



# Supercapacitors and their Application

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## Abstract—

Supercapacitors, often referred to as Ultracapacitors, are electrochemical energy storage devices with high power density and moderate energy storage which serves as a bridge between the conventional capacitors and batteries. While conventional capacitors offer extreme power but negligible energy and batteries provide high energy density for long-term storage, Supercapacitors fill the gap between these technologies. By combining the rapid charge-discharge characteristics of conventional capacitors with comparatively enhanced energy storage capability associated with electrochemical systems, supercapacitors become highly suitable for applications that require substantial power delivery over short time interval. These distinct abilities of supercapacitors offer exceptional cycle stability, operational reliability and long service durability. The review focuses on the use of supercapacitors in power density and long cycle life applications, such as quick acceleration and regenerative braking in HEVs, power management in HESS, and battery-less electric vehicle technology based on supercapacitors with ultra-fast charging capabilities. In this paper, a comprehensive review of supercapacitor technology is presented, including the working principle, classification, materials, characteristics, and latest developments in supercapacitor technology. Moreover, the review critically discusses the applications of supercapacitors, such as RBS and HESS, along with the current challenges, limitations, and future research avenues for the betterment of supercapacitor technology.

**Keywords—** Supercapacitors; High Power Density; Hybrid Energy Storage System (HESS); Regenerative Braking System (RBS); Electric Vehicles; Energy Management



## I. INTRODUCTION

The use of capacitors for the storage of electrical energy dates back to before the invention of the battery in 1800 [1]. In the 18th century, scientists used Leyden jars, a form of capacitors, to store and produce electrical discharges of significant intensity. This contrasts sharply with the battery, as the storage of energy by a supercapacitor is governed by the fundamental principle of the storage of energy in the electrostatic field. This results in the high capabilities of a supercapacitor, as the storage of energy takes place at the nano-meter level, and the charge is separated by the electrostatic attraction of the ions to the polarized surface consequently leading to the ability of a supercapacitor to store and release energy over a very short period of time.

The current technology trends point to a rising need for effective and efficient energy storage systems. Conventional battery systems, though well-established, often face the problem of low power density, slow transient response, and increased internal resistance [2]. In situations where a large power surge is desired over a very short period of time, batteries often fail to deliver the desired power without compromising their useful life.

Supercapacitors are electrochemical energy storage devices with high power density and moderate energy storage which are charged through electrostatic charge accumulation at the electrode–electrolyte interface. They provide high power density, rapid charge–discharge capability, and long cycle life compared to conventional batteries. Their performance depends on electrode materials, electrolyte properties, and internal resistance, enabling efficient short-duration energy delivery in high-power applications [1]. Supercapacitors are broadly classified into three types, known as pseudo-capacitors, Electric Double layer Capacitors (EDLC) and hybrid Capacitors [2].

Hybrid Energy Storage Systems (HESS) in electric vehicles combine high energy density batteries with high power supercapacitors to improve overall system efficiency. Batteries provide sustained energy while supercapacitors handle instantaneous load variation. This energy storage architecture combines battery and supercapacitor to reduce stress on primary battery, suppress degradation and enhance operational life. Effective intelligent control strategies are required to regulate energy flow and maintain thermal stability [5].

Regenerative braking is an energy recovery mechanism in EV and hybrid vehicles which converts the kinetic energy produced by moving vehicle into electrical energy during deceleration [4]. This recovered energy is stored in energy storage devices such as batteries or supercapacitors, which improves the overall energy efficiency and extends driving range along with reducing the losses by mechanical braking.

The remainder of this paper is organized as follows; Section II discusses the fundamental working principles and electrical characteristics of supercapacitors, Section III presents the classification and structural configurations of supercapacitor devices, Section IV reviews various electrode materials and recent material innovations, Section V analyses major application areas including transportation and hybrid energy storage systems. Finally, Section VI summarizes the key findings and outlines future research prospects.

## II. LITERATURE REVIEW

Reviewing a number of research papers and writing a review article on supercapacitors and their applications is important to solidify the current knowledge on the topic, as this field is growing rapidly. A review article will help identify the challenges and opportunities that may be useful for further research [2].

In this review article, a systematic study of the available textbook, review articles, and some recent research articles is done which are related to the supercapacitor technology and hybrid energy storage systems for electric vehicles. The available literature has been compared in terms of the performance characteristics such as power density, energy density, cycle life, and efficiency of the device for its suitability in electric vehicles. The basic concepts such as regenerative braking, energy management systems, and battery-less electric vehicles have been compared in order to identify the areas of improvement in the near future.



