explores the various forms of textile-integrated energy storage devices, including yarn-based, fabric-based, and embroidered configurations, and discusses their fabrication methods, washability, sewing techniques, and real-world applications.

4.1.1. Yarn-Based Energy Storage Devices

Yarn-based energy storage devices are developed by incorporating energy storage materials into individual fibers or yarns, which are subsequently used in textile manufacturing through weaving, knitting, or braiding. This approach allows for a high degree of mechanical flexibility and adaptability, making it ideal for applications in dynamic environments such as wearable systems. Among the commonly used techniques is dip-coating, where conductive polymers or carbon-based materials are uniformly applied to yarns. Another approach is electrospinning, which facilitates the fabrication of nanofiber yarns embedded with active materials, enabling both capacitive and faradaic storage behaviors. Furthermore, the twisting and braiding of composite yarns allow for the enhancement of structural and electrochemical integrity.

Recent studies have demonstrated the effectiveness of this approach. For instance, research by Shang et al. [70] illustrated the fabrication of carbon nanotube yarn supercapacitors capable of withstanding over 10,000 bending cycles while maintaining high energy density. Similarly, Wang et al. [71] engineered twisted graphene-fiber-based yarn batteries exhibiting stable performance during mechanical deformations. However, achieving uniform material coating and ensuring long-term mechanical durability remain challenges, particularly under repeated wear, wash, and environmental exposure.

4.1.2. Fabric-Based Energy Storage Devices

Fabric-based energy storage devices involve the direct deposition or integration of energy storage materials onto woven or non-woven textiles, thereby transforming traditional fabrics into functional energy components. This method supports large-area production and allows for spatial patterning of the active materials. Techniques such as screen printing and layer-by-layer assembly are frequently employed to apply pseudocapacitive or battery-type materials onto textile substrates. These methods offer control over film thickness and uniformity, enabling tailored electrochemical properties for specific applications.

The work by Yong et al. [72] showcased a screen-printed zinc-ion battery integrated on cotton fabric, demonstrating a high degree of stretchability and consistent voltage output during repeated mechanical loading. Additionally, studies by Zhang et al. [73] employed conductive inks composed of reduced graphene oxide and polypyrrole, achieving capacitive retention of over 90% after extensive cycling. Nonetheless, adhesion of the active layers to fabric substrates remains a critical challenge, especially in humid conditions or under mechanical stress, necessitating the development of stronger binding agents and encapsulation strategies.

4.1.3. Embroidered Energy Storage Devices

The embroidery of conductive threads into fabrics represents another viable route for integrating energy storage devices into textiles. This method provides spatial control and the aesthetic advantage of embedding functional materials in decorative patterns. Conductive yarns, composed of silver-coated nylon, carbon nanotube composites, or metallic fibers, can be stitched into fabric layers to form interdigitated or planar electrode configurations. In some designs, embroidery patterns are combined with coating methods to enhance charge storage capabilities [74,75].

In the findings of Wen et al. [76], embroidered supercapacitors using silver-plated threads achieved stable capacitance even after repeated bending and washing cycles. These embroidered systems maintained mechanical compliance with fabric substrates and did not hinder air permeability or comfort. However, variations in stitch tightness, thread conductivity, and contact resistance pose reproducibility challenges. Additionally, maintaining the consistency of electrochemical performance across differently embroidered patterns requires further standardization of design and manufacturing techniques.

4.1.4. Washability and Sewing Techniques

A crucial consideration for textile-based energy storage systems is their durability during real-life usage, especially in terms of washability and mechanical robustness. Energy storage materials and devices must endure exposure to water, detergents, and mechanical agitation during laundering processes. Encapsulation techniques using polyurethane, silicone, or thermoplastic elastomers have been developed to protect internal components from moisture and physical damage. These encapsulants must retain flexibility and transparency while ensuring long-term environmental stability.

Furthermore, researchers such as Tanabe et al. [77] have investigated the incorporation of water-resistant binders and hydrophobic coatings on electrode surfaces, achieving sustained electrochemical performance after multiple washing cycles. To enhance mechanical robustness, reinforced stitching and integration with garment seams are employed. These methods secure the energy devices within the textile matrix and minimize delamination or detachment during use. Moreover, modular designs, wherein energy units can be detached from garments prior to washing, are gaining popularity in commercial prototypes.

