IJEES

International Journal of Electrical Engineering and Sustainability (IJEES)

ISSN (online): 2959-9229

https://ijees.org/index.php/ijees/index

ISI 2023-2024: (0.557) Arab Impact Factor: 1.51 SJIF 2024 = 5.274

Volume 3 | Number 2 | April-June 2025 | Pages 01-18

Article

Materials of Supercapacitor: Applications and Developments

Mohamed Amer[1*], Ahmed Elmojarrush[2], Adel Alsosi[3]

[1,2,3] Aeronautical Engineering Department, College of Civil Aviation, Misrata, Libya

[*]Corresponding author: **amer6924@gmail.com**

Received: February 10, 2025 Accepted: March 25, 2025 Published: April 08, 2025

Abstract: Supercapacitors (SCs), also known as electrochemical capacitors, have emerged as promising energy storage devices due to their high-power density, rapid charge–discharge capabilities, and long cycle life. Central to their performance is the selection and optimization of materials used in electrodes, electrolytes, separators, and current collectors. This article presents a comprehensive review of the latest advancements in supercapacitor materials, focusing on carbon-based structures, metal oxides, conducting polymers, and emerging hybrid composites. The role of electrolytes—aqueous, organic, and ionic liquids—in determining the electrochemical window and overall device efficiency is also discussed. Furthermore, the article explores recent trends such as nanostructuring, sustainable material synthesis, and solid-state supercapacitor design. Applications of SCs across portable electronics, electric vehicles, renewable energy systems, and grid storage are examined in detail. Finally, the paper identifies existing challenges in enhancing energy density, mechanical stability, and cost-effectiveness, and highlights future perspectives including the use of AI-assisted material discovery and hybrid energy system integration.

Keywords: Supercapacitors, Material, Energy Storage, Applications.

1. Introduction

In the face of accelerating climate change and the global energy transition, the demand for efficient, reliable, and sustainable energy storage systems has intensified. Supercapacitors (SCs), also known as ultracapacitors or electrochemical capacitors, have emerged as promising alternatives or complements to conventional batteries and dielectric capacitors [1,2]. They offer unique advantages such as high-power density, rapid charging and discharging, long cycle life, and wide operating temperatures. These characteristics make them highly suitable for various modern applications, from portable electronics and electric vehicles (EVs) to renewable energy systems and industrial backup power. As energy storage technologies evolve to meet the demands of next-generation smart grids and green technologies, supercapacitors are gaining increased attention in research and industry alike [3-7].

The performance of a supercapacitor is primarily governed by the materials used in its electrodes, electrolytes, and separators. Among these, the electrode materials play the most critical role in determining the device's capacitance, energy density, rate capability, and long-term stability. Over the past two decades, extensive efforts have been made to explore and optimize a wide range of materials for supercapacitor electrodes [8-10]. These include traditional carbon-based materials such as activated carbon and carbon nanotubes, advanced nanostructured materials like graphene, and pseudocapacitive materials such as metal oxides and conducting polymers. The development of hybrid and composite materials, which combine the advantageous properties of multiple constituents, has further enhanced the electrochemical performance of supercapacitors, bridging the gap between energy density and power capability.

SCs function primarily as pulse current systems, engineered to deliver exceptionally high specific power—often exceeding 10,000 $W \cdot kg^{-1}$—for short durations typically under one minute. This unique capability renders them suitable for deployment either as standalone energy storage devices or in hybrid configurations with batteries, thereby enhancing overall power efficiency and prolonging cycle life in demanding applications such as hybrid electric vehicles, cranes, railway systems, and elevators [10-13]. The foundational concept of the SC was first introduced in 1957 through the issuance of an early patent. However, commercial interest in supercapacitor technology remained relatively limited until the 1990s, when its potential was increasingly recognized, particularly in the context of hybrid electric vehicle systems. Recent advancements have focused on optimizing the electrical performance of SCs through the development of advanced electrode materials, thereby expanding their applicability across diverse sectors [13-17].

In power electronics and electric drive systems, various types of supercapacitors are already integrated to address high instantaneous power demands, such as those required during system start-up and regenerative braking. As a result, SCs have emerged as a robust and reliable energy storage solution for numerous applications, including backup power systems designed to mitigate the impact of electrical power disruptions. In this direction, the fundamental components of a Superconducting is illustrated in Figure 1. Typically, the system consists of three primary elements: (i) a superconducting coil magnet—either based on low-temperature superconductors (LTS) or high-temperature superconductors (HTS), responsible for storing energy in the form of a persistent magnetic field; (ii) a cryogenic refrigeration unit that maintains the superconducting state by cooling the system below the critical temperature; and (iii) a cryogenic medium, typically liquid helium or nitrogen, used to facilitate and sustain the low-temperature environment required for superconductivity [17].

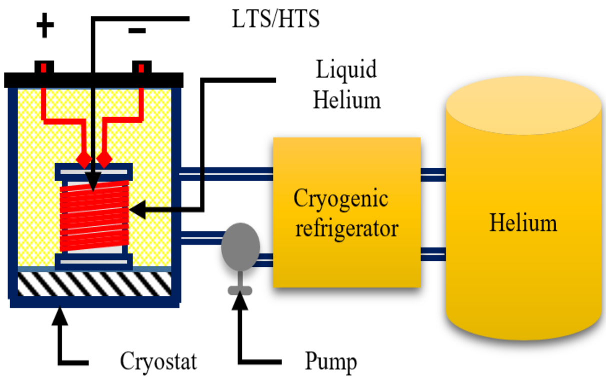
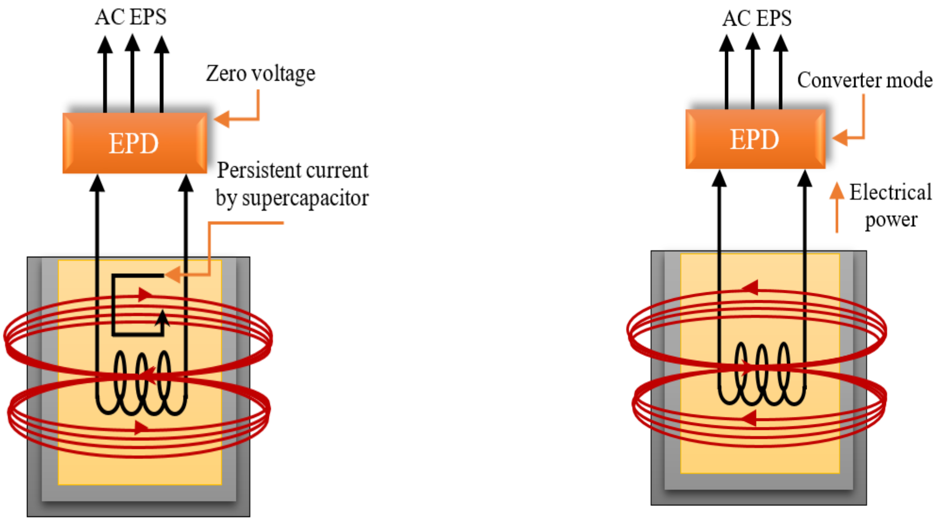


Figure 1. General components of SC [17].

In the context of supercapacitors (SCs), Figure 2 illustrates the fundamental structure and operational dynamics during (a) the charging process and (b) the discharging process. Unlike conventional batteries, SCs store energy through electrostatic mechanisms, which enable ultra-fast charging and discharging cycles. However, one of the notable drawbacks of SCs is their relatively high self-discharge rate, which can be particularly pronounced under cryogenic conditions. The immersion of SC systems in cryogenic liquids, such as liquid nitrogen, facilitates self-cooling but also introduces additional complexity in managing energy retention. Despite this, cryogenic cooling may offer specific advantages in reducing internal resistance and improving power performance, making SCs potentially viable for specialized applications in low-temperature environments.



(a) (b)

Figure 2. The main structure of SC, (a) the charging process, and (b) the discharging process [17].

In particular, supercapacitors (SCs) have garnered increasing attention over conventional batteries due to their exceptional charge-storage kinetics—characterized by significantly reduced discharge times (typically 1–10 seconds for SCs compared to 10–60 minutes for lithium-ion batteries)—and superior cyclic durability, often exceeding 30,000 hours in contrast to the approximately 500-hour lifespan of standard battery systems. Although traditionally constrained by relatively low energy density, recent breakthroughs in the development of advanced electrode materials and optimized electrolyte formulations have considerably enhanced the functional capabilities of SCs [17]. These innovations position supercapacitors as a compelling intermediary technology capable of bridging the performance gap between conventional batteries, fuel cells, and traditional electrolytic capacitors, particularly in applications demanding both high power density and extended operational longevity [18-21].

A few studies have explored the materials employed in supercapacitors, focusing on their applications and recent developments. These investigations provide valuable insights into the design, functionality, and performance optimization of electrode and electrolyte materials, which are critical to advancing supercapacitor technology. The following studies exemplify significant contributions to this evolving research landscape.

