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FLEXIBLE ELECTROCHEMICAL ENERGY SOURCES FOR WEARABLE SYSTEMS: TECHNICAL SOLUTIONS AND INTEGRATION WITH A MILITARY APPLICATION ASPECT

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Abstract: *The development of wearable electronic systems has led to an increased need for compact, lightweight and mechanically flexible energy sources that can be integrated into textile materials. This paper analyzes flexible electrochemical energy sources intended for wearable systems, with a special focus on technical solutions, materials and possibilities for their integration into smart textiles. The main categories of flexible energy devices are discussed, including flexible batteries, supercapacitors and fiber energy systems, as well as their advantages over traditional batteries. Special attention is given to the role of advanced nanomaterials, such as graphene and MXene, which allow improvement of the electrochemical and mechanical properties of these devices. Different methods of integrating energy components into textiles are also analyzed, including weaving conductive fibers, printing functional materials and coating fibers. The paper also discusses the potential of these systems in military wearable technologies, where it is necessary to provide reliable power supply for numerous electronic devices with minimal increase in the mass of the equipment. The analysis presented in this paper indicates that flexible electrochemical energy sources represent a promising solution for the development of a new generation of smart textiles and wearable systems.*

Keywords: *flexible batteries, supercapacitors, wearable electronics, MXenes, textile integration.*

1. INTRODUCTION

The modern development of wearable electronic systems has led to a significant increase in the demand for reliable, lightweight, and energy-efficient power sources. In military applications, wearable electronic systems include communication devices, navigation systems, biomedical sensors, and systems for real-time data acquisition and processing. Traditional batteries exhibit limitations in the context of wearable systems, primarily due to their rigid structure, limited mechanical flexibility, and relatively high mass. These drawbacks affect mobility, ergonomics, and operational efficiency in military conditions [1].

In this context, flexible electrochemical energy sources represent a promising solution that enables the combination of electrochemical performance and mechanical adaptability [2]. The development of these systems is based on the application of advanced materials, such as nanostructured composites and two-dimensional materials, as well as innovative structural approaches that enable integration into textile structures. The integration of energy systems into smart textiles is of particular importance, as it enables uniform mass distribution, improved comfort, and the application of self-powered devices [3].

The aim of this paper is to provide a comprehensive analysis of flexible electrochemical energy sources, primarily flexible batteries and supercapacitors, with an emphasis on their performance and design constraints. Special attention is given to their comparison with conventional rigid battery systems, particularly in terms of mechanical flexibility and operational stability under deformation.

Furthermore, the paper examines recent technical solutions enabling flexibility, including novel architectures and the use of advanced materials such as MXene and other conductive nanostructures. A dedicated focus is placed on strategies for integrating these energy

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sources into textile platforms, including weaving conductive fibers, printing functional materials, and coating fibers with electrochemically active layers.

Finally, the study explores the applicability of these systems in wearable technologies, with particular emphasis on military applications.

2. FLEXIBLE ENERGY SOURCES

Flexible electrochemical energy storage devices may be defined as systems typically composed of electrodes, current collectors, electrolytes, separators, and supporting substrates, designed to storage chemical energy and preserve performance under bending, twisting, folding, and stretching [4]. The rapid development of portable and wearable electronics, including wireless sensors, flexible displays, electronic skins, and foldable devices, has created a growing demand for these systems.

To enable fully autonomous wearable devices, flexible energy storage technologies must provide high energy density, long lifespan, fast charging and discharging capability, and operational safety at an acceptable cost [5]. In addition, these systems must maintain stable performance under mechanical deformation, requiring both electrical reliability and mechanical durability. As shown in Figure 1, significant research efforts have been directed toward designing materials and architectures capable of withstanding bending, twisting, folding, and stretching without compromising functionality [1].

