

ADVANCES IN BATTERY-SUPERCAPACITOR HYBRID ENERGY STORAGE SYSTEMS: A COMPREHENSIVE REVIEW OF PERFORMANCE, CHALLENGES AND FUTURE PROSPECTS

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Abstract

Battery-supercapacitor hybrid energy storage systems (BS-HESSs) have emerged as promising solutions for improving energy storage performance, battery durability and power management in modern energy applications. The increasing use of renewable energy sources and the growing demand for reliable electricity have highlighted the need for storage technologies that can provide both high energy density and rapid power delivery. The present review examines the design strategies, materials, configurations, performance characteristics, economic aspects and future prospects of BS-HESSs. Different integration approaches, including passive, semi-active, converter-controlled, switched and material-level configurations, are discussed in terms of their operational benefits and limitations. Particular attention is given to energy management and control strategies that regulate power sharing between batteries and supercapacitors, reduce battery current peaks and improve system efficiency and service life. Literature demonstrates improvements in fuel economy, battery durability and capacity-fade costs under specific operating conditions. However, the benefits depend on system configuration, component sizing, operating temperature, load profiles and control methods. High initial costs, thermal management requirements, component ageing, system integration and long-term reliability remain important challenges.

Keywords: Battery-supercapacitor hybrid energy storage system; electrochemical energy storage; economic; configuration.

1. Introduction: -

Energy is essential for the operation of almost every sector. The global energy sector is currently undergoing a major transition. Although energy demand continues to rise and has reached record levels, the rapid development and adoption of renewable energy technologies are gradually changing the global energy mix [1]. India, as one of the world's most densely populated countries, has a growing demand for energy to support economic development and meet the needs of its population. To fulfil these requirements, the country has traditionally relied heavily on non-renewable energy sources. India ranks among the world's largest energy consumers, with China, Russia and the United States also being major energy-consuming nations [2]. The country faces increasing electricity demand and the Indian government aims to meet a substantial part of this demand through cleaner energy sources. In this direction, India has set a target of achieving 500 GW of non-fossil fuel-based energy capacity by 2030. However, it remains uncertain whether this target will be sufficient to meet the continuously rising demand for electricity and reduce dependence on coal [3]. The growing use of renewable energy also creates technical difficulties for power grids because sources such as solar and wind depend on changing weather and environmental conditions. These variations can lead to an imbalance between electricity generation and consumption, making it difficult to maintain a stable and reliable power supply. Energy storage systems (ESSs) have therefore become important for supporting the transition to cleaner energy by storing excess electricity when production is high and supplying it when demand exceeds generation [4].

For the effective utilization of renewable energy and the maintenance of grid stability during periods of peak electricity demand, the development of large-scale, affordable electrochemical energy storage (EES) systems is particularly important. These systems can store electrical energy in chemical or electrochemical form and release it when required, helping to reduce the gap between energy generation and consumption. Electrochemical energy storage, which includes different types of batteries and related storage technologies, is widely used because its capacity and design can be adapted to meet the requirements of different applications [5,6]. Batteries and supercapacitors are among the most widely studied and used electrochemical energy storage devices because of their efficient charge-storage characteristics, good cycle life and flexibility in design [7,8]. Batteries are particularly important because different battery chemistries are available for specific energy storage requirements. For example, sodium-sulphur batteries are also used for large-scale energy storage, particularly in applications requiring

substantial energy storage capacity and sustained power delivery. Flow batteries, meanwhile, are suitable for large storage installations and are being explored for renewable energy integration and power grid stabilization [9,10]. The selection of an appropriate battery technology depends on factors such as energy requirements, operating conditions, cost, safety and the intended application.