Ramzan et al. [22] underscore the potential of metal-organic frameworks (MOFs) as advanced electrode materials, emphasizing their inherently high specific surface area and the abundance of exposed active sites—attributes that critically enhance charge storage performance in SC applications. In particular, nickel-based bimetallic MOFs (Ni-BMOFs) have emerged as highly promising electroactive candidates for SCs. The incorporation of nickel within the MOF architecture significantly improves the intrinsic physicochemical properties, while also promoting the development of extensive porosity and structural defects through the synergistic interaction of the constituent metal ions. Nevertheless, the complex reaction mechanisms and the specific roles of active sites within Ni-BMOFs remain inadequately understood, primarily due to their heterogeneous structural nature.

Raza et al. [23] highlight the growing prominence of SCs as high-performance energy storage systems, particularly in response to the escalating demand for both low-power electronic applications—such as wearable and portable devices—and high-power military technologies, including guided missile systems and advanced naval warheads. The electrochemical performance of SCs is fundamentally governed by the intricate interplay between electrode and electrolyte materials, with their charge storage capacities being markedly influenced by the selection and design of these components, particularly through surface redox reactions and related interfacial phenomena.

Wang et al. [24] emphasize that the development of highly efficient and cost-effective supercapacitors represents one of the most promising strategies to address the intermittency and geographical disparities associated with the integration of renewable energy sources such as hydropower, wind, and solar energy. As the fundamental components governing the electrochemical performance of supercapacitors, electrode materials necessitate careful design and optimization. Among various candidates, nickel–carbon composites have garnered significant attention in recent years due to their low production cost, superior mechanical robustness, and exceptional electrochemical properties—particularly high specific capacitance and prolonged cycle life—stemming from the strong interfacial compatibility and synergistic interaction between nickel and carbon.

Zuo et al. [25] underscore the critical importance of designing and fabricating electrochemical energy storage systems that simultaneously deliver high energy and power densities alongside prolonged cycling stability. Among such systems, battery–supercapacitor hybrid devices (BSHs) have emerged as highly promising solutions, owing to their strategic integration of a high-capacity battery-type electrode with a high-rate capacitive electrode. This hybrid configuration enables BSHs to fulfill the rigorous demands of next-generation energy storage technologies, with potential applications spanning electric vehicles, smart power grids, and compact electronic or optoelectronic devices.

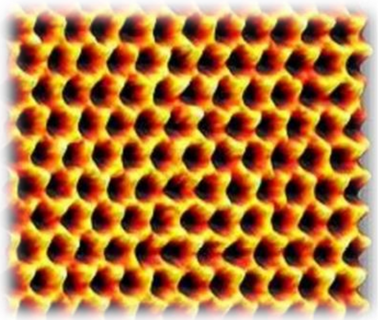
Despite these advancements, several challenges remain in terms of improving energy density, ensuring mechanical and chemical stability, lowering production costs, and enabling large-scale manufacturing. Moreover, the search for eco-friendly and sustainable materials has gained momentum as the global focus shifts toward greener technologies. This article presents a comprehensive overview of the current state of supercapacitor materials, highlighting their key properties, limitations, and recent developments. Furthermore, it explores the broad range of supercapacitor applications across multiple sectors and discusses emerging trends and future directions in material innovation aimed at enhancing the efficiency and adaptability of supercapacitors for next-generation energy storage systems.

2. Materials of Supercapacitors

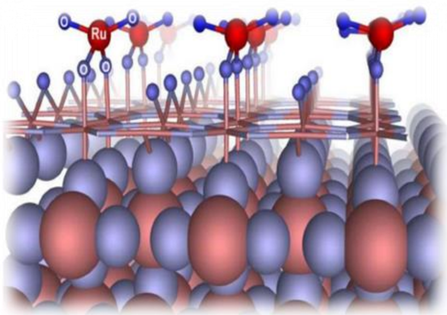
The performance and characteristics of supercapacitors (SCs) are fundamentally governed by the selection of electrode and electrolyte materials. In recent years, significant progress has been made in the investigation of advanced materials that can enhance the energy and power densities, cycle stability, and cost-efficiency of SC systems. Numerous comprehensive studies have focused on hierarchical and hexahedral electrode architectures, underscoring the central role materials will play in shaping the next generation of SC technologies. SC components are generally categorized into four primary material classes: electrode materials, electrolyte materials, separators, and current collectors [26].

SC electrodes are typically fabricated as thin conductive layers affixed to a current collector, forming the core sites for charge accumulation and transfer. The ideal electrode material must exhibit high electrical conductivity, chemical stability, low cost, low corrosion susceptibility, and environmental compatibility. Carbon-based materials remain the most widely used for electric double-layer capacitors (EDLCs) due to their structural versatility and electrochemical properties. Commonly employed carbonaceous materials include activated carbon (AC), carbon aerogels, carbon nanotubes (CNTs), graphene, and graphite [27-29]. Although activated carbon offers sufficient performance for EDLC electrodes, its electrical conductivity is lower than that of metallic conductors. A solid, compact form of activated carbon known as consolidated amorphous carbon (CAC) is extensively utilized, offering improved performance. Activated carbon fibers (ACFs), typically with diameters around 10 μm, are derived from processed activated carbon and offer high surface area-to-volume ratios. Another promising class is carbide-derived carbons (CDCs), which are tuneable nanoporous materials offering tailored pore size distribution for enhanced ion transport. Random porous carbon structures are also commonly explored due to their ease of fabrication and favorable surface area characteristics [28-30].

In addition to carbon-based materials, metal oxides such as manganese dioxide (MnO_2) and ruthenium dioxide (RuO_2) are widely used as pseudocapacitive electrode materials. These materials exhibit Faradaic charge storage behavior through fast and reversible redox reactions at or near the surface of the active electrode. As illustrated in Figure 3, these pseudocapacitors differ from EDLCs by incorporating Faradaic processes into the energy storage mechanism, thereby enabling significantly higher specific energies. Graphene, with its single-atom-thick hexagonal lattice structure, has also emerged as a high-performance material due to its exceptional conductivity, mechanical strength, and large specific surface area. Nanocomposite materials incorporating graphene and other conductive polymers continue to receive attention for their synergistic electrochemical advantages. All commercial hybrid SCs are asymmetric and incorporate an electrode.



(a)



(b)

Figure 3. (a) Scanning probe microscopy image of graphene; (b) pseudocapacitance surface of RuO2 cathode.

While a substantial portion of recent supercapacitor (SC) research has centered on electrode materials, the role of electrolytes in governing device performance is equally critical. Electrolytes, composed of a solvent and dissolved ionic species, facilitate ionic conductivity and determine the electrochemical environment within the SC cell. Their primary function is to provide mobile ions that enable charge separation and energy storage at the electrode–electrolyte interface. The choice of electrolyte significantly influences key performance parameters such as cell voltage, internal resistance, electrochemical stability, and energy density [30-33].

Currently, three main classes of electrolytes are employed in SCs: aqueous, organic, and ionic liquids. Aqueous electrolytes, commonly based on inorganic salts dissolved in water, offer high ionic conductivity and are cost-effective and environmentally benign. However, their use is limited by a narrow electrochemical stability window, with water undergoing decomposition at approximately 1.15 V per electrode. Despite this limitation, aqueous systems are preferred in applications where high specific power and rapid charge/discharge rates are prioritized. Organic electrolytes, which utilize organic solvents such as acetonitrile or propylene carbonate, offer a wider electrochemical stability window—typically allowing cell voltages in the range of 2.5 to 3.0 V. This enables significantly higher energy densities compared to aqueous systems [32-35]. Moreover, organic electrolytes are thermally more stable and suitable for broader temperature ranges. However, they are often more expensive and pose safety concerns due to their flammability and volatility. Ionic liquid electrolytes represent a third category, composed entirely of room-temperature molten salts. These systems are non-volatile, non-flammable, and thermally stable, allowing for operational voltages exceeding 3.5 V. Although their electrochemical and thermal stability is superior, ionic liquids suffer from lower ionic conductivity and higher viscosity, which can impede charge transport and reduce power performance [36-38]. Despite these drawbacks, they remain a promising choice for high-voltage, long-life SC applications.

In addition to separators, current collectors are essential in maintaining efficient electron flow throughout the SC system. Since most active electrode materials—particularly carbon-based structures—possess limited intrinsic electrical conductivity, external current collectors are required to facilitate charge transfer and support high charge–discharge currents. These collectors must be lightweight, corrosion-resistant, and capable of withstanding repetitive electrochemical cycling.

3. Supercapacitors: Emerging Energy Stores

With ongoing technological advancements in electrically powered systems—particularly in terms of charge/discharge cycle life, rapid energy transfer, and high specific power—supercapacitors (SCs) have emerged as viable and promising candidates across a wide spectrum of applications [39-42]. These include sectors demanding both high and stable energy throughput, such as hybrid electric vehicles, precision automation systems, microelectronic components, and portable consumer electronics. The inherent capability of SCs to deliver rapid and efficient power output makes them especially suitable for systems where high-power density is prioritized over long-duration energy storage. Nevertheless, the intrinsic limitation of SCs lies in their relatively low energy density compared to conventional batteries [42-44].