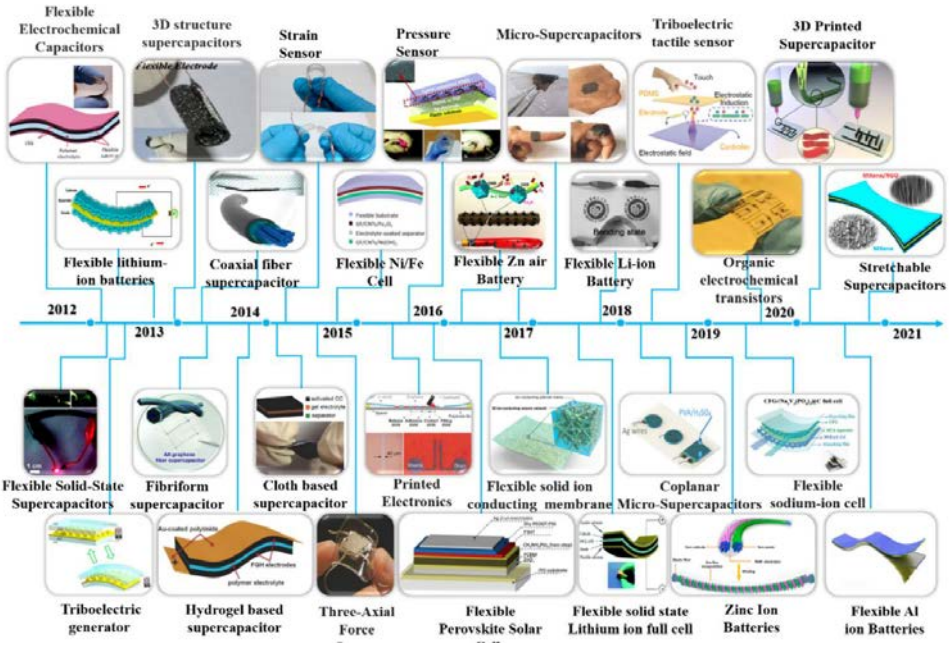


Figure 1. The evolution of flexible energy storage devices [1]

Flexible electrodes play a key role in meeting these requirements and are often designed without binders, conductive additives, or rigid current collectors. Namely, conventional electrode materials are typically rigid and mechanically brittle, limiting their use in flexible devices. Additionally, inactive binders may reduce capacity and introduce safety concerns, leading to the development of binder-free electrode designs [1].

Self-charging systems combining flexible energy storage with energy harvesting devices have also been developed, allowing wearable systems to achieve partial or continuous energy autonomy during operation [5]. The application of such storage + harvesting concept is illustrated in Figure 2 [2].

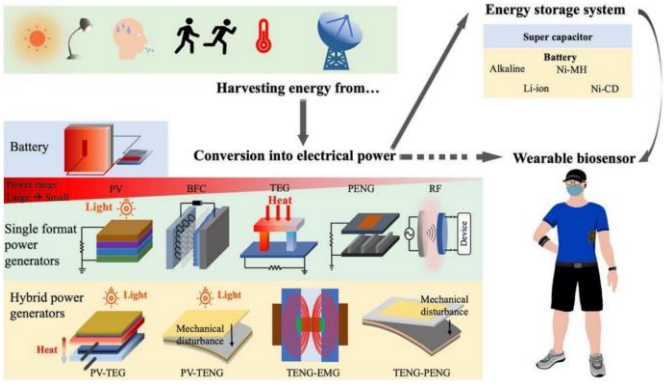


Figure 2. Schematic flow diagram of self-powered smart wearable sensors. Harvesting energy from various energy sources, converting into electric power, storing energy in storage section and powering wearable sensors. PV: photovoltaic; BFCs: biofuel cells; TEGs: thermoelectric generators; PENGs: piezoelectric nanogenerators; TENGs: triboelectric nanogenerators; RF: radio frequency; EMGs: electromagnetic generators [2]

Figure 2 illustrates the pathway from harvesting energy from various sources to its conversion into electrical energy, storage, and use for powering wearable sensors. The depicted energy sources include light, heat, radio waves, and vibrations. Photovoltaic (PV) systems are used for harvesting light energy, while biofuel cells (BFCs) represent an electrochemical energy source. Thermoelectric generators (TEGs) are used for harvesting thermal energy, whereas piezoelectric nanogenerators (PENGs) and triboelectric nanogenerators (TENGs) are technologies for harvesting mechanical energy. Radio-frequency (RF) systems utilize radio-frequency energy sources, while electromagnetic generators (EMGs) represent an additional technology for energy harvesting. The harvested energy is converted into electrical power, stored, and subsequently used to supply power to wearable sensors [2].