4.1.5. Real-World Use Cases

The practicality of textile-integrated energy storage devices is evident in a growing number of real-world applications. Smart clothing embedded with supercapacitors or batteries is being developed for continuous physiological monitoring, powering temperature sensors, and enabling communication functionalities. A good instance is research by Heo et al. [78], which demonstrated energy-storing garments capable of powering wireless Bluetooth modules and wearable displays. In the field of emergency services and military operations, uniforms with integrated energy storage support long-range communication, navigation systems, and night-vision equipment, thereby enhancing operational efficiency.

In healthcare, patient garments with built-in energy storage enable uninterrupted operation of biosensors for real-time monitoring of cardiac and respiratory activities, especially in remote or ambulatory settings [79,80]. Additionally, applications in sportswear facilitate tracking of physical performance metrics through wearable sensors powered by textile-based energy storage units [81]. The seamless integration of energy functionality into wearable textiles thus not only extends the operational capacity of portable electronics but also paves the way for innovative solutions in health, defense, and recreational technologies.

4.2. On-Skin and Implantable Devices

The convergence of flexible electronics and biomedical engineering has given rise to on-skin and implantable energy storage devices, tailored for continuous health monitoring, disease diagnostics, and therapeutic interventions. These devices are specifically engineered to accommodate the complex biomechanical movements of human tissue while ensuring stable electrical performance [82,83]. Their significance lies in the expanding application space of epidermal sensors for electrocardiogram (ECG), electroencephalogram (EEG), and electromyogram (EMG) measurements, as well as drug delivery systems and neural interfacing. From the findings of Liu et al. [84], wearable electrochemical energy storage systems with mechanical properties matching that of human skin exhibited superior performance during continuous motion cycles, which is crucial for real-time physiological data acquisition.

Biocompatibility is central to the successful deployment of these systems, especially in implantable configurations. In a study by Zhang et al. [85], researchers developed a biodegradable zinc-ion battery with a gelatin-based hydrogel electrolyte and a magnesium current collector that exhibited excellent cytocompatibility and in vivo degradability. Such biocompatible architectures eliminate the need for surgical retrieval, reducing the risk of inflammation or tissue rejection. Similarly, according to Sun et al. [86], implantable lithium-ion batteries encapsulated in soft, silicone elastomers demonstrated long-term operational stability and minimal inflammatory response in murine models, highlighting the viability of flexible encapsulation strategies for chronic implantation.

Safety considerations in on-skin and implantable devices extend beyond biocompatibility to include electrochemical and thermal safety. Short-circuit prevention, leakage resistance, and controlled heat generation are critical parameters in these constrained biological environments. A detailed study by Cheng et al. [87] on skin-mounted micro-supercapacitors integrated with stretchable thermoplastic elastomers revealed that optimized ionogel electrolytes not only enhanced flexibility but also ensured thermal stability during repeated stretch/release cycles. Additionally, thermal insulation layers and encapsulants made from breathable polymers such as PDMS have been implemented to mitigate heat transfer to the skin, preserving both performance and user comfort [88,89].

Moreover, power requirements for on-skin and implantable systems are uniquely low, often in the range of microwatts to milliwatts. Therefore, the energy storage devices used must offer high energy and power densities within minimal volumetric and areal footprints. In a comprehensive study reviewed by Sun et al. [90], flexible microsupercapacitors based on carbon-MXene composites achieved energy densities of 10.4 mWh cm^{-3} while maintaining over 90% capacitance after 5000 deformation cycles. These metrics point to the growing feasibility of powering bio-integrated systems with next-generation flexible energy storage technologies. Continued advances in material miniaturization, in situ energy monitoring, and biodegradable componentry will further reinforce the integration of energy storage into human-interfacing platforms.