SCs serve as a crucial intermediary technology, effectively bridging the performance gap between conventional dielectric capacitors and electrochemical batteries in terms of cell voltage, specific power, and operational cost. While traditional dielectric capacitors are ideally suited for applications requiring rapid energy storage and release, offering instantaneous power delivery capabilities as high as 196 $kW \cdot kg^{-1}$—approximately 10 to 100 times greater than those of electrolytic capacitors—SCs extend these capabilities further by offering markedly enhanced energy densities. Specifically, SCs can attain energy densities in the range of 0.5–0.6 $kJ \cdot L^{-1}$, vastly surpassing the approximate 0.01 $Wh \cdot L^{-1}$ achievable with conventional dielectric capacitors [45-47]. These properties render SCs particularly advantageous for dynamic energy recovery applications, such as regenerative braking in transportation systems, where both high-power output and rapid response times are critical. Figure 4 illustrates Ragone plots for energy storage devices that are representative of the industry, including supercapacitors, fuel cells, and batteries.

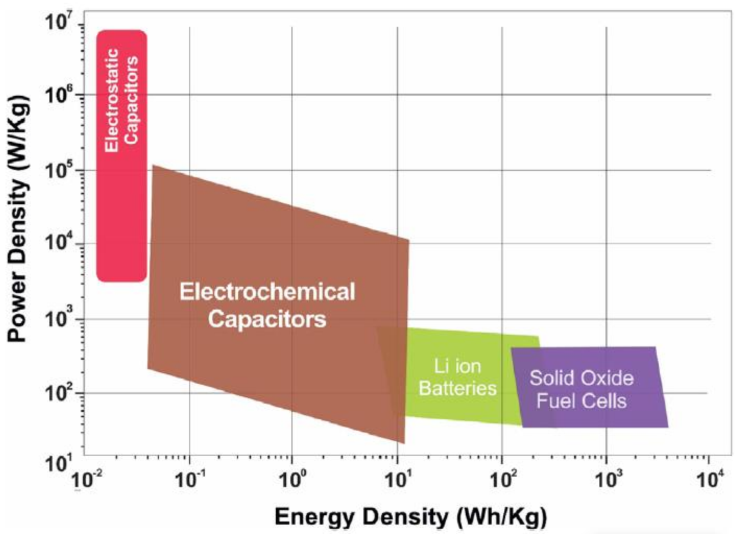


Figure 4. Ragone plots for energy storage devices that are representative of the industry, including supercapacitors, fuel cells, and batteries.

The distinctive attributes of SCs, including elevated power densities and swift charge–discharge kinetics, enable them to deliver stable and reliable power throughput across a range of high-performance systems. The relationship between energy and power density in energy storage devices is often illustrated using the Ragone plot, which provides a comparative graphical representation of various storage technologies. While the Ragone plot is a valuable tool for understanding the trade-off between energy and power density, it falls short of incorporating other essential parameters such as cost-effectiveness, long-term cycle stability, and safety [48-51]. Therefore, a comprehensive evaluation of energy storage systems must consider these additional metrics to accurately assess the practical viability and technological potential of supercapacitors in real-world applications.

The fundamental distinctions between batteries and SCs in terms of charge storage mechanisms, power limitations, energy density, charge/discharge rates, and service life are systematically illustrated in Figure 5. Unlike batteries, which are constrained by kinetically limited electrochemical processes during charging, SCs exhibit symmetrical high charge and discharge rates due to their electrostatic or surface redox-based energy storage mechanisms. A particularly notable advantage of SCs lies in their extended cycle life, ranging from 30,000 to over 1,000,000 cycles, significantly outperforming conventional batteries, which typically sustain only around 500 cycles. Furthermore, SCs are capable of near-instantaneous recharging—often within 1 to 10 seconds—whereas batteries require considerably longer recharge durations, typically between 10 and 60 minutes [50-53].

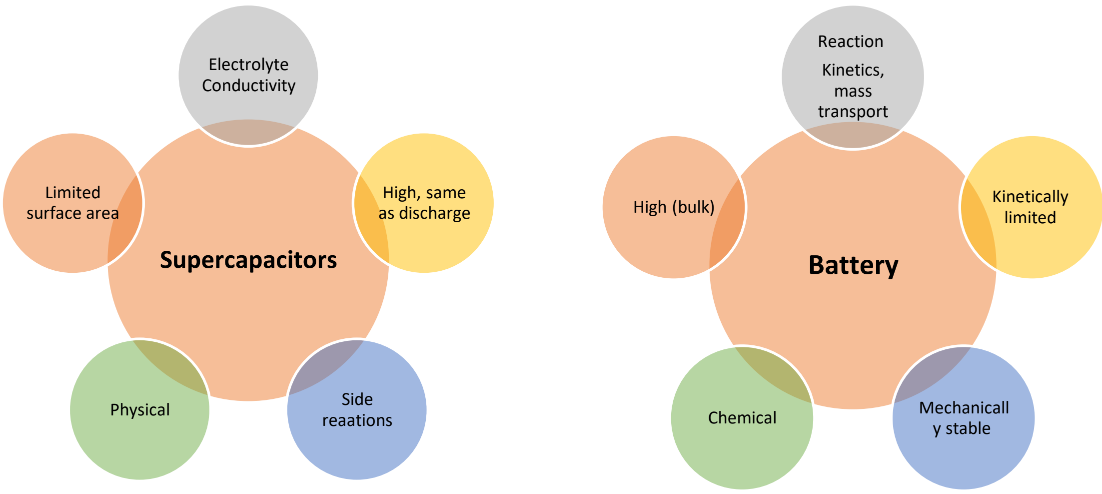


Figure 5. The comparison of batteries and SCs based on various operational parameters.

A comparative summary of key attributes—such as specific energy, cycle life, charge/discharge duration, and the underlying charge storage mechanism—between conventional capacitors, SCs, and batteries is presented in Table 1. This comparison highlights the superior durability of SCs, which stems from their non-Faradaic or quasi-Faradaic storage processes that avoid irreversible chemical transformations. Among the various parameters used to evaluate energy storage devices, operating temperature range is particularly critical, especially in harsh or variable environments. The thermal robustness of SCs can be significantly enhanced through strategic selection of electrode materials and electrolytes, enabling reliable performance across a broad temperature window ranging from –40 °C to 100 °C. In contrast, batteries typically operate within a narrower range of –20 °C to 60 °C, which further limits their applicability in extreme-temperature applications.

Table 1. A comparison of the fundamental performance metrics of various electrochemical energy storage systems [54-58].

Num.	Characteristics	Capacitor	Supercapacitor	Battery
1	Specific energy (Wh kg^{-1})	< 0.1	Up to 1091.0	Up to 1606.0
2	Specific power (W kg^{-1})	> 10,000	Up to 19,6000	< 1000
3	Discharge time	10^{-6} – 10^{-3} s	s to min	0.03–3 h
4	Charge time	10^{-6} – 10^{-3} s	s to min	1–5 h
5	Coulombic efficiency (%)	About 100.0	Up to 99.0	70.0–85.0
6	Cycle life	Almost infinite	> 500,000.0	About 1000.0
7	Charge storage determinants	Electrode area and dielectric	Microstructure of electrode and electrolyte	Thermodynamics and active mass

Table 1 provides a comparative overview of key performance metrics across three primary energy storage technologies: conventional capacitors, supercapacitors (SCs), and batteries. This comparative analysis reveals the unique operational advantages and limitations of each system, highlighting the contexts in which SCs serve as an effective intermediary solution. From a specific energy standpoint, batteries demonstrate the highest values (up to 1606 Wh·kg^{-1}), making them the preferred choice for applications requiring long-term energy storage. In contrast, capacitors exhibit extremely low energy density (<0.1 Wh·kg^{-1}), thereby limiting their role to high-speed but low-capacity charge/discharge tasks. Supercapacitors, however, offer a favorable compromise, achieving energy densities up to 1091 Wh·kg^{-1}—substantially higher than capacitors, though still lower than batteries—making them suitable for applications requiring moderate energy capacity with rapid accessibility. With regard to specific power, capacitors and SCs significantly outperform batteries. Capacitors deliver power in excess of 10,000 W·kg^{-1}, with SCs reaching up to 196,000 W·kg^{-1}, whereas batteries lag behind at <1,000 W·kg^{-1}. This reinforces the suitability of SCs for high-power, short-duration applications such as regenerative braking, voltage stabilization, and pulse power systems. The charge and discharge times further underscore the speed advantage of SCs. Capacitors operate on the microsecond to millisecond scale (10^{-6}–10^{-3} s), while SCs manage rapid energy exchange over seconds to minutes. Batteries, conversely, require significantly longer durations—typically ranging from 0.03 to 3 hours for discharge and 1 to 5 hours for full recharge. This latency limits their utility in time-sensitive applications, where SCs or capacitors are better suited. Coulombic efficiency, a critical measure of energy retention during cycling, is nearly ideal for capacitors (~100%) and remains high for SCs (up to 99%), but is relatively lower in batteries (70–85%) due to the inherent inefficiencies of Faradaic processes. Additionally, cycle life is one of the most distinguishing attributes of SCs, capable of enduring over 500,000 cycles, compared to ~1,000 cycles for batteries. Capacitors, by virtue of their purely electrostatic storage mechanism, exhibit almost infinite cycling potential.