### III. METHODOLOGY

The methodology for this review paper involved a systematic collection and analysis of existing literature regarding supercapacitor technology and its applications. The process was divided into the following steps:

#### A. Information Sourcing –

Research was gathered from academic databases including IEEE Access, Google Scholar, and ScienceDirect. We focused on highly cited review articles, recent research papers (primarily from 2015–2026), and technical textbooks.

#### B. Selection Criteria –

Papers were selected based on their relevance to three main areas: electrode material innovations, Hybrid Energy Storage Systems (HESS), and regenerative braking applications in electric vehicles.

#### C. Data Comparison -

We analyzed the results provided in these papers by comparing key performance metrics such as power density (W/kg), energy density (Wh/kg), and cycle life across different types of supercapacitors (EDLC, Pseudocapacitors, and Hybrid).

#### D. Synthesis -

The collected findings were combined to show the present advantages of supercapacitors over conventional batteries and the main technical challenges that still remain.

### IV. FUNDAMENTALS OF SUPERCAPACITORS

#### A. Fundamentals of supercapacitors

The Fundamental working principle of a supercapacitor is based on the parallel plate capacitance equation, where capacitance (C) is in relation with the dielectric constant of the electrolyte ( $\epsilon_r$ ), the dielectric constant of a vacuum ( $\epsilon_0$ ), the surface area of the electrode (A), and the distance between the electrodes (d) [2]. The Mathematical equation is as follows,

$$C = (\epsilon_0 \epsilon_r A) / d \quad [2]$$

Supercapacitors attain higher capacitance than conventional capacitors by utilizing electrodes with massive surface area and maintaining a nanometric separation distance between the charges [2]. Unlike conventional capacitors that move electrons between

electrodes, supercapacitors store energy electrostatically within the electrolyte through the polarization of ions [2].

#### B. Types of supercapacitors

Based on the charge storage technique [3], supercapacitors are classified as follows:

- 1) Electric Double-Layer Capacitor (EDLC) – Electric Double Layer Capacitor stores electrical energy through electrostatic accumulation at the electrode-electrolyte interface [2] without any chemical reaction. EDLC demonstrate high power density, rapid charge-discharge ability and reliable cycle stability and operational lifespan. These abilities make supercapacitor suitable for applications which require short-duration high power energy delivery.
- 2) Pseudo-capacitors - Pseudo-capacitors are electrochemical storages that have reversible redox reactions [2] occurring at or near electrode surface. These capacitors consist of electrodes, a separator, a current collector, and an electrolyte with metal oxide/conduction polymers. Pseudo-capacitors with short charging and high efficiency are well suit to rechargeable standalone power sources [2].
- 3) Hybrid Supercapacitors - Hybrid supercapacitors combine the non-faradaic [2] electrostatic charge storage mechanism of EDLCs with the faradaic [2] electrochemical charge storage mechanism of batteries or pseudo-capacitors [2]. This arrangement enhances the maximum output and energy density. Hybrid supercapacitors require longer charging time compared to both, EDLC's and Pseudo-Capacitors, and their life cycle is relatively shorter.

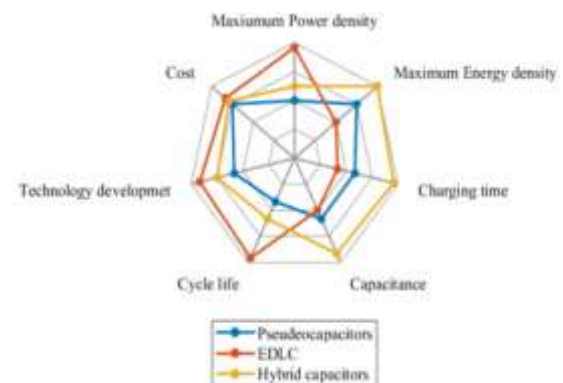


Fig. 1. Characteristics comparison of supercapacitor types [2]

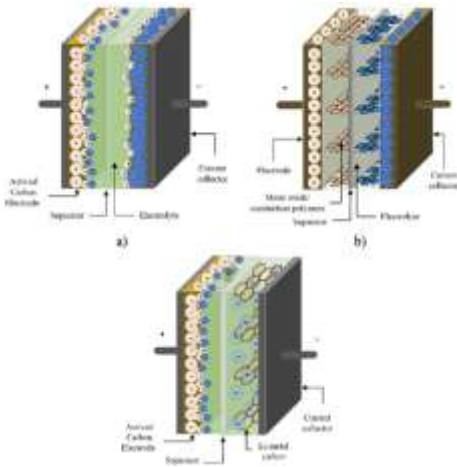


Fig. 2. Structure of supercapacitor types (a) EDLC, (b) pseudocapacitor, and (c) hybrid supercapacitor [2]

### C. Ragone plot

The Ragone plot [2] is a fundamental graphical tool used to compare the performance of various electrochemical energy storage devices by plotting their power density ( $\frac{W}{Kg}$ ) against their energy density ( $\frac{Wh}{Kg}$ ) [2].