4.3. Self-Powered and Hybrid Systems

The integration of energy harvesting and storage components into unified platforms has emerged as a pivotal advancement in the development of autonomous wearable and bio-integrated electronics. These self-powered and hybrid systems are designed to capture ambient energy—mechanical, solar, or thermal—and store it efficiently, thereby reducing or eliminating the reliance on external power sources. This approach not only enhances the portability and usability of wearable devices but also aligns with the growing demand for sustainable and maintenance-free energy solutions in personal electronics.

4.3.1. Integration with Triboelectric and Piezoelectric Nanogenerators

Triboelectric nanogenerators (TENGs) and piezoelectric nanogenerators (PENGs) have garnered significant attention for their ability to convert mechanical energy from human motion into electrical energy. The integration of these nanogenerators with energy storage devices, such as supercapacitors and batteries, forms the basis of self-charging power systems (SCPSs). Recent studies have demonstrated the feasibility of such integrations. For instance, a study by Yi et al. [91] reported the development of a flexible SCPS comprising a TENG and a supercapacitor, capable of harvesting biomechanical energy and storing it for powering wearable electronics. The system exhibited high energy conversion efficiency and mechanical durability, making it suitable for continuous operation in dynamic environments.

Similarly, Islam et al. [92] developed a hybrid energy harvester by integrating a PENG with a lithium-ion battery. The device effectively captured low-frequency mechanical vibrations and stored the energy, demonstrating potential applications in powering implantable medical devices and remote sensors.

4.3.2. Integration with Solar Cells

Solar energy harvesting presents another viable avenue for powering wearable electronics. The incorporation of flexible photovoltaic (PV) cells into textiles and wearable platforms enables continuous energy generation under ambient light conditions. The integration of PV cells with energy storage units ensures a stable power supply, even during periods without sunlight.

In a notable example, Saifi et al. [93] developed an ultraflexible energy harvesting and storage system (FEHSS) by integrating high-performance organic photovoltaics with zinc-ion batteries. The system achieved a power conversion efficiency exceeding 16% and an energy density beyond 5.82 mWh cm^{-2}, sufficient to meet the power demands of various wearable sensors and devices. Figure 3 presents various configurations of photoresponsive zinc-ion batteries, highlighting their potential in solar energy harvesting and storage.

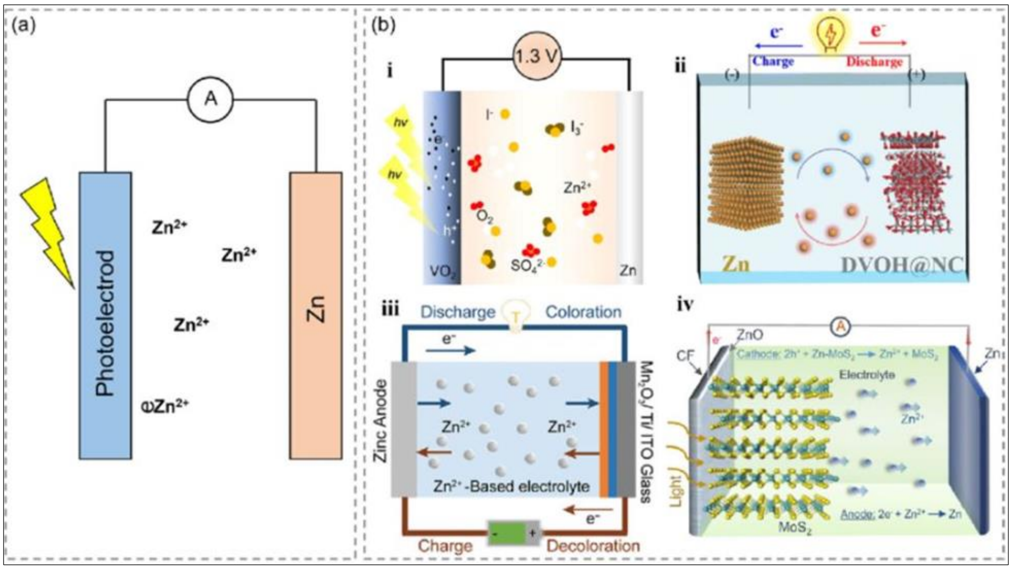

Figure 3 Photoresponsive Zinc-Ion Battery Configurations: a) Photoresponsive zinc-ion battery general type. b) Schematic diagram of photoresponsive Zn-ion batteries with: i) VO2 photoelectrode. ii) DVOH@NC photoelectrode. iii) Mn2O3/Ti/ITO photoelectrode, and iv) MoS2 photoelectrode. Reproduced with permission from Ref [88]