3. COMPARISON WITH TRADITIONAL BATTERIES

Traditional batteries, particularly lithium-ion batteries, remain the dominant energy storage technology due to their relatively high energy density and proven stability in portable electronic systems [1,4]. However, their rigid structure and limited mechanical flexibility represent a significant limitation for applications in wearable systems [1,2]. Flexible electrochemical energy sources have been developed to overcome these limitations.

While conventional batteries retain an advantage in energy density, flexible supercapacitors and hybrid systems exhibit higher power density and rapid charge/discharge capability, making them suitable for short-term but intensive energy demands in wearable devices [5,6]. This indicates that flexible energy sources are not a direct replacement for conventional batteries, but rather their complement in specific wearable applications.

Additionally, flexible systems enable new device architectures, such as fiber-based and textile-based configurations, which are not possible with traditional batteries. These approaches allow better integration into wearable systems, more uniform mass distribution, and improved ergonomics [7,8]. Furthermore, as highlighted in [9], distributed textile-based battery systems represent a paradigm shift compared to centralized conventional batteries. Instead of relying on a single rigid energy source, energy can be spatially distributed across clothing, significantly improving redundancy, fault tolerance, and ergonomic performance.

4. TECHNICAL SOLUTIONS FOR FLEXIBLE ELECTROCHEMICAL ENERGY SOURCES

The two most important flexible energy storage systems have been rechargeable batteries (flexible alkaline, zinc–carbon, polymer, etc.) and supercapacitors. Flexible rechargeable batteries offer high energy density but are limited by relatively low power density and slower charge/discharge rates. In contrast, supercapacitors provide high power density, rapid charge/discharge capability, and long cycle life, making them suitable for complementary applications.

4.1 Devices

4.1.1 Flexible Batteries

Flexible batteries represent one of the most important solutions for powering wearable electronic systems. The modern development of these systems is based on modifying conventional lithium-ion batteries using thin-film structures, polymer electrolytes, and flexible current collectors [4].

Two dominant structural configurations of flexible energy sources are ultrathin flexible structures (UFS) and one-dimensional fiber-based architectures (Figure 3). Depending on fiber density and structural orientation, fiber-based batteries can be classified as coaxial, multi-axial, or ultrathin flexible structures. Each configuration offers different advantages in terms of mechanical flexibility and electrochemical performance [4].

As shown in Figure 3, the following configurations can be observed: (a) coaxial one-dimensional structure, (b) multi-axial one-dimensional structures, (c) ultrathin flexible structure for AMAD, (d) spine-like structure, (e) interwoven structure, (f) node-type structure for AMAD, (g) serpentine interconnection, (h) origami and kirigami structures, and (i) coplanar electrode structure for IAMA [6].

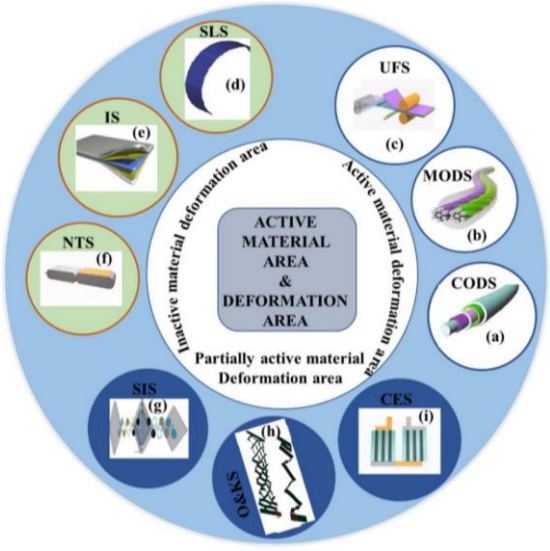


Figure 3. Structural designs for flexible and stretchable batteries, including active and inactive regions and deformation zones [4]

The integration of textile-based triboelectric nanogenerators (TENGs) with flexible batteries enables the development of self-charging hybrid systems. These systems can convert biomechanical energy generated during human motion into electrical energy, which is then stored in flexible batteries, extending operational time without external charging infrastructure [10].

Advanced design approaches include the development of fiber-based and textile-integrated batteries, as well as printed battery systems that can be applied in flexible wearable devices [9]. Additionally, techniques such as screen printing and inkjet printing allow deposition of functional materials onto textile substrates [7,8].

4.1.2 Supercapacitors

Flexible supercapacitors represent an alternative to batteries in applications requiring high power density and rapid charging, making them suitable for energy-demanding wearable systems [6]. Significant progress has been achieved in the development of fiber-shaped supercapacitors that can be directly integrated into textile structures. These systems are typically realized in coaxial, twisted, or layered configurations [11].