4. Applications of Supercapacitors

Supercapacitors (SCs) have emerged as indispensable energy storage devices in a wide array of applications where high-power density, rapid energy delivery, and extended cycle life are essential as demonstrated in Figure 6. Their operational characteristics—bridging the gap between conventional capacitors and batteries—make them suitable for both standalone and hybrid energy systems. The following subsections highlight key application areas in which SCs are making a significant impact.

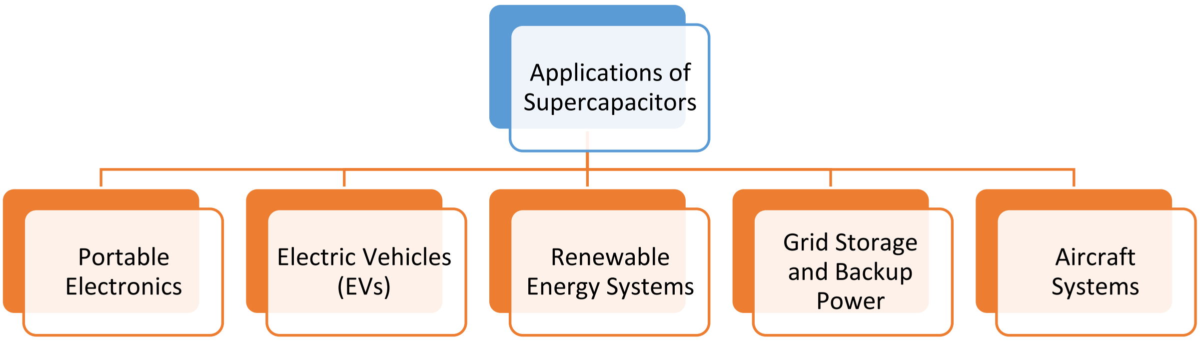


Figure 6. Several Applications of Supercapacitors.

A. Portable Electronics

In the domain of portable electronic devices, supercapacitors are increasingly utilized due to their ability to deliver rapid bursts of energy and support fast recharge cycles. Devices such as digital cameras, smartwatches, fitness trackers, and wireless audio systems benefit from the SC's low equivalent series resistance (ESR) and excellent power performance [59-61]. These devices often require immediate energy availability during short, high-demand intervals—for instance, powering camera flashes or initiating Bluetooth connectivity—where traditional batteries may fall short due to slower electrochemical kinetics. Moreover, the high durability and compact form factor of SCs contribute to extended product lifespan and enhanced user convenience, particularly in wearable technologies.

B. Electric Vehicles (EVs)

Electric mobility systems, especially electric vehicles (EVs) and hybrid electric vehicles (HEVs), represent one of the most transformative application areas for SCs. SCs are particularly valuable in regenerative braking systems, where kinetic energy during deceleration is recovered and stored for reuse. Their fast charge–discharge capability allows for efficient energy capture and immediate redeployment, thus improving overall energy efficiency and reducing fuel consumption or battery strain. In addition to regenerative braking, SCs provide auxiliary power for functions such as engine start-stop systems, suspension controls, and onboard electronics [62-64]. Their robustness over extensive charge–discharge cycles and wide temperature tolerances makes them highly reliable in dynamic automotive environments.

C. Renewable Energy Systems

In renewable energy systems, supercapacitors play a vital role in energy smoothing, peak shaving, and load balancing. Given the intermittent nature of solar and wind energy sources, energy storage systems must rapidly buffer fluctuations and maintain consistent power delivery. SCs are well-suited for these tasks due to their superior cycling ability and fast response times. When integrated with photovoltaic (PV) panels or wind turbines, SCs help regulate output by compensating for rapid changes in input or load demand. This improves the reliability and performance of microgrids, hybrid systems, and distributed energy networks, ensuring stability and reducing dependency on fossil-fuel-based grid support [65-70].

D. Grid Storage and Backup Power

Supercapacitors are also being adopted in grid-scale and backup power applications, where rapid energy availability and resilience are critical. In uninterruptible power supply (UPS) systems, SCs provide immediate power during outages or transitions, buying valuable time for backup generators or batteries to activate. They are also used for grid frequency stabilization, mitigating short-term voltage drops and maintaining power quality across transmission networks. SCs can respond within milliseconds, making them ideal for mitigating the effects of power fluctuations and transient disturbances. Their long operational life and low maintenance requirements further enhance their appeal for utility-scale deployment [71-75].

E. Aircraft Systems

Supercapacitors are increasingly being integrated into modern aircraft systems due to their high-power density, rapid charge/discharge capability, and long cycle life. They play a crucial role in emergency power backup, engine start systems, flight control actuation, and avionics power stabilization. In hybrid-electric and fully electric aircraft, supercapacitors complement batteries by handling peak power loads during takeoff and landing, thereby optimizing energy efficiency and extending battery life. Additionally, they enhance braking energy recovery, support electric de-icing systems, and improve UAV performance. Their ability to provide instant power, reduce reliance on hydraulic systems, and increase overall energy efficiency makes them a vital component in advancing More Electric Aircraft (MEA) and sustainable aviation technologies [76-84].

To sum up, the versatility of supercapacitors across a wide range of modern applications underscores their pivotal role in the evolving energy storage landscape. From portable electronics to electric vehicles, and from renewable energy integration to grid stabilization, SCs have demonstrated unique advantages where rapid charge–discharge cycles, high power density, and long operational lifetimes are paramount. Their ability to complement or replace traditional batteries in transient power-demand scenarios not only enhances system performance but also contributes to improved energy efficiency and sustainability. As technological advances continue to optimize the material properties and system integration of SCs, their deployment is expected to expand further into emerging sectors such as smart infrastructure, advanced robotics, and green mobility. Ultimately, the growing adoption of supercapacitors reflects a broader shift toward flexible, high-performance energy storage solutions capable of meeting the demands of next-generation electronic and power systems.

5. Recent Developments and Trends of Supercapacitor

Ongoing innovations in material science, device engineering, and fabrication techniques continue to push the boundaries of supercapacitor (SC) performance. These advancements not only address limitations in energy density and device integration but also align with broader trends in sustainability, miniaturization, and multifunctionality. Several key developments have emerged in recent years as illustrated in Figure 7, each offering transformative potential for the next generation of energy storage technologies [85-91].

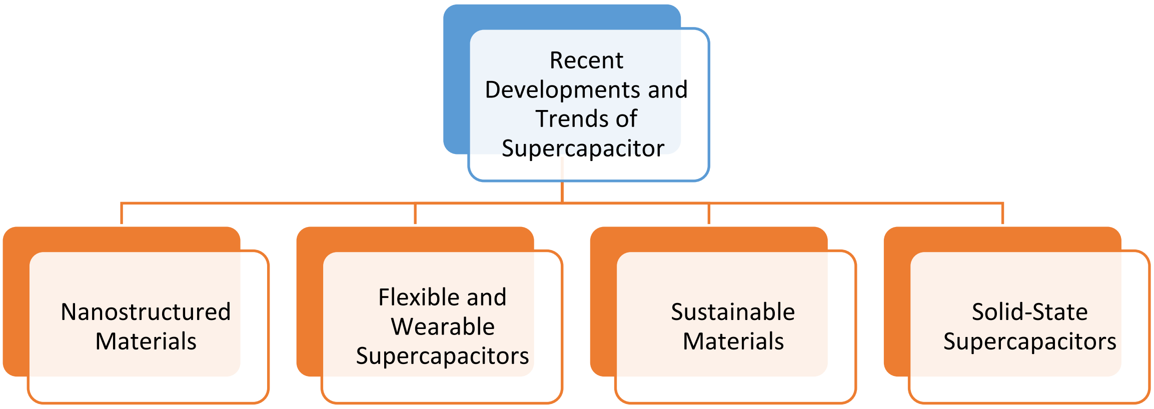


Figure 7. Recent developments and trends aspect of Supercapacitor.

A. Nanostructured Materials

The use of nanostructured materials has significantly improved the electrochemical performance of SCs by enhancing surface area, charge transport kinetics, and electrode–electrolyte interactions. Nanomaterials such as graphene, carbon nanotubes (CNTs), transition metal dichalcogenides (TMDs), and metal–organic frameworks (MOFs) have been engineered into complex architectures to maximize active surface sites and minimize ion diffusion paths.