Furthermore, advancements in textile-based solar cells have led to the development of solar fabrics, where PV materials are woven directly into the textile fibers. This approach maintains the flexibility and breathability of the fabric while enabling energy harvesting capabilities. Such innovations pave the way for the creation of energy-autonomous garments and accessories. Table 6 outlines representative examples of integrated hybrid energy systems, categorizing them by their energy harvesting mechanism, corresponding storage type, performance metrics, and use case applications in wearable technology.

Table 6 Integrated Hybrid Systems—Harvesting Mechanism vs. Storage Pairing

Harvesting Source	Conversion Mechanism	Storage Device Type	System Output	Application Scenario	Citation
Triboelectric (TENG)	Friction-induced charge	Supercapacitor	200 μW/cm^2 stored in 10 mins	Self-powered motion sensors	Yi et al. [91]
Piezoelectric (PENG)	Strain-induced polarization	Li-ion battery	1.2 mWh/cm^2	Implantable or gait-harvesters	Islam et al. [92]
Photovoltaic (Organic)	Solar energy harvesting	Zn-ion battery	5.82 mWh/cm^2, 16% PCE	Smart clothing / mobile power	Saifi et al. [93]

4.3.3. Unified Energy Harvesting and Storage Platforms

The convergence of energy harvesting and storage into a single, integrated platform represents a significant stride toward fully autonomous wearable systems. These unified platforms are designed to simultaneously capture ambient energy and store it, ensuring a continuous and reliable power supply for wearable electronics.

One such innovation is the development of sandwich-structured devices that combine TENGs with supercapacitors. These devices are engineered to harvest mechanical energy from human motion and store it within the integrated supercapacitor layers. The compact design and high energy conversion efficiency make them ideal for applications in wearable health monitors and fitness trackers [94,95].

Additionally, hybrid systems that integrate multiple energy harvesting mechanisms—such as combining TENGs, PENGs, and PV cells—have been explored to maximize energy capture from diverse sources. These multi-modal energy harvesters are particularly beneficial in environments with variable energy availability, ensuring consistent power generation for wearable devices.

Challenges and Future Perspectives

Despite the promising advancements, several challenges persist in the development of self-powered and hybrid systems for wearable applications. Key issues include the optimization of energy conversion efficiency, miniaturization of components, and the development of flexible and biocompatible materials that can withstand mechanical stresses and environmental factors [96,97].