A schematic overview of supercapacitor operation, the number of publications in this field, and their integration into wearable electronics are shown in Figure 4 [6].

Fabric-based flexible supercapacitors show strong potential for integration into multifunctional wearable systems due to their high-power density and mechanical durability. Such systems can be directly embedded into military clothing, enabling energy delivery to components such as communication modules and sensor arrays [12].

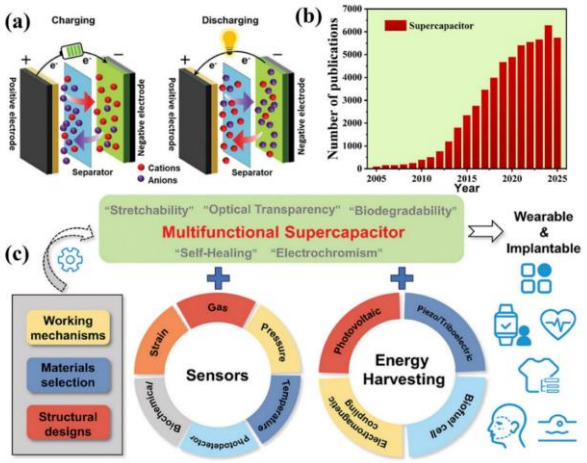


Figure 4. Overview of supercapacitor integration with sensors and electronic devices: (a) energy storage mechanisms, (b) publication trends, (c) schematic integration with wearable and implantable systems [6]

4.2 Advanced Materials

4.2.1 MXenes

Two-dimensional transition metal carbides, nitrides, and carbonitrides known as MXenes have emerged as a revolutionary class of materials for the development of multifunctional wearable electronic textiles [13]. Due to their unique structure and tunable surface functional groups, MXenes exhibit a range of exceptional properties, as shown in Figure 5 [13]. Their outstanding mechanical flexibility, hydrophilicity, tunable surface chemistry, and high electrical conductivity make them ideal for integration into textile systems [13].

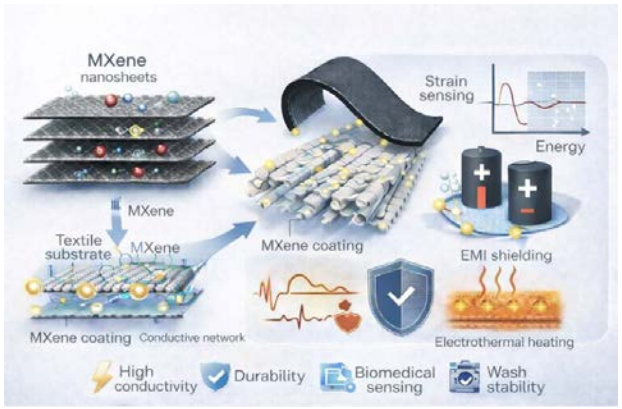


Figure 5. Structure and properties of MXenes [13].

Thanks to their large specific surface area and excellent electrical conductivity, MXenes enable improved energy and power density in flexible energy devices [14]. Particular attention has been given to their application in electrochemical energy storage, especially in supercapacitors. MXenes are highly suitable electrode materials due to their superior mechanical flexibility, energy density, and electrochemical performance [15].

Six main categories of MXene–polymer nanocomposites, classified based on dispersion state and macroscopic form, are shown in Figure 6 [16].

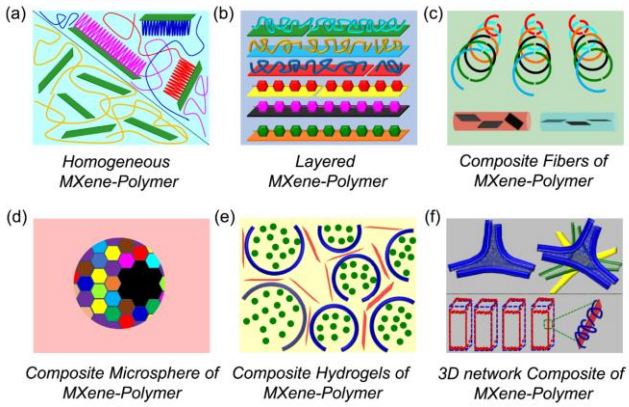


Figure 6. The Six Main Types of MXene–Polymer Nanocomposites [16]

4.2.2 Graphene

Graphene, a two-dimensional material composed of a single layer of sp^2-hybridized carbon atoms, has emerged as a key advanced material for flexible electrochemical energy storage systems. Owing to its exceptional electrical conductivity, high specific surface area, and outstanding mechanical strength, graphene exhibits a unique combination of properties that makes it highly suitable for wearable electronic applications. In addition, its intrinsic flexibility and low density enable seamless integration into textile-based platforms, supporting the development of lightweight and mechanically adaptable energy storage devices [7].