B. Flexible and Wearable Supercapacitors

Driven by the rise of wearable and flexible electronics, researchers have developed flexible supercapacitors that can conform to non-planar surfaces and withstand mechanical deformation without performance degradation. These devices are fabricated using flexible substrates such as polymers, textiles, or paper, and incorporate stretchable current collectors and gel-based electrolytes. Applications include smart textiles, health monitoring systems, and foldable electronic devices.

C. Sustainable Materials

In response to environmental concerns and material scarcity, increasing efforts have focused on developing supercapacitors from renewable and biodegradable sources. Biomass-derived carbons—produced from materials such as coconut shells, wood, agricultural waste, and even food scraps—have demonstrated favorable surface properties, tunable porosity, and sufficient conductivity for SC applications. These eco-friendly materials reduce reliance on petrochemical-based carbons and lower the environmental footprint of SC production. Furthermore, green synthesis routes utilizing low-temperature and solvent-free processing have been explored to improve the sustainability of electrode fabrication.

D. Solid-State Supercapacitors

Solid-state SCs represent a significant shift in supercapacitor design by replacing liquid electrolytes with solid or gel-based electrolytes. These devices offer superior safety, improved mechanical integrity, and greater packaging flexibility—critical features for miniaturized and embedded systems. Solid-state designs eliminate leakage risks and enable thinner, compact architectures suitable for integration into microelectronic and biomedical devices. Despite challenges related to ionic conductivity and interface compatibility, ongoing research in polymer electrolytes, ionic gels, and composite systems is steadily improving the performance and reliability of solid-state SCs.

To end up, the recent advancements in supercapacitor technology reflect a dynamic convergence of materials science, device innovation, and sustainability. The integration of nanostructured materials has significantly enhanced electrochemical performance by improving charge transport and surface interactions, while the emergence of flexible and wearable supercapacitors has opened new frontiers in next-generation electronics. Concurrently, the exploration of sustainable, biomass-derived materials and environmentally friendly synthesis methods aligns with global imperatives for green energy solutions. The development of solid-state supercapacitors further exemplifies the transition toward safer, compact, and more versatile energy storage platforms.

6. Challenges and Future Perspectives

A. Challenges

Although supercapacitors (SCs) have undergone remarkable advancements in recent years—particularly in electrode materials, device architectures, and application domains—a number of persistent challenges continue to constrain their widespread adoption and integration into next-generation energy systems. Addressing these technical, economic, and scalability-related limitations will be crucial for unlocking the full potential of SCs across diverse sectors.

- Balancing Energy and Power Density

One of the most fundamental challenges in supercapacitor development lies in overcoming the trade-off between energy density and power density. SCs are inherently designed for rapid energy delivery, enabling them to achieve power densities significantly higher than traditional batteries. However, this advantage comes at the expense of energy density, which remains markedly lower. While conventional batteries can store large quantities of energy for prolonged discharge, SCs typically offer only short-term energy supply. Bridging this performance gap without sacrificing the rapid charge–discharge capabilities of SCs is a key area of ongoing research. Hybrid devices, which combine electric double-layer capacitance (EDLC) with pseudocapacitance, offer a promising pathway to enhance energy density. However, these hybrids often face challenges related to structural complexity, reduced cycle life, and increased internal resistance, necessitating careful design optimization.

- Improving Cycle Life and Mechanical Stability

Although SCs generally exhibit superior cycle life compared to batteries—often exceeding hundreds of thousands of cycles—certain materials and designs, particularly those involving pseudocapacitive or hybrid electrodes, can suffer from degradation over extended use. Repeated ion intercalation, structural strain, and electrochemical instability can lead to loss of capacitance, increased internal resistance, and mechanical failure. These issues are particularly critical in flexible and wearable SCs, where mechanical deformation adds another layer of complexity. Strategies such as surface modification, nanostructuring, and the incorporation of flexible binders and substrates have shown potential to enhance mechanical integrity and electrochemical durability. Nevertheless, developing robust, long-life SCs that can perform reliably under dynamic operating and environmental conditions remains a major technical hurdle.

- Scaling Up Low-Cost and Sustainable Material Production

The development of advanced electrode and electrolyte materials—such as graphene, carbon nanotubes, transition metal oxides, and ionic liquids—has dramatically improved SC performance in laboratory settings. However, the scalability and economic viability of these materials remain questionable. High costs, complex synthesis processes, and limited resource availability often prevent their commercialization at a meaningful scale. Moreover, environmentally friendly production techniques are still under development. The shift toward biomass-derived carbons, green chemistry, and low-temperature, solvent-free synthesis methods offer a more sustainable pathway, but further optimization is required to ensure consistent material quality, electrochemical performance, and supply chain feasibility.

B. Future Perspectives

To overcome these challenges, future research should be directed toward several key areas:

- Development of Multi-functional Hybrid Materials

Designing electrodes that combine EDLC and pseudocapacitive behavior in a controlled and stable manner can significantly boost energy and power densities. Material interfaces must be engineered to minimize resistance and degradation while maximizing charge storage capacity.

- AI-Assisted Materials Discovery and Device Optimization

Machine learning (ML) and artificial intelligence (AI) are emerging as powerful tools for accelerating the discovery of novel materials, predicting performance, and optimizing device parameters. AI-driven simulations can reduce experimental costs and identify optimal material combinations and operating conditions.

- Integration into Hybrid Energy Systems

SCs should be increasingly considered as part of hybrid energy storage systems, working in tandem with batteries or fuel cells to combine high energy density with fast power delivery. Such integration can support applications in electric vehicles, smart grids, aerospace systems, and remote energy management.

- Advancement of Solid-State and Flexible Architectures

The development of solid-state SCs and flexible/wearable configurations will open up new possibilities in biomedical devices, wearable electronics, and IoT applications. These formats require further innovation in electrolyte materials, substrate design, and encapsulation techniques.

- Standardization and Commercial Scaling

Efforts must be made to bridge the gap between academic innovation and industrial practice through standardized testing protocols, long-term reliability studies, and cost-performance benchmarking.

In summary, while supercapacitors have established themselves as critical components in modern energy storage ecosystems, addressing their current limitations through interdisciplinary research and engineering innovation will be vital to achieving their full potential. With targeted efforts in material design, system integration, and sustainable manufacturing, SCs are poised to become a cornerstone technology in the global transition to resilient, high-efficiency, and low-carbon energy solutions.

7. Conclusions

Materials play a pivotal role in shaping the performance, longevity, and adaptability of supercapacitors in modern energy systems. Recent developments in electrode design—ranging from porous carbon-based materials to pseudocapacitive metal oxides and conductive polymers—have significantly improved energy storage capabilities. Advances in electrolyte chemistry and separator engineering have further enhanced the charge–discharge dynamics and operating voltage of SCs. Emerging technologies, such as flexible, solid-state, and biomass-derived SCs, are expanding the scope of applications while promoting environmental sustainability. Despite these achievements, challenges persist in balancing energy and power density, ensuring long-term mechanical and electrochemical stability, and scaling up the production of high-performance materials at low cost. Looking forward, interdisciplinary approaches that combine materials science, nanotechnology, and artificial intelligence are expected to accelerate the development of next-generation supercapacitors. These innovations will not only meet the growing demands for efficient energy storage but also drive the transition toward greener and more resilient energy infrastructures.

Author Contributions: Authors have contributed significantly to the development and completion of this article.

Funding: This article received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The author would likes to express their sincere gratitude to Research and Development Department, College of Civil Aviation Misrata, Libya for their invaluable support and resources throughout the course of this research.

Conflicts of Interest: The author(s) declare no conflict of interest.

ORCID
Mohamed Amer https://orcid.org/0009-0002-7918-7711
Ahmed Elmojarrush https://orcid.org/0009-0004-6314-0163
Adel Alsosi https://orcid.org/0009-0003-2148-0605

References

[1] A. U. Ammar *et al.*, "Lithium-induced defect centers in nanorod-shaped zinc oxide for supercapacitor applications," *Electrochimica Acta*, vol. 519, p. 145806, Feb. 2025, doi: https://doi.org/10.1016/j.electacta.2025.145806.

[2] P. Mohapatra and A. K. Barick, "Ionic liquids based polymer electrolytes for supercapacitor applications," *Journal of Power Sources*, vol. 626, p. 235749, Nov. 2024, doi: https://doi.org/10.1016/j.jpowsour.2024.235749.

[3] M. G. Tadesse, A. S. Ahmmed, and J. F. Lübben, "Review on Conductive Polymer Composites for Supercapacitor Applications," *Journal of Composites Science*, vol. 8, no. 2, p. 53, Feb. 2024, doi: https://doi.org/10.3390/jcs8020053.

[4] Muhammad Fakhar Shehzad, Ashraf M.M. Abdelbacki, J. Fatima, A. Kumar, M. Ali, and J. Kaur, "Development of Mn-doped SmCoO3 electrode material for supercapacitor application," *Materials Science and Engineering B*, vol. 311, pp. 117795–117795, Nov. 2024, doi: https://doi.org/10.1016/j.mseb.2024.117795.