Despite their widespread use, batteries have certain limitations that affect their performance in applications requiring rapid and frequent changes in power demand. They generally provide higher energy density than supercapacitors, meaning that they can store more energy relative to their size or mass. However, their power density is comparatively lower, which limits their ability to respond efficiently to sudden changes in power demand or repeated high-power pulses. Battery operation also involves electrochemical reactions that generate heat, particularly under high-current or demanding operating conditions. Excessive heat can accelerate battery degradation and create safety risks if it is not properly managed. These limitations indicate that batteries alone may not be sufficient for applications requiring both high energy storage and rapid power delivery. Electrostatic capacitors can also store electrical energy and are useful in applications requiring quick charge and discharge, although their energy storage capacity is generally limited [11]. Supercapacitors, also known as ultracapacitors or electrochemical capacitors, have attracted considerable attention because of their ability to deliver high power, charge and discharge rapidly and withstand a large number of charge-discharge cycles. They can complement batteries in applications where sudden power fluctuations must be managed efficiently. A typical supercapacitor consists of two porous electrodes separated by a thin separator, with an electrolyte providing the medium for charge movement. The performance of a supercapacitor depends strongly on the properties and arrangement of its constituent materials. Factors such as electrode surface area, electrical conductivity, pore structure and electrolyte accessibility influence its energy storage capacity, power density, charging and discharging rates and overall service life [12,13]. Thus, batteries and supercapacitors offer different but complementary advantages, creating an opportunity to combine them in a single energy storage system.

In recent years, hybrid energy storage systems (HESSs), which combine two or more energy storage devices, have received growing attention in research and industrial applications. Unlike systems that rely on a single storage technology, HESSs are designed to combine the advantages of different devices to achieve a better balance between energy density, power density, response time and operating life. These systems have found applications in microgrids, urban rail transport, electric vehicles and other areas where energy demand can vary considerably over time. Figure 1 illustrates the major application areas of BS-HESSs, including transportation, renewable energy systems, smart grids and microgrids, industrial and backup power applications and electronic and energy storage systems. These applications utilize the complementary energy and power characteristics of batteries and supercapacitors to improve power delivery, stabilize energy supply, manage peak loads, recover braking energy and extend battery service life.

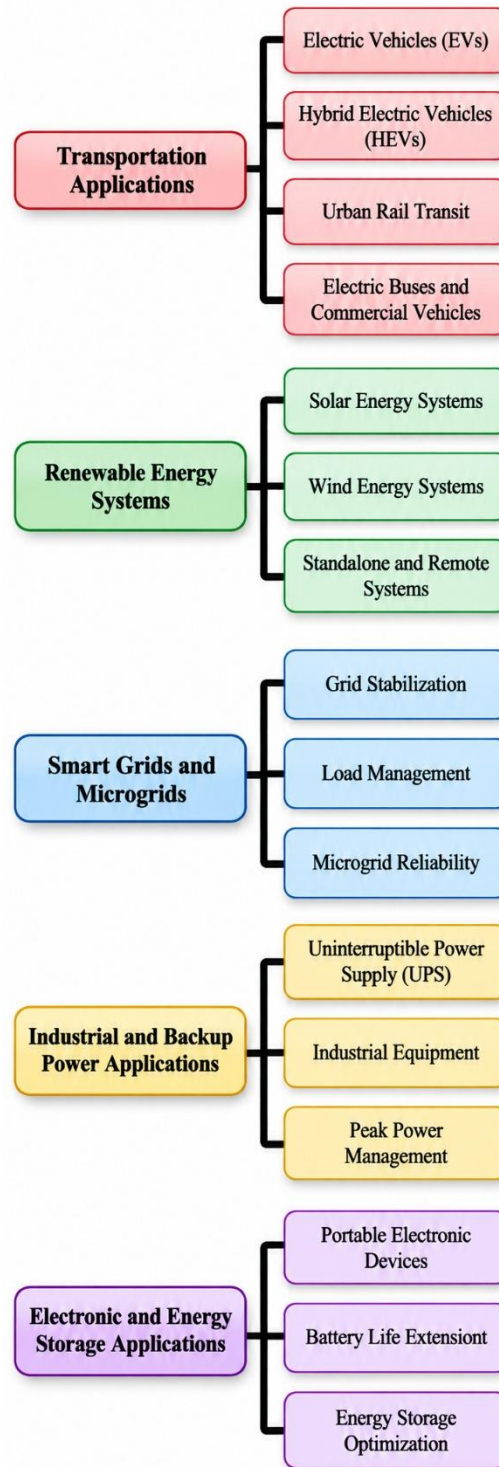


Fig.1. Major Applications of Battery–Supercapacitor Hybrid Energy Storage Systems (BS-HESSs)