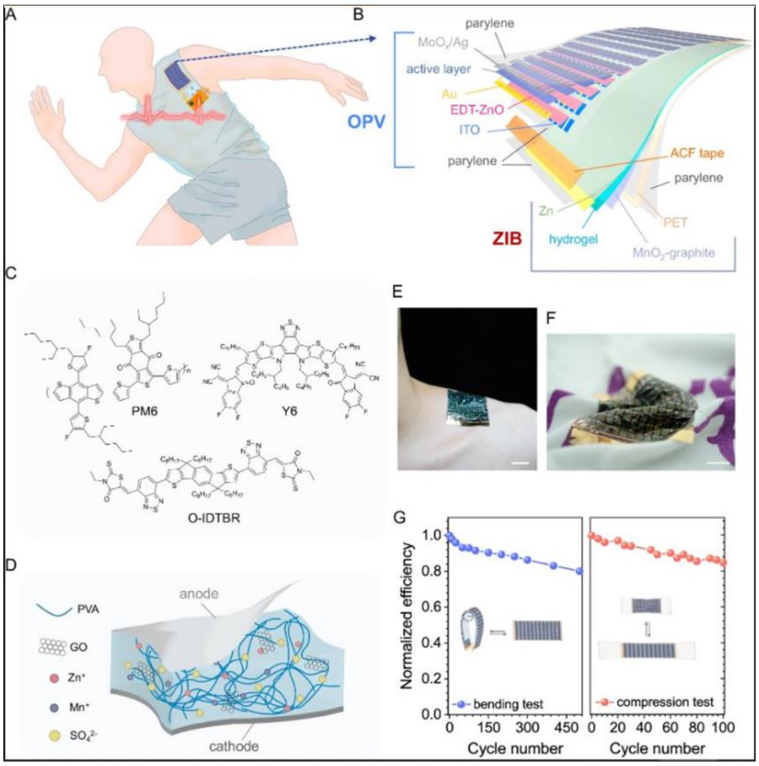

Figure 4 Structural overview of the ultraflexible energy harvesting–storage system (FEHSS). (A) Illustration showing the FEHSS powering an on-skin electrocardiogram (ECG) sensor patch for healthcare monitoring. (B) Schematic diagram of the layered configuration combining a flexible organic photovoltaic (OPV) module with zinc-ion (Zn-ion) batteries. (C) Chemical structures of the OPV active layer components: donor polymer PM6, acceptor Y6, and third component O-IDTBR. (D) Schematic of the Zn/MnO_2–graphite battery, highlighting the composition of the hydrogel electrolyte. (E) Photograph of a 90 µm-thick FEHSS adhered to a volunteer's shoulder (scale bar: 2 cm). (F) Photograph of the FEHSS integrated into a textile substrate (scale bar: 1 cm). (G) Mechanical durability assessment showing performance after 500 bending cycles at 1 mm radius (left) and 100 compression-stretch cycles under 10% strain (right), with normalized photo-conversion and storage efficiency plotted on the y-axis. Insets show the testing configurations. Reproduced with permission from Ref [93]

Future research is expected to focus on the integration of advanced materials, such as two-dimensional nanomaterials and conductive polymers, to enhance the performance and durability of these systems. Moreover, the incorporation of intelligent power management circuits and wireless communication modules will be crucial in realizing fully autonomous and interconnected wearable devices [96]. To exemplify the advancements in integrating energy harvesting and storage components into a cohesive, flexible system, Figure 4 presents a detailed schematic of an ultraflexible energy harvesting-storage system (FEHSS). This system demonstrates the feasibility of combining high-performance organic photovoltaics with zinc-ion batteries in a thin, conformable format suitable for wearable applications.

In essence, the integration of energy harvesting and storage into unified platforms holds immense potential for revolutionizing wearable and bio-integrated electronics. By harnessing ambient energy sources and ensuring efficient storage, these self-powered systems pave the way for the development of sustainable, maintenance-free, and user-friendly wearable technologies.

5. Applications and Demonstrations

The integration of flexible energy storage systems into wearable and bio-integrated platforms has catalyzed significant advancements across various sectors, including healthcare, sports, military, and real-time wireless sensing. These applications not only demonstrate the versatility of flexible energy storage technologies but also underscore their potential to revolutionize traditional practices by offering enhanced functionality, user comfort, and operational efficiency. To contextualize the practical implementation of flexible energy storage technologies across key domains, Table 7 categorizes current applications by sector, detailing their configurations, technical requirements, and representative examples from recent literature.

Table 7 Applications of Flexible Energy Storage Devices—Sector-Wise Analysis

Application Sector	Device Configuration	Key Performance Needs	Use Case Examples	References
Healthcare	On-skin supercapacitor / implant battery	Biocompatibility, safety, flexibility	ECG patches, drug delivery devices	Liu et al. [84], Sun et al. [86]
Sports	Textile-based supercapacitor	Washability, durability, high power	Smart shirts tracking vitals	Heo et al. [78]
Military	Fabric-embedded battery + sensor array	Ruggedness, stealth, mechanical robustness	Powering tactical sensors, body temp monitors	Zhang et al. [73], Tanabe et al. [77]
Mobile Systems	PV-Zn battery combo or SCPS	Lightweight, autonomy, durability	Mobile drone refuelers, remote sensor charging	Saifi et al. [93], Yi et al. [91]

5.1. Wearables in Healthcare

In the healthcare domain, wearable devices equipped with flexible energy storage systems have emerged as pivotal tools for continuous health monitoring and disease management. Electrocardiogram (ECG) sensors, for instance, have been miniaturized and integrated into wearable formats, enabling real-time cardiac monitoring without impeding the user's daily activities. These devices facilitate the early detection of arrhythmias and other cardiac anomalies, thereby improving patient outcomes through timely interventions [98,99].