[5] K. Dissanayake and D. Kularatna-Abeywardana, "A review of supercapacitors: Materials, technology, challenges, and renewable energy applications," *Journal of Energy Storage*, vol. 96, p. 112563, Aug. 2024, doi: https://doi.org/10.1016/j.est.2024.112563.

[6] Y. Cao *et al.*, "Challenge and technological trends of flexible solid-state supercapacitors," *Journal of Energy Storage*, vol. 97, p. 112837, Jul. 2024, doi: https://doi.org/10.1016/j.est.2024.112837.

[7] J. Lu *et al.*, "A review of advanced electrolytes for supercapacitors," *Journal of Energy Storage*, vol. 103, pp. 114338–114338, Nov. 2024, doi: https://doi.org/10.1016/j.est.2024.114338.

[8] A. Afif, S. M. Rahman, A. Tasfiah Azad, J. Zaini, M. A. Islan, and A. K. Azad, "Advanced materials and technologies for hybrid supercapacitors for energy storage – A review," *Journal of Energy Storage*, vol. 25, p. 100852, Oct. 2019, doi: https://doi.org/10.1016/j.est.2019.100852.

[9] B. K. Saikia, S. M. Benoy, M. Bora, J. Tamuly, M. Pandey, and D. Bhattacharya, "A brief review on supercapacitor energy storage devices and utilization of natural carbon resources as their electrode materials," *Fuel*, vol. 282, p. 118796, Dec. 2020, doi: https://doi.org/10.1016/j.fuel.2020.118796.

[10] Yu.M. Volfkovich, "High power supercapacitors. Review," *Journal of Electroanalytical Chemistry*, pp. 118290–118290, Apr. 2024, doi: https://doi.org/10.1016/j.jelechem.2024.118290.

[11] Abdullah Abodwair, Muhammet Guneser, M. Khaleel, Y. Nassar, Hala El-Khozondar, and A. Elbaz, "Feasibility Assessment of Hybrid Renewable Energy Based EV Charging Station in Libya," *Solar Energy and Sustainable Development*, vol. 13, no. 2, pp. 311–349, Nov. 2024, doi: https://doi.org/10.51646/jsesd.v13i2.292.

[12] Y. Wang, "Nanowire materials for supercapacitor electrode: Preparation, performance and prospects," *Journal of Energy Storage*, vol. 97, p. 112848, Jul. 2024, doi: https://doi.org/10.1016/j.est.2024.112848.

[13] J. Zhao and A. F. Burke, "Review on supercapacitors: Technologies and performance evaluation," *Journal of Energy Chemistry*, vol. 59, no. 1, pp. 276–291, Aug. 2021, doi: https://doi.org/10.1016/j.jechem.2020.11.013.

[14] H. Hu *et al.*, "A state-of-the-art review on biomass-derived carbon materials for supercapacitor applications: From precursor selection to design optimization," *The Science of The Total Environment*, vol. 912, pp. 169141–169141, Dec. 2023, doi: https://doi.org/10.1016/j.scitotenv.2023.169141.

[15] A. Alsharif *et al.*, "Impact of Electric Vehicle on Residential Power Distribution Considering Energy Management Strategy and Stochastic Monte Carlo Algorithm," vol. 16, no. 3, pp. 1358–1358, Jan. 2023, doi: https://doi.org/10.3390/en16031358.

[16] M. Khaleel, E. Yaghoubi, E. Yaghoubi, and M. Z. Jahromi, "The Role of Mechanical Energy Storage Systems Based on Artificial Intelligence Techniques in Future Sustainable Energy Systems," *Int. J. Electr. Eng. and Sustain.*, pp. 01-31, Oct. 2023, Accessed: Jan. 18, 2024. [Online]. Available: https://ijees.org/index.php/ijees/article/view/65

[17] M. Khaleel, Z. Yusupov, Y. Nassar, H. J. El-khozondar, A. Ahmed, and A. Alsharif, "Technical challenges and optimization of superconducting magnetic energy storage in electrical power systems," *e-Prime - Advances in Electrical Engineering Electronics and Energy*, vol. 5, pp. 100223–100223, Aug. 2023, doi: https://doi.org/10.1016/j.prime.2023.100223.

[18] M. M. Khaleel, Mohd Rafi Adzman, and Samila Mat Zali, "An Integrated of Hydrogen Fuel Cell to Distribution Network System: Challenging and Opportunity for D-STATCOM," *Energies*, vol. 14, no. 21, p. 7073, Oct. 2021, doi: https://doi.org/10.3390/en14217073.

[19] M. M. Khaleel, T. Mohamed Ghandoori, A. Ali Ahmed, A. Alsharif, A. J. Ahmed Alnagrat, and A. Ali Abulifa, "Impact of Mechanical Storage System Technologies: A Powerful Combination to Empowered the Electrical Grids Application," *2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, pp. 628–636, May 2022, doi: https://doi.org/10.1109/mi-sta54861.2022.9837670.

[20] A. Alsharif, C. W. Tan, R. Ayop, A. Ali Ahmed, M. Mohamed Khaleel, and A. K. Abobaker, "Power Management and Sizing Optimization for Hybrid Grid-Dependent System Considering Photovoltaic Wind Battery Electric Vehicle," *2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, pp. 645–649, May 2022, doi: https://doi.org/10.1109/mi-sta54861.2022.9837749.

[21] M. Khaleel *et al.*, "Towards hydrogen sector investments for achieving sustainable electricity generation," *Journal of Solar Energy and Sustainable Development*, vol. 13, no. 1, pp. 71–96, 2024, Available: https://www.ajol.info/index.php/jsesd/article/view/276744

[22] M. Ramzan *et al.*, "A roadmap to nickel-based bimetallic metal-organic frameworks for supercapacitor applications," *Coordination Chemistry Reviews*, vol. 532, p. 216547, Feb. 2025, doi: https://doi.org/10.1016/j.ccr.2025.216547.

[23] W. Raza *et al.*, "Recent advancements in supercapacitor technology," *Nano Energy*, vol. 52, no. 2211–2855, pp. 441–473, Oct. 2018, doi: https://doi.org/10.1016/j.nanoen.2018.08.013.

[24] L. Wang, X. Gao, D. Wang, H. Shang, Y. Zhao, and B. Zhang, "Nickel-carbon composites toward supercapacitor and self-charging systems: A review," *Fuel*, vol. 381, p. 133639, Nov. 2024, doi: https://doi.org/10.1016/j.fuel.2024.133639.

[25] W. Zuo, R. Li, C. Zhou, Y. Li, J. Xia, and J. Liu, "Battery-Supercapacitor Hybrid Devices: Recent Progress and Future Prospects," *Advanced Science*, vol. 4, no. 7, p. 1600539, Feb. 2017, doi: https://doi.org/10.1002/advs.201600539.

[26] Z. S. Iro, "A Brief Review on Electrode Materials for Supercapacitor," *International Journal of Electrochemical Science*, vol. 11, no. 12, pp. 10628–10643, Dec. 2016, doi: https://doi.org/10.20964/2016.12.50.

[27] P. Forouzandeh, V. Kumaravel, and S. C. Pillai, "Electrode Materials for Supercapacitors: A Review of Recent Advances," *Catalysts*, vol. 10, no. 9, p. 969, Aug. 2020, doi: https://doi.org/10.3390/catal10090969.

[28] R. Dubey and V. Guruviah, "Review of carbon-based electrode materials for supercapacitor energy storage," *Ionics*, vol. 25, no. 4, pp. 1419–1445, Feb. 2019, doi: https://doi.org/10.1007/s11581-019-02874-0.

[29] S. Chaudhary, M. Raja, and O. P. Sinha, "A review on the different types of electrode materials for aqueous supercapacitor applications," *Advances in Natural Sciences Nanoscience and Nanotechnology*, vol. 12, no. 1, pp. 015011–015011, Mar. 2021, doi: https://doi.org/10.1088/2043-6262/abe93e.

[30] T. E. Balaji, H. Tanaya Das, and T. Maiyalagan, "Recent Trends in Bimetallic Oxides and Their Composites as Electrode Materials for Supercapacitor Applications," *ChemElectroChem*, vol. 8, no. 10, pp. 1723–1746, Apr. 2021, doi: https://doi.org/10.1002/celc.202100098.

[31] K. S. Kumar, N. Choudhary, Y. Jung, and J. Thomas, "Recent Advances in Two-Dimensional Nanomaterials for Supercapacitor Electrode Applications," *ACS Energy Letters*, vol. 3, no. 2, pp. 482–495, Jan. 2018, doi: https://doi.org/10.1021/acsenergylett.7b01169.

[32] A. S. Lemine, M. M. Zagho, T. M. Altahtamouni, and N. Bensalah, "Graphene a promising electrode material for supercapacitors-A review," *International Journal of Energy Research*, vol. 42, no. 14, pp. 4284–4300, Aug. 2018, doi: https://doi.org/10.1002/er.4170.