Among the different hybrid configurations, the battery–supercapacitor hybrid energy storage system (BS-HESS) is particularly promising because it combines the high energy storage capability of batteries with the rapid power delivery and long cycle life of supercapacitors. In such systems, the battery can provide energy over longer periods, while the supercapacitor can respond to sudden increases or fluctuations in power demand. This division of work can reduce stress on the battery, improve system performance and potentially extend battery service life. However,

the practical implementation of BS-HESSs requires careful attention to several technical and economic factors. Key research areas include the development of battery management systems (BMSs) that are safe, fast and cost-effective; power conversion systems (PCSs) that support efficient energy transfer and flexible connections between multiple power sources and storage devices; energy management systems (EMSs) that distribute power effectively between the battery and supercapacitor; and control strategies that provide reliable performance under changing operating conditions [14,15]. In this context, the present paper aims to examine the recent developments in battery-supercapacitor hybrid energy storage systems, with particular emphasis on their performance, system configurations, energy management approaches, control strategies, major challenges and future prospects.

2. Design Strategies, Materials and Configurations of Battery-Supercapacitor Hybrid Energy Storage Systems: -

Battery-supercapacitor hybrid energy storage systems (BS-HESSs) can be developed using passive, semi-active, active or material-level integration approaches. Each configuration offers a different balance between system complexity, power management, efficiency and cost. Material-level hybridisation combines battery and supercapacitor characteristics within a single electrode arrangement, potentially reducing the need for additional power converters. A lithium iron phosphate (LiFePO_4) system incorporating a lithium anode and a composite cathode of LiFePO_4 and activated carbon achieved a specific capacity of 180 mAh g^{-1} of cathode material and was investigated under charging and discharging rates ranging from 0.1C to 10C [16]. Passive configurations provide a simpler alternative by directly connecting storage devices in parallel. For example, the direct integration of a vanadium redox flow battery with a supercapacitor reduced the voltage drop associated with the battery's internal resistance and improved energy delivery at higher currents. Equivalent electrical modelling also provided a basis for selecting the appropriate supercapacitor capacity, while economic and life-cycle assessments indicated potential cost and environmental benefits [17]. Similarly, the addition of an inductor to a passively connected battery-supercapacitor system improved its ability to stabilize power supply under intermittent renewable generation and fluctuating loads, with experimental tests supporting the modelling results [18]. These findings suggest that passive and material-level approaches can reduce system complexity, although their effectiveness depends on the electrical characteristics and operating conditions of the selected storage devices.

Semi-active and converter-controlled configurations offer greater flexibility in regulating power flow between batteries and supercapacitors. Their fabrication and design require appropriate matching of battery capacity, supercapacitor size, converter ratings and control parameters. In hybrid electric vehicles, comparisons of battery-supercapacitor and supercapacitor-battery arrangements showed that both could satisfy the required power demand when appropriately designed. However, the supercapacitor-battery configuration made better use of the supercapacitor's rapid power response and long cycle life, achieving a 7% improvement in fuel economy compared with battery-only storage in an experimental vehicle [19]. For urban commercial vehicles, the integration of supercapacitors with ZEBRA batteries through a bidirectional DC/DC converter reduced the effects of high charging and discharging currents, with the estimated improvement in battery lifespan reaching 52% under specific driving conditions [20]. Further optimization of energy management strategies using nonlinear programming and calculus of variations produced a control approach with up to 57% effectiveness in reducing battery current transients, supported by laboratory testing [21]. These results demonstrate that converter-based systems can improve power distribution and battery durability, but their additional components increase system complexity and may raise initial costs. Consequently, the benefits of advanced configurations must be evaluated against their converter requirements, control demands and overall system cost.