The Ragone plot graph highlights the following characteristics:

- 1) Conventional capacitors are present at the top-left region of the plot, indicating the highest power density along with the lowest energy density.
- 2) Batteries and fuel cells appear at the bottom-right region of plot, indicating high energy density and delivering power relatively slowly.
- 3) Supercapacitors appear intermediate region of plot, indicating power density much higher than batteries but lower than the conventional capacitors and having energy density higher than conventional capacitors.

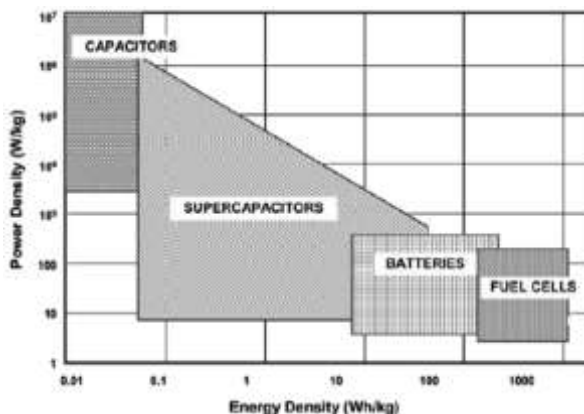


Fig. 3. Ragone plot of different electrochemical energy storages [3]

## V. HYBRID ENERGY STORAGE SYSTEM (HESS) IN EV

Rising concerns for environmental damage and strict emission regulation have accelerated the adoption of Electric Vehicles (EV's) which has increased the demand for efficient and advance energy storage systems. Due to the dynamic power demands such as rapid acceleration – deceleration and regenerative braking, the performance of conventional batteries like lithium-ion batteries degrade.

Hybrid Energy Storage System (HESS) in EV's are designed to integrate power sources i.e. batteries and supercapacitors to utilize the unique abilities of each technology [5]. The Batteries offer high energy density for long-term storage and sustained energy supply, whereas supercapacitors provide high power density and the ability to handle rapid charge and discharge cycle.

Key benefits of HESS in EV's are as follows [5]:

- 1) Hybrid integration improves overall system efficiency by enabling effective handling of dynamic power demands.
- 2) Coordinated power sharing reduces electrochemical stress on batteries and extends their operational cycle life.
- 3) Supercapacitors enhance dynamic response during acceleration-deceleration and regenerative braking conditions.
- 4) The system architecture improves the voltage stability and ensures reliable power delivery under varying load conditions.
5. Hybrid storage systems contribute to improved energy utilization and enhanced vehicle performance.

Despite the advantages of HESS, integrating it into EV architecture present several engineering challenges, which are as follows :

- 1) Efficient thermal management is necessary to control heat generation during high-power operations and helps in ensuring safe and reliable system performance.
- 2) For both components, i.e. supercapacitors and batteries, accurate estimation of (State of Charge) and (State of health) [5] are essential for hybrid operations but are difficult to obtain with higher accuracy.



3) Integrating advanced power electronics increases vehicle complexity, weight, and cost. These drawbacks largely stem from the engineering required to manage wide voltage ranges and power fluctuations.

The Energy Management System (EMS) plays a vital role in controlling power flow within a Hybrid Energy Storage System to meet vehicle power requirements while maintaining the health of energy storage components. It considers factors such as battery state of charge, vehicle speed, acceleration, load current, and state of health for real-time decision making. Appropriate control strategies improve regenerative energy utilization, reduce battery stress, and enhance overall system efficiency and lifespan. Effective coordination between storage devices ensures better utilization of recovered braking energy, stable voltage supply, and optimized energy distribution, ultimately leading to enhanced vehicle performance and extended operational lifespan.

Parameter	Battery Only	HESS
Peak Power Response	Moderate	High
Thermal Stress	High	Reduced
Life Cycle	Lower	Improved
Efficiency	Moderate	Higher

Table 1. – Comparison between Battery only and HESS

Recent research has implemented advanced algorithms to enhance HESS energy flow. The PIDA-PCA-KF-ISGO [5] hybrid technique is one of these methods. It uses:

1) PIDA-PCA-KF [5]: To forecast low-frequency battery power requirements utilising real-time load characteristics. Improved Snow Geese

2) Optimisation (ISGO): To keep the voltage of the supercapacitor within a certain range and cut down on power losses. This method has been shown to lower the battery current THD to 10.49% [5], which is much better than other control methods.