[33] B. Arumugam, Mayakrishnan Gopiraman, S. Manickavasagam, Seong Cheol Kim, and Ramkumar Vanaraj, "An Overview of Active Electrode Materials for the Efficient High-Performance Supercapacitor Application," *Crystals*, vol. 13, no. 7, pp. 1118–1118, Jul. 2023, doi: https://doi.org/10.3390/cryst13071118.

[34] W. Yang *et al.*, "Graphene in Supercapacitor Applications," *Current Opinion in Colloid & Interface Science*, vol. 20, no. 5–6, pp. 416–428, Oct. 2015, doi: https://doi.org/10.1016/j.cocis.2015.10.009.

[35] K. O. Oyedotun *et al.*, "Advances in Supercapacitor Development: Materials, Processes, and Applications," *Journal of Electronic Materials*, vol. 52, no. 1, pp. 96–129, Oct. 2022, doi: https://doi.org/10.1007/s11664-022-09987-9.

[36] K. Deng *et al.*, "Nonflammable organic electrolytes for high-safety lithium-ion batteries," *Energy Storage Materials*, vol. 32, pp. 425–447, Nov. 2020, doi: https://doi.org/10.1016/j.ensm.2020.07.018.

[37] B. Flamme *et al.*, "Guidelines to design organic electrolytes for lithium-ion batteries: environmental impact, physicochemical and electrochemical properties," *Green Chemistry*, vol. 19, no. 8, pp. 1828–1849, 2017, doi: https://doi.org/10.1039/c7gc00252a.

[38] M. Li *et al.*, "Electrolytes in Organic Batteries," *Chemical Reviews*, vol. 123, no. 4, pp. 1712–1773, Feb. 2023, doi: https://doi.org/10.1021/acs.chemrev.2c00374.

[39] D. Majumdar, M. Mandal, and S. K. Bhattacharya, "Journey from supercapacitors to supercapatteries: recent advancements in electrochemical energy storage systems," *Emergent Materials*, vol. 3, no. 3, pp. 347–367, May 2020, doi: https://doi.org/10.1007/s42247-020-00090-5.

[40] M. R. Benzigar, Venkata D.B.C. Dasireddy, X. Guan, T. Wu, and G. Liu, "Advances on Emerging Materials for Flexible Supercapacitors: Current Trends and Beyond," *Emergent Materials*, vol. 30, no. 40, pp. 2002993–2002993, Aug. 2020, doi: https://doi.org/10.1002/adfm.202002993.

[41] M. I. A. Abdel Maksoud *et al.*, "Advanced materials and technologies for supercapacitors used in energy conversion and storage: a review," *Environmental Chemistry Letters*, vol. 19, no. 1, pp. 375–439, Aug. 2020, doi: https://doi.org/10.1007/s10311-020-01075-w.

[42] M. F. Iqbal *et al.*, "Supercapacitors: An Emerging Energy Storage System," *Advanced Energy and Sustainability Research*, Mar. 2025, doi: https://doi.org/10.1002/aesr.202400412.

[43] Yedluri Anil Kumar, N. Roy, T. Ramachandran, M. Hussien, Md Moniruzzaman, and Sang Woo Joo, "Shaping the future of energy: The rise of supercapacitors progress in the last five years," *Journal of Energy Storage*, vol. 98, pp. 113040–113040, Jul. 2024, doi: https://doi.org/10.1016/j.est.2024.113040.

[44] Mert Akın and X. Zhou, "Recent advances in solid-state supercapacitors: From emerging materials to advanced applications," *International Journal of Energy Research*, vol. 46, no. 8, pp. 10389–10452, Apr. 2022, doi: https://doi.org/10.1002/er.7918.

[45] M. Salanne *et al.*, "Efficient storage mechanisms for building better supercapacitors," *Nature Energy*, vol. 1, no. 6, pp. 1–10, May 2016, doi: https://doi.org/10.1038/nenergy.2016.70.

[46] A. Dutta, S. Mitra, M. Basak, and T. Banerjee, "A comprehensive review on batteries and supercapacitors: Development and challenges since their inception," *Energy Storage*, Apr. 2022, doi: https://doi.org/10.1002/est2.339.

[47] J. Sun, B. Luo, and H. Li, "A Review on the Conventional Capacitors, Supercapacitors, and Emerging Hybrid Ion Capacitors: Past, Present, and Future," *Advanced Energy and Sustainability*

Research, vol. 3, no. 6, p. 2100191, Apr. 2022, doi: https://doi.org/10.1002/aesr.202100191.

[48] M. Khaleel, Z. Yusupov, A. A. Ahmed, A. Alsharif, A. Alarga, and I. Imbayah, "The Effect of Digital Technologies on Energy Efficiency Policy," *International Journal of Electrical Engineering and Sustainability (IJEES)*, vol. 1, no. 1, pp. 1–8, Jan. 2023, Accessed: Aug. 14, 2023. [Online]. Available: https://ijees.org/index.php/ijees/article/view/5

[49] T. S. Bhat, P. S. Patil, and R. B. Rakhi, "Recent trends in electrolytes for supercapacitors," *Journal of Energy Storage*, vol. 50, p. 104222, Jun. 2022, doi: https://doi.org/10.1016/j.est.2022.104222.

[50] A. Muzaffar, M. B. Ahamed, and C. M. Hussain, "Green supercapacitors: Latest developments and perspectives in the pursuit of sustainability," *Renewable and Sustainable Energy Reviews*, vol. 195, p. 114324, May 2024, doi: https://doi.org/10.1016/j.rser.2024.114324.

[51] A. Noori, M. F. El-Kady, M. S. Rahmanifar, R. B. Kaner, and M. F. Mousavi, "Towards establishing standard performance metrics for batteries, supercapacitors and beyond," *Chemical Society Reviews*, vol. 48, no. 5, pp. 1272–1341, 2019, doi: https://doi.org/10.1039/c8cs00581h.

[52] C. Zou, L. Zhang, X. Hu, Z. Wang, T. Wik, and M. Pecht, "A review of fractional-order techniques applied to lithium-ion batteries, lead-acid batteries, and supercapacitors," *Journal of Power Sources*, vol. 390, pp. 286–296, Jun. 2018, doi: https://doi.org/10.1016/j.jpowsour.2018.04.033.

[53] A. Ray and B. Saruhan, "Application of Ionic Liquids for Batteries and Supercapacitors," *Materials*, vol. 14, no. 11, p. 2942, May 2021, doi: https://doi.org/10.3390/ma14112942.

[54] A. Eftekhari, "Metrics for Fast Supercapacitors as Energy Storage Devices," *ACS Sustainable Chemistry & Engineering*, vol. 7, no. 4, pp. 3688–3691, Sep. 2018, doi: https://doi.org/10.1021/acssuschemeng.7b04532.

[55] T. S. Mathis, N. Kurra, X. Wang, D. Pinto, P. Simon, and Y. Gogotsi, "Energy Storage Data Reporting in Perspective—Guidelines for Interpreting the Performance of Electrochemical Energy Storage Systems," *Advanced Energy Materials*, vol. 9, no. 39, p. 1902007, Sep. 2019.

[56] J. M. Baptista, J. S. Sagu, U. W. KG, and K. Lobato, "State-of-the-art materials for high power and high energy supercapacitors: Performance metrics and obstacles for the transition from lab to industrial scale – A critical approach," *Chemical Engineering Journal*, vol. 374, pp. 1153–1179, Oct. 2019, doi: https://doi.org/10.1016/j.cej.2019.05.207.

[57] L. Yu and G. Z. Chen, "Supercapatteries as High-Performance Electrochemical Energy Storage Devices," *Electrochemical Energy Reviews*, vol. 3, no. 2, pp. 271–285, Feb. 2020, doi: https://doi.org/10.1007/s41918-020-00063-6.

[58] G. Z. Chen, "Supercapacitor and supercapattery as emerging electrochemical energy stores," *International Materials Reviews*, vol. 62, no. 4, pp. 173–202, Oct. 2016, doi: https://doi.org/10.1080/09506608.2016.1240914.

[59] S. Banerjee, B. De, P. Sinha, J. Cherusseri, and K. K. Kar, "Applications of Supercapacitors," *Handbook of Nanocomposite Supercapacitor Materials I*, pp. 341–350, 2020, doi: https://doi.org/10.1007/978-3-030-43009-2_13.

[60] Z. Zhao, K. Xia, Y. Hou, Q. Zhang, Z. Ye, and J. Lu, "Designing flexible, smart and self-sustainable supercapacitors for portable/wearable electronics: from conductive polymers," *Chemical Society Reviews*, vol. 50, no. 22, pp. 12702–12743, 2021, doi: https://doi.org/10.1039/d1cs00800e.

[61] W. Zhao, M. Jiang, W. Wang, S. Liu, W. Huang, and Q. Zhao, "Flexible Transparent Supercapacitors: Materials and Devices," *Advanced Functional Materials*, vol. 31, no. 11, Dec. 2020, doi: https://doi.org/10.1002/adfm.202009136.