Energy management and control strategies are equally important because the performance of a hybrid system depends not only on its physical configuration but also on how power is shared between its components. Rule-based control systems can regulate battery current and maintain the supercapacitor's state of charge within a suitable operating range. Experimental evaluation has been used to assess their effects on energy efficiency, battery life and cost [22]. More advanced approaches combine filtering techniques with fuzzy logic to limit battery current peaks while maintaining the supercapacitor voltage within a desired range. In a 30kW experimental system, this strategy reduced the estimated battery capacity-fade cost by 44.42%, 30.44% and 57.16% under the New European Driving Cycle, highway driving cycle and Indian urban driving cycle, respectively, compared with battery-only storage [23]. Switched hybrid configurations provide another option by changing the connection between the battery, supercapacitor and DC bus according to operating requirements. An improved switched structure expanded the usable operating range of the supercapacitor and reduced its required installed capacity by 50% without

reducing its available energy; the proposed operating modes were evaluated through simulation and scaled experimental testing [24]. Collectively, these approaches highlight the importance of selecting a control strategy that balances battery protection, supercapacitor utilization, system efficiency and implementation complexity.

The economic value of BS-HESSs is particularly evident in applications involving frequent power fluctuations and repeated high-current operation. Under pulsed-load ageing tests, a lead-acid battery supported by supercapacitors completed 70% more cycles before reaching the end of its life than a battery-only system. The hybrid configuration also reduced battery capacity fade by 60%, limited the increase in internal resistance by 83% and lowered the amortized system cost by 17.6% [25]. These findings indicate that the higher initial investment associated with hybridisation may be offset by longer battery service life and lower replacement costs. However, the economic and technical benefits are influenced by temperature, component ageing and system sizing. A passive hybrid system designed to meet the demands of hybrid electric vehicles showed less temperature-dependent performance than a battery-only system, although the heat generated indicated the need for suitable thermal management. As the system aged, the battery's resistance increased more rapidly than the supercapacitor's resistance, leading to a greater supercapacitor contribution to current and a reduction in battery energy throughput, temperature rise and degradation [26]. This evidence suggests that hybridisation can improve operational durability, but thermal control and long-term performance must remain central considerations in system design.

Recent investigations combining simulation with experimental validation further support the role of supercapacitors in managing sudden load changes and reducing battery stress. Models developed using MATLAB/Simulink and tests involving resistive and dynamic loads have demonstrated the practical value of coordinating battery and supercapacitor operation. Agreement between simulated and experimental results strengthens confidence in the proposed system models, while also indicating the importance of appropriate component sizing and accurate representation of supercapacitor behaviour [27]. Nevertheless, the reported improvements cannot be treated as universal because they depend on the battery chemistry, hybrid topology, driving or load profile, control strategy, temperature and evaluation method. A configuration that performs well under short-duration laboratory tests may not deliver the same economic advantage during prolonged real-world operation. Therefore, future development should focus on standardized performance and ageing tests, optimized component sizing, effective thermal management, reliable control systems and life-cycle cost assessments. Such improvements are necessary to establish whether the gains in battery life, power delivery and operational efficiency justify the additional investment required for BS-HESS deployment.

3. Challenges and Future Prospects of Battery-Supercapacitor Hybrid Energy Storage Systems: -

Despite several advantages, the widespread application of BS-HESSs still faces several technical, economic and environmental challenges. The overall performance of these systems depends on the selection of suitable materials, the design and integration of storage components, effective power management and the ability to maintain safe and reliable operation over extended periods. In addition, the initial investment, system complexity, component degradation and difficulties in integrating hybrid systems with renewable energy sources and existing power networks can limit their practical use. Addressing these issues requires improvements in material development, system configuration, intelligent control strategies and manufacturing processes. The following are some of the major challenges faced by BS-HESSs:

- 1. Cost, Material Development and Environmental Sustainability:** The high initial cost of batteries, supercapacitors, power converters and control systems remains a major barrier to widespread adoption. Future research should focus on cost-effective and resource-abundant electrode materials, advanced composites, improved manufacturing techniques and recyclable components. Developing sustainable materials, safer battery chemistries and efficient recycling processes will help reduce environmental impacts while improving the economic feasibility of hybrid energy storage systems [28,29].
- 2. System Integration, Optimal Sizing and Performance Enhancement:** Integrating batteries and supercapacitors is challenging because of their different electrochemical characteristics, operating limits, charging-discharging behaviour and degradation mechanisms. Appropriate sizing and selection of passive, semi-active, or fully active configurations are essential to balance energy density, power delivery, efficiency and cost. Future studies should investigate advanced electrode architectures, three-dimensional porous structures and improved electrolytes to enhance electrochemical performance. Standardized communication

protocols and compatible power electronics are also necessary for effective integration with renewable energy systems, microgrids and electric vehicles [29,30].

3. **Intelligent Energy Management and Aging-Aware Control:** Batteries experience capacity loss and increasing internal resistance, while supercapacitors may exhibit increasing equivalent series resistance and leakage current during aging. Advanced energy management strategies should incorporate real-time state-of-health estimation, temperature monitoring and degradation models to optimize power sharing and extend component lifetimes. Model predictive control, fuzzy logic, machine learning and reinforcement learning offer promising approaches for adapting system operation to changing loads and operating conditions. Digital twins, Internet of Things (IoT)-enabled monitoring and edge computing may further improve real-time optimization, predictive maintenance and fault detection, although computational requirements, data availability and cybersecurity remain important concerns [31].
4. **Safety, Reliability and Long-Term Experimental Validation:** Differences in component degradation, thermal behaviour and failure mechanisms can affect the safety and reliability of hybrid systems. Future research should prioritize thermal management, protective mechanisms, fault detection and predictive maintenance. Standardized testing protocols and long-duration experimental investigations are needed to evaluate failure rates, system availability, degradation and performance under realistic operating conditions. Reliability assessment techniques, including Markov models, Monte Carlo simulation and fault-tree analysis, can help identify system vulnerabilities and improve design robustness [30,31].
5. **Renewable Energy Integration and Future Applications:** Battery-supercapacitor hybrid systems offer promising opportunities for renewable energy smoothing, peak-load management, regenerative braking, grid stabilization and vehicle-to-grid applications. Their future development will depend on improved bidirectional power management, intelligent control, standardized grid interfaces and supportive policy frameworks. Flexible and multifunctional devices based on advanced electrode architectures and gel or polymer electrolytes may also expand applications in wearable electronics and portable technologies. Greater collaboration among materials scientists, electrical engineers, control researchers, manufacturers and policymakers will be essential to translate laboratory advances into reliable, cost-effective and commercially viable systems [28,29,30].

4. Conclusion: -

The literature highlights the importance of selecting suitable system configurations, including passive, semi-active, converter-controlled, switched and material-level designs. While simpler configurations can reduce component requirements and initial costs, converter-based systems provide greater flexibility in power distribution and control. The choice of configuration must therefore reflect the specific requirements of the intended application. Energy management and control strategies play a central role in determining the overall performance of BS-HESSs. Appropriate control can reduce battery current fluctuations, limit degradation, improve energy utilization and potentially lower long-term operating costs. Experimental findings also indicate that hybridisation can improve fuel economy and extend battery service life under certain conditions. However, these improvements are not universal and depend on factors such as battery chemistry, supercapacitor capacity, operating temperature, load characteristics and control strategy. Moreover, the additional costs of power converters, control systems, thermal management and maintenance must be considered when assessing the economic benefits of hybrid storage. Despite substantial progress, challenges related to material costs, system integration, component ageing, safety and long-term reliability continue to limit wider adoption. Future research should prioritize affordable and environmentally sustainable materials, optimized component sizing, intelligent and ageing-aware energy management, effective thermal control and standardized experimental evaluation. Greater emphasis on long-term field testing and life-cycle economic and environmental assessments is also necessary to establish the practical benefits of these systems.

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