Continuous glucose monitors (CGMs) represent another significant application of wearable technology in healthcare. These devices, often worn on the skin, provide real-time glucose readings, allowing individuals with diabetes to manage their condition more effectively. The integration of flexible batteries into CGMs has enhanced their wearability and user comfort, promoting better adherence to glucose monitoring regimens.

The development of these healthcare wearables necessitates a focus on biocompatibility and safety. Materials used in these devices must be non-toxic and hypoallergenic to prevent adverse skin reactions. Moreover, the devices must be designed to withstand the mechanical stresses of daily wear, including bending, stretching, and exposure to moisture, without compromising their functionality or the integrity of the stored energy [99].

5.2. Smart Textiles for Sports and Military Use

Smart textiles, embedded with flexible energy storage systems, have found extensive applications in sports and military settings. In sports, these textiles can monitor physiological parameters such as heart rate, respiration, and body temperature, providing athletes and coaches with valuable data to optimize performance and prevent injuries. The integration of energy storage components into the fabric ensures that these monitoring systems are self-powered, eliminating the need for external power sources and enhancing the user's mobility [100,101].

In military applications, smart textiles serve a dual purpose of monitoring soldier health and enhancing operational capabilities. These fabrics can detect environmental hazards, monitor vital signs, and even provide adaptive camouflage. The incorporation of flexible batteries into military uniforms ensures that these functionalities are powered reliably, even in remote or harsh environments [102,103]. Furthermore, the durability and washability of these energy storage systems are critical, as military textiles must endure rigorous conditions without degradation of performance.

5.3. Real-Time Demonstrations of Wireless Sensing and Mobile Power Systems

The practical implementation of flexible energy storage systems is exemplified through real-time demonstrations of wireless sensing and mobile power applications. These demonstrations showcase the feasibility of integrating energy harvesting, storage, and sensing capabilities into compact, wearable formats [104]. For instance, self-powered sensors have been developed that can monitor environmental parameters or physiological signals and transmit data wirelessly, all while being powered by integrated flexible batteries. Mobile power systems, such as drones equipped with flexible energy storage, have also been demonstrated. These systems can perform tasks like wireless charging of remote sensors or delivering power to inaccessible locations, highlighting the potential of flexible batteries in expanding the operational range and functionality of mobile platforms [105,106].

These real-world applications underscore the transformative impact of flexible energy storage systems across various sectors. By enabling the development of self-powered, wearable, and wireless devices, these technologies are paving the way for more responsive, efficient, and user-friendly solutions in healthcare, sports, military, and beyond.

6. Current Challenges and Limitations

Despite significant advancements in the development of flexible energy storage devices (FESDs), several critical challenges hinder their widespread adoption and practical application. These challenges encompass trade-offs between energy density and flexibility, concerns regarding long-term cycling and mechanical reliability, safety and environmental impacts, as well as issues related to scalability, manufacturing, and cost.

6.1. Energy Density vs. Flexibility Trade-Off

One of the foremost challenges in FESDs is balancing high energy density with mechanical flexibility. Traditional energy storage devices prioritize energy density, often at the expense of flexibility. Conversely, enhancing flexibility typically leads to a reduction in energy storage capacity. This trade-off arises because materials that offer high energy densities, such as certain metal oxides, are inherently rigid and brittle, making them unsuitable for flexible applications [107,108]. On the other hand, materials that provide excellent flexibility, like polymers, often suffer from lower energy storage capabilities.

Recent studies have highlighted this dilemma. For instance, research indicates that achieving a balance between mechanical flexibility and electrochemical performance remains a significant hurdle in the development of FESDs [108,109]. Innovative approaches, such as the incorporation of nanomaterials and the development of novel composite structures, are being explored to address this issue. However, these solutions often introduce additional complexities in fabrication and may not fully resolve the inherent trade-offs.