Due to its high specific surface area and excellent charge transport properties, graphene is widely used as electrode

material in flexible supercapacitors and batteries, enabling high power density through electric double-layer capacitance. It also maintains stable performance under mechanical deformation, which is essential for wearable systems. However, challenges such as sheet restacking and low intrinsic pseudocapacitance can limit its overall energy storage performance. To address these limitations, graphene is often combined with nanostructured materials and conductive polymers, forming composite systems with improved ion transport, enhanced capacitance, and better mechanical stability [17].

The schematic illustration (Figure 7) presents typical graphene-based composite electrode architectures, including polymer-functionalized and hybrid nanostructures. These designs enhance ion transport and prevent restacking, resulting in improved electrochemical performance and flexibility, which are essential for wearable and textile-integrated energy storage systems [17].

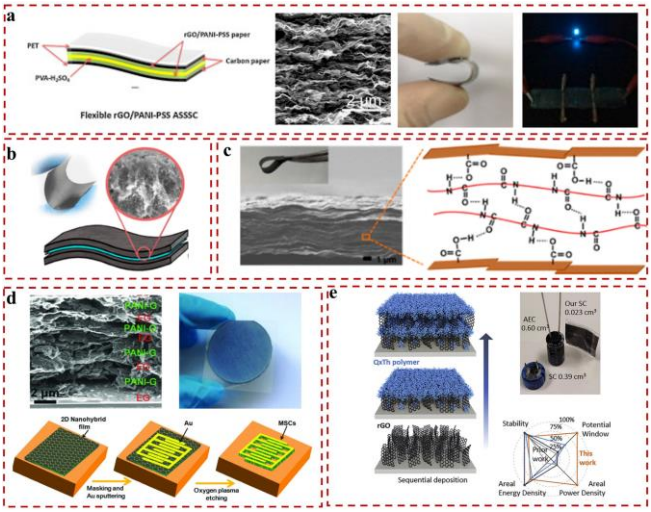


Figure 7. Flexible graphene-based supercapacitors [17]

5. INTEGRATION INTO TEXTILES

The integration of flexible electrochemical energy sources into textile structures represents a key step in the development of wearable systems, enabling direct incorporation of energy functions into clothing and equipment. This approach provides improved ergonomics, reduced weight, and uniform distribution of functional components, which is particularly important in military applications [8]. Modern integration strategies include weaving conductive fibers, printing functional materials, and coating textile substrates, often combining multiple methods to achieve optimal performance [7].

Printed distributed energy storage systems enable seamless integration into textile architectures without significantly altering mechanical properties, which is crucial for maintaining comfort and flexibility in long-term military use. [9]

5.1 Weaving Conductive Fibers

Weaving conductive fibers is one of the most direct approaches for integrating functional components into textiles.

Fiber-based supercapacitors and conductive fibers based on graphene, MXene, and conductive polymers can be incorporated during weaving or knitting processes, forming functional fabrics capable of storing and delivering energy [8].

5.2 Printing Functional Materials

Printing techniques provide a flexible and precise approach for integrating electrochemical components into textiles. Methods such as inkjet printing, screen printing, and direct ink writing (DIW) enable direct deposition of functional materials onto textile substrates, allowing fabrication of electrodes, interconnections, and energy devices with high geometric control [8,18]. Printing enables the development of thin-film, lightweight and flexible systems that can be adapted to complex textile structures.

Inkjet printing involves controlled deposition of microdroplets containing conductive or electrochemically active materials, enabling thin and uniform layers with high precision [18].

Screen printing allows thicker and more uniform layers, offering advantages in simplicity, cost-effectiveness, and scalability [18].