There are usually three types of HESS topologies which are as follows:

1) Passive Topology: This is the easiest and cheapest way to work, where both sources are connected to the DC link without a converter.

2) Semi-Active Topology: Only one of the sources is connected to a bidirectional converter, which gives you a fair amount of control over how things work.

3) Active Topology: In this mode, both the battery and the supercapacitor are connected to a bidirectional converter. This gives you the most control options and costs more, but it also helps the battery last longer.

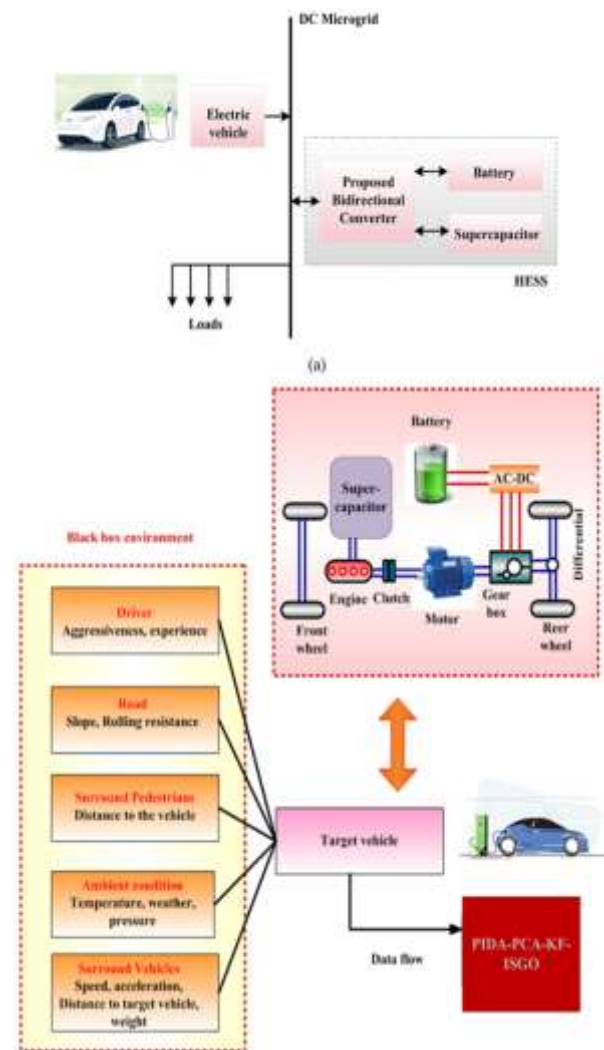


Fig. 4. Configuring EVs' Energy Management System of HESS with the suggested hybrid method [5]



## VI. Regenerative braking system (RBS)

Regenerative Braking System is a vital mechanism in the recuperation of energy. It has the capability to harness the kinetic energy normally dissipated as heat through the brakes. Supercapacitors are the most suitable choice to harness the energy because of their ability to store a high level of energy over a short period compared to other capacitors. In the Hybrid Energy Storage System, the supercapacitors have the ability to harness the high level of mechanical energy bursts, thus efficiently harvesting the energy over a period of less than a minute.

### A. Transient Power Absorption

One of the major problems associated with the power systems of the electric vehicles is the inability of the chemical batteries to withstand high transient power absorption due to their high internal resistance. This results in the destruction of the batteries because of the high current pulses. The supercapacitors have the ability to absorb the high peak power because of their high-power density and low ESR, thus efficiently absorbing the high-frequency energy bursts occurring over a short period of instantaneous braking.

### B. Improvement in Driving Efficiency

The addition of supercapacitors to the RBS has the potential to improve the overall driving efficiency. The results of the simulation show that the overall peak efficiency of the RBS is about 40%, thus resulting in an increase in the State of Charge (SOC). The overall driving range is improved because the supercapacitors have the ability to harness the free energy through the braking system, thus reducing the losses associated with the traditional braking systems.

### C. Impact on Battery Life

Although the RBS has the ability to recover a high level of energy, the high recharging current has the potential to reduce the overall life of the batteries through the plate-out effect on the anode, especially when the SOC is high. The supercapacitors have the ability to reduce the overall capacity fade of the batteries, thus enhancing the overall life of the batteries.