6.2. Long-Term Cycling and Mechanical Reliability

The durability of FESDs under prolonged mechanical deformation and electrochemical cycling is another critical concern. Repeated bending, stretching, and twisting can lead to mechanical fatigue, delamination, and cracking of electrode materials, ultimately compromising device performance. Moreover, continuous electrochemical cycling can result in capacity fading, reduced coulombic efficiency, and structural degradation of active materials.

For example, studies on flexible zinc-ion batteries have shown that mechanical stability of the electrode during long-term deformation and uncontrollable dendrite growth during cycling severely limit the service life of these batteries [110,111]. Similarly, research on lithium-ion batteries indicates that mechanical stress and vibration can significantly deteriorate cycling performance. Addressing these issues requires the development of robust materials and device architectures that can withstand mechanical stresses without compromising electrochemical performance [112].

6.3. Safety, Toxicity, and Environmental Impact

Safety concerns, toxicity, and environmental impacts pose significant challenges to the deployment of FESDs. The use of flammable electrolytes in many flexible batteries raises the risk of thermal runaway, leading to fires or explosions under certain conditions. Additionally, the incorporation of toxic materials, such as heavy metals and per- and polyfluoroalkyl substances (PFAS), in battery components can have detrimental effects on human health and the environment [113].

Research has discovered that bis-FASI, a subclass of toxic PFAS "forever chemicals" used in lithium-ion batteries, poses significant environmental and health risks. These chemicals have been found in high levels near manufacturing plants and remote areas, indicating their mobility and persistence in the environment. Improper disposal of batteries can lead to the leaching of toxic substances into soil and water, causing long-term ecological damage. Furthermore, the recycling processes for flexible batteries are still underdeveloped, leading to low recycling rates and increased environmental burden [114,115].

6.4. Scalability, Manufacturing, and Cost Barriers

The transition of FESDs from laboratory prototypes to commercially viable products faces significant scalability, manufacturing, and cost challenges. The fabrication of flexible batteries often involves complex processes, specialized materials, and precise control over device architecture, all of which contribute to high production costs [116]. Moreover, the lack of standardized manufacturing techniques and equipment for flexible electronics hampers large-scale production.

Economic barriers further exacerbate these issues. High initial costs, limited market stimulation, and intense competition from established energy storage technologies, such as conventional lithium-ion batteries, make it difficult for flexible batteries to gain a foothold in the market. Additionally, scaling production involves significant capital investment, and economic frameworks for long-duration storage solutions are not yet mature. Policy and regulatory uncertainties also contribute to the risk profile of investing in flexible energy storage technologies [117].

7. Future Directions and Outlook

The advancement of flexible energy storage devices (FESDs) is poised to revolutionize various sectors, including healthcare, consumer electronics, and environmental sustainability. As the field progresses, several emerging trends, interdisciplinary collaborations, and strategic recommendations are shaping the future landscape of FESDs.

7.1. Emerging Trends: Biodegradable Electronics, AI-Powered Wearables, and Edge-Computing Integration

One of the most promising trends in FESDs is the development of biodegradable electronics. These devices are designed to decompose naturally after their functional lifespan, reducing electronic waste and environmental impact. Materials such as organic semiconductors and biodegradable polymers are being utilized to create flexible, lightweight, and even compostable electronic components. For instance, researchers have developed biodegradable electronic textiles (e-textiles) that integrate sensors and circuits into fabrics, enabling applications in healthcare monitoring and environmental sensing [118,119].

The integration of artificial intelligence (AI) into wearable devices is another significant trend. AI-powered wearables can analyze data in real-time, providing personalized feedback and enhancing user experience [120]. These devices leverage machine learning algorithms to interpret complex physiological signals, enabling applications such as predictive health monitoring and adaptive fitness coaching. The combination of AI with flexible electronics allows for the development of smart wearables that are both intelligent and comfortable to wear.

Edge computing integration is also gaining traction in the realm of FESDs. By processing data locally on the device, edge computing reduces latency and power consumption, which is crucial for wearable applications. This approach enables real-time data analysis and decision-making without relying on cloud computing, enhancing the efficiency and responsiveness of wearable systems. The convergence of edge computing with flexible energy storage solutions paves the way for autonomous, self-sustaining wearable devices [121].