Direct ink writing (DIW) enables extrusion of viscous inks into continuous or 3D structures, allowing precise control over electrode architecture and mechanical stability [18].

5.3 Coating of Fibers with Functional Materials

Coating represents one of the simplest methods for integrating functional materials into textiles. Techniques such as dip-coating, spray-coating, and vacuum filtration enable deposition of thin conductive and electrochemically active layers while preserving textile flexibility [7,13].

Dip-coating involves immersion of the substrate in a solution, forming a uniform conductive layer after drying. Complex multilayer systems such as PU@PMA@EGaIn exhibit high conductivity (>10^5 S/m) and stretchability up to 500% [7].

Spray coating enables controlled deposition with efficient material usage, producing CNT–graphene/PU fibers with conductivity up to 8 S/m and stretchability up to 620% [7].

Vacuum filtration produces uniform nanocomposite films, such as aramid nanofiber/Ag nanowire papers with low surface resistance (0.12 Ω/sq) and high thermal stability (>500 °C), which represent model systems applicable also in flexible textile structures [7].

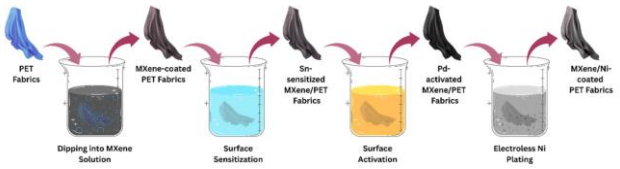


Figure 8. MXene/Ni coating process on PET fabrics [13]

By combining these methods, it is possible to achieve advanced functional structures, as illustrated in Figure 8. For example, the formation of a bilayer MXene/Ni coating on polyester fabric resulted in a significant improvement in electrical conductivity (up to 113.8 S/cm), hydrophobicity, and electromagnetic interference shielding effectiveness, while preserving the porosity of the material [13].

6. MILITARY APPLICATION

After discussing the integration of flexible energy devices into textile structures, it is important to consider their practical role in military applications. Modern wearable military systems require reliable, lightweight, and efficient energy sources to power communication devices, navigation systems, and biomedical sensors [2]. Flexible electrochemical energy sources provide a more uniform distribution of mass across uniforms and equipment, while supporting advanced wearable concepts such as smart uniforms with integrated systems for monitoring health status and tactical parameters [5].

In practical military applications, these technologies involve the direct integration of energy systems into uniforms, vests, and soldier equipment, allowing multiple devices to be powered without reliance on a centralized energy source [9].

These approaches are aligned with NATO soldier modernization programs, such as the “Future Soldier System” and related initiatives, which aim to digitalize and network the individual soldier as a combat platform. Within these systems, the soldier operates as a carrier of multiple electronic subsystems (communications, positioning, sensors), significantly increasing energy demands and necessitating distributed and flexible power solutions.

A specific application example includes powering wearable sensors for monitoring physiological parameters such as body temperature, heart rate, and fatigue level. These data enable real-time assessment of a soldier’s combat readiness, representing a key component of modern soldier system concepts [12].

Furthermore, NATO initiatives emphasize reducing logistical burden, where flexible and hybrid energy systems can significantly decrease the number of spare batteries a soldier must carry. The integration of multiple energy sources (storage + harvesting) enhances reliability, redundancy, and continuity of power supply under diverse operational conditions [12].

Overall, flexible electrochemical energy sources represent a key enabling technology for future soldier systems, as they support direct integration of energy functionalities into equipment, increase energy autonomy, and reduce logistical constraints.

7. CONCLUSION

Flexible electrochemical energy sources represent a key technological foundation for next-generation wearable electronic systems, particularly in smart textiles and military applications.

Their primary advantage lies in combining electrochemical performance with mechanical adaptability, enabling reliable operation under real-world conditions.

Comparative analysis shows that flexible systems complement rather than replace conventional batteries, forming hybrid energy architectures combining high energy density (batteries) and high power density (supercapacitors).

Advanced materials, particularly MXenes and their nanocomposites, significantly enhance conductivity, capacity, and mechanical stability.

Integration strategies such as fiber-based systems, printing, and coating enable distributed energy systems directly within textiles.

In military applications, these technologies support the “soldier-as-a-system” concept by reducing weight, improving ergonomics, and increasing energy autonomy.

Future research should focus on robust hybrid systems, interface optimization, and scalable manufacturing technologies.

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