[62] A. A. Ahmed, A. Alsharif, Triwiyanto Triwiyanto, M. Khaleel, C. W. Tan, and Razman Ayop, "Using of Neural Network-Based Controller to Obtain the Effect of Hub Motors Weight on Electric Vehicle Ride Comfort," *2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, pp. 189–192, May 2022, doi: https://doi.org/10.1109/mi-sta54861.2022.9837608.

[63] S. Rajagopal, R. Pulapparambil Vallikkattil, M. Mohamed Ibrahim, and D. G. Velev, "Electrode

Materials for Supercapacitors in Hybrid Electric Vehicles: Challenges and Current Progress," *Condensed Matter*, vol. 7, no. 1, p. 6, Jan. 2022, doi: https://doi.org/10.3390/condmat7010006.
[64] M. Khaleel, Abdussalam Ali Ahmed, and A. Alsharif, "Technology Challenges and Trends of Electric Motor and Drive in Electric Vehicle," *Int. J. Electr. Eng. and Sustain.*, vol. 1, no. 1, pp. 41–48, Nov. 2023, Available: https://ijees.org/index.php/ijees/article/view/14
[65] H. Rezk and A. Fathy, "Hydrogen reduction-based energy management strategy of hybrid fuel cell/PV/battery/supercapacitor renewable energy system," *Journal of energy storage*, vol. 86, pp. 111316–111316, May 2024, doi: https://doi.org/10.1016/j.est.2024.111316.
[66] Banele Mbendane, B. Abe, and C. Richards, "Analysis of Supercapacitors in Renewable Energy Systems for Managing Power Fluctuations," *International journal of energy research*, vol. 2024, pp. 1–13, Apr. 2024, doi: https://doi.org/10.1155/2024/4575761.
[67] Q. He *et al.*, "Supercapacitor-isolated water electrolysis for renewable energy storage," *Chemical Engineering Journal*, pp. 153461–153461, Jun. 2024, doi: https://doi.org/10.1016/j.cej.2024.153461.
[68] M. El-Sayed *et al.*, "Improving Micro-Grid Management: A Review of Integration of Supercapacitor across Different Operating Modes," *Heliyon*, pp. e42178–e42178, Jan. 2025, doi: https://doi.org/10.1016/j.heliyon.2025.e42178.
[69] Y. F. Nassar *et al.*, "Design of reliable standalone utility-scale pumped hydroelectric storage powered by PV/Wind hybrid renewable system," *Energy Conversion and Management*, vol. 322, pp. 119173–119173, Oct. 2024, doi: https://doi.org/10.1016/j.enconman.2024.119173.
[70] Omer. S. M. Jomah, N. Mohamed, A. A. Ahmed, A. Alsharif, M. Khaleel, and Y. F. Nassar, "Simulating Photovoltaic Emulator Systems for Renewable Energy Analysis," *2024 IEEE 4th International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, May 2024, doi: https://doi.org/10.1109/mi-sta61267.2024.10599755.
[71] M. Khaleel *et al.*, "The Impact of SMES Integration on the Power Grid: Current Topologies and Nonlinear Control Strategies," *Lecture Notes in Networks and Systems*, pp. 108–121, 2024, doi: https://doi.org/10.1007/978-3-031-66271-3_12.
[72] S. R., V. M., D. P., and S. R. P., "An efficient power management control strategy for grid-independent hybrid renewable energy systems with hybrid energy storage: Hybrid approach," *Journal of Energy Storage*, vol. 96, p. 112685, Aug. 2024, doi: https://doi.org/10.1016/j.est.2024.112685.
[73] M. Khaleel, Z. Yusupov, A. Ahmed, A. Alsharif, Y. Nassar, and Hala El-Khozondar, "Towards Sustainable Renewable Energy," *Applied solar energy*, vol. 59, no. 4, pp. 557–567, Aug. 2023, doi: https://doi.org/10.3103/s0003701x23600704.
[74] A. Bensalem, B. Toual, M. Elbar, M. Khaleel, and Z. Belboul, "A framework to quantify battery degradation in residential microgrid operate with maximum self-consumption based energy management system," *STUDIES IN ENGINEERING AND EXACT SCIENCES*, vol. 5, no. 1, pp. 354–370, Feb. 2024, doi: https://doi.org/10.54021/seesv5n1-021.
[75] M. F. Elmorshedy, M. R. Elkadeem, K. M. Kotb, I. B. M. Taha, and D. Mazzeo, "Optimal design and energy management of an isolated fully renewable energy system integrating batteries and supercapacitors," *Energy Conversion and Management*, vol. 245, p. 114584, Oct. 2021, doi: https://doi.org/10.1016/j.enconman.2021.114584.
[76] B. Wang, C. Wang, Z. Wang, S. Ni, Y. Yang, and P. Tian, "Adaptive state of energy evaluation for supercapacitor in emergency power system of more-electric aircraft," *Energy*, vol. 263, pp. 125632–125632, Jan. 2023, doi: https://doi.org/10.1016/j.energy.2022.125632.
[77] A. M. Fares, M. Kippke, M. Rashed, C. Klumpner, and S. Bozhko, "Development of a Smart Supercapacitor Energy Storage System for Aircraft Electric Power Systems," *Energies*, vol. 14, no. 23, p. 8056, Jan. 2021, doi: https://doi.org/10.3390/en14238056.
[78] M. Emimi, M. Khaleel, and A. Alkrash, "The Current Opportunities and Challenges in Drone Technology," *International Journal of Electrical Engineering and Sustainability (IJEES)*, vol. 1, no. 3,

pp. 74–89, Jul. 2023.

[79] M. Khaleel, S. A. Abulifa, and A. A. Abulifa, "Artificial Intelligent Techniques for Identifying the Cause of Disturbances in the Power Grid", *Brilliance*, vol. 3, no. 1, pp. 19-31, Mar. 2023.

[80] L. Barelli, G. Bidini, P. A. Ottaviano, F. Gallorini, and D. Pelosi, "Coupling Hybrid Energy Storage System to Regenerative Actuators in a More Electric Aircraft: Dynamic Performance Analysis and CO2 Emissions Assessment concerning the Italian Regional Aviation Scenario," *Journal of Energy Storage*, vol. 45, p. 103776, Jan. 2022, doi: https://doi.org/10.1016/j.est.2021.103776.

[81] M. Khaleel, A. A. Ahmed, and A. Alsharif, "Artificial Intelligence in Engineering", *Brilliance*, vol. 3, no. 1, pp. 32-42, Mar. 2023.

[82] Y. Song, J. Chen, X. Chen, and J. Chen, "Impedance modelling and analysis of the fuel cell-supercapacitor hybrid power supply system for electrical propulsion-based aircraft," *IET Conference Proceedings*, vol. 2024, no. 13, pp. 2303–2309, Jan. 2025, doi: https://doi.org/10.1049/icp.2024.3393.

[83] M. Khaleel, "Intelligent Control Techniques for Microgrid Systems", *Brilliance*, vol. 3, no. 1, pp. 56-67, Mar. 2023.

[84] M. Khaleel, Z. Yusupov, M. T. Güneşer, A. A. Abulifa, A. A. Ahmed, and A. Alsharif, "The effect of PEMFC on power grid using advanced equilibrium optimizer and particle swarm optimisation for voltage sag mitigation," in *2023 IEEE 3rd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2023, pp. 755–760.

[85] K. O. Oyedotun and B. B. Mamba, "New trends in supercapacitors applications," *Inorg. Chem. Commun.*, vol. 170, no. 113154, p. 113154, 2024.

[86] V. Molahalli, Chaithrashree, M. K. Singh, M. Agrawal, S. G. Krishnan, and G. Hegde, "Past decade of supercapacitor research – Lessons learned for future innovations," *J. Energy Storage*, vol. 70, no. 108062, p. 108062, 2023.

[87] G. Sriram *et al.*, "Recent trends in hierarchical electrode materials in supercapacitor: Synthesis, electrochemical measurements, performance and their charge-storage mechanism," *J. Energy Storage*, vol. 94, no. 112454, p. 112454, 2024.

[88] P. Sinha *et al.*, "Recent trends in supercapacitor electrode materials and devices," in *Handbook of Nanocomposite Supercapacitor Materials II*, Cham: Springer International Publishing, 2020, pp. 435–461.

[89] W. Zuo, R. Li, C. Zhou, Y. Li, J. Xia, and J. Liu, "Battery-supercapacitor hybrid devices: Recent progress and future prospects," *Adv. Sci. (Weinh.)*, vol. 4, no. 7, p. 1600539, 2017.

[90] X. Li, J. Zhang, B. Liu, and Z. Su, "A critical review on the application and recent developments of post-modified biochar in supercapacitors," *J. Clean. Prod.*, vol. 310, no. 127428, p. 127428, 2021.

[91] S. Satpathy, N. K. Misra, D. K. Shukla, V. Goyal, B. K. Bhattacharyya, and C. S. Yadav, "An in-depth study of the electrical characterization of supercapacitors for recent trends in energy storage system," *J. Energy Storage*, vol. 57, no. 106198, p. 106198, 2023.