7.2. Interdisciplinary Collaborations in Materials Science, Bioengineering, and Human–Device Interfaces

The advancement of FESDs is inherently interdisciplinary, requiring collaboration across materials science, bioengineering, and human–device interface design. Materials scientists are developing novel materials with enhanced flexibility, conductivity, and biocompatibility to meet the demands of wearable applications. For example, the use of conductive polymers and nanomaterials has led to the creation of stretchable and durable energy storage components.

Bioengineering plays a critical role in integrating FESDs with the human body. This includes designing devices that conform to the skin, are comfortable to wear, and can safely interact with biological tissues. Advancements in biohybrid systems, which combine living tissues with electronic components, are opening new avenues for medical applications such as implantable sensors and prosthetics [122].

Human–device interface design focuses on creating intuitive and seamless interactions between users and wearable devices. This involves developing user-friendly interfaces, haptic feedback mechanisms, and adaptive systems that respond to user behavior. The integration of flexible energy storage into these interfaces ensures that devices remain lightweight and unobtrusive, enhancing user acceptance and adoption [123].

7.3. Recommendations for Research Focus and Industrial Adoption

To accelerate the development and adoption of FESDs, several strategic recommendations are proposed:

- **Material Innovation**: Research should focus on developing new materials that offer a balance between flexibility, energy density, and environmental sustainability. This includes exploring biodegradable materials and recyclable components to reduce environmental impact.
- **Standardization and Scalability**: Establishing standardized manufacturing processes and design protocols will facilitate the scalability of FESDs. This will enable mass production and integration into various applications, from consumer electronics to medical devices.
- **Interdisciplinary Collaboration**: Encouraging collaboration between academia, industry, and government agencies will foster innovation and accelerate the translation of research into practical applications. Joint initiatives can address challenges related to material development, device integration, and regulatory compliance.
- **User-Centric Design**: Incorporating user feedback into the design process ensures that FESDs meet the needs and preferences of end-users. This approach enhances user experience and promotes widespread adoption of wearable technologies.
- **Policy and Regulatory Support**: Developing supportive policies and regulatory frameworks will facilitate the commercialization of FESDs. This includes providing funding for research and development, as well as establishing safety and performance standards for wearable energy storage devices.

Putting it all together, the future of flexible energy storage devices is promising, with emerging trends and interdisciplinary collaborations driving innovation. By focusing on material development, standardization, user-centric design, and supportive policies, the field can overcome current challenges and realize the full potential of FESDs in transforming various industries.

8. Conclusion

The evolution of flexible energy storage devices (FESDs) marks a significant leap in the convergence of electronics, materials science, and bioengineering, particularly in their integration into modern wearable systems. From early-stage developments in stretchable electrodes and deformable substrates to sophisticated, multifunctional devices embedded in textiles and even implanted within the human body, the field has made tremendous progress. These advancements have been facilitated by breakthroughs in material innovations—such as nanostructured electrodes, gel-based electrolytes, and biodegradable substrates—as well as by engineered device architectures that accommodate mechanical deformation while preserving electrochemical performance. Furthermore, demonstrations in real-world applications, including healthcare monitoring, soft robotics, and smart textiles for military and athletic performance, emphasize the practicality and growing relevance of these technologies.

The future of smart energy-integrated electronics lies in creating systems that are not only high-performing and safe but also intelligent, self-sustaining, and environmentally responsible. The merging of flexible storage systems with self-powered energy harvesters, edge computing modules, and AI-enhanced signal processing units will yield next-generation wearables capable of autonomous operation and real-time decision-making. As the field continues to mature, collaborative efforts between researchers, industrial stakeholders, and policymakers will be vital to overcoming remaining challenges, such as improving long-term reliability, ensuring scalability, and addressing environmental concerns. Ultimately, the vision is clear: a future where flexible, adaptive, and sustainable energy systems seamlessly power our daily lives through integration into the very fabrics we wear and the biomedical devices we trust.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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