Simulation (using MATLAB) [4] results from real-world driving cycles quantify the impact of integrating supercapacitors in Hybrid Energy Storage Systems (HESS):

- 1) Immediate Energy Recovery: In the Indian Driving cycle (IDC), regenerative braking can recover enough energy to improve the battery's State of Charge (SOC) by 4% in a single cycle [4].
- 2) System Efficiency: The peak efficiency of regenerative energy recovery throughout various cycles reaches approximately 40% [4].
- 3) Long-Term SOH Impact: Over a simulation of 800 cycles, aggressive braking in the IDC causes a State of Health (SOH) decline to 70%[4], whereas more stable real-world driving cycles maintain a higher SOH of 80%.
- 4) Impedance Growth: Repeated high-current pulses from regenerative braking can cause internal resistance to rise from an initial 0.008  $\Omega$  to approximately 0.08  $\Omega$  [4], signaling significant battery aging.
- 5) Validation Metrics: The integrated simulation models are validated with a Root Mean Square Error (RMSE) of 2.8567% SOC [4], ensuring high predictive accuracy.

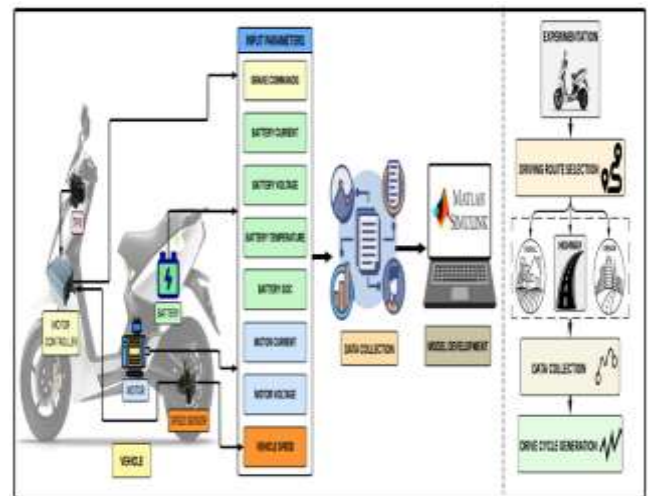


Fig. 5. Framework for Regenerative braking [4]

The above illustration of framework for regenerative braking shows a complete setup to gather EV data, build models, and run experiments to analyze energy efficiency or regenerative braking performance. It connects real vehicle hardware like the motor, battery, motor controller, and various sensors to measure speed, temperature, current, voltage, throttle position, etc., to gather real-time data. This data is then used to build the model in MATLAB Simulink.



It also shows a framework to design an experiment by choosing various routes like rural, highway, or urban routes to gather data and then define specific drive cycles.

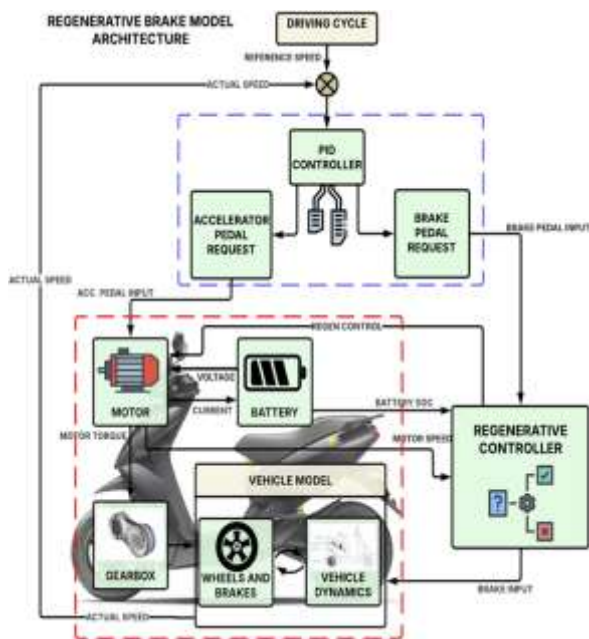


Fig. 6. Working framework of the proposed regenerative model integrating different vehicle systems [4]

The fig. 6. above describes the architecture of the regenerative braking model in an energy management system for an electric scooter. The architecture in the figure describes how the system manages the speed of the vehicle and coordinates the energy flows, with specific attention to the utilization of kinetic energy in regenerative braking to charge the battery. There are different parts and control systems in the regenerative braking system (RBS) which are as follows -

- 1) Driving Cycle and Speed Control: The system uses a proportional-integral-derivative (PID) controller to figure out what inputs the accelerator and brake pedals need by comparing the reference speed to the actual speed.
- 2) User Input: The system gets requests from the accelerator and brake pedals and uses those requests to make the inputs that the system needs.
- 3) Vehicle Model: The system models the motor, battery, gearbox, wheels, and brakes to make the electric scooter look and feel like it does in real life.
- 4) Regenerative Controller: The system changes the regen control signal based on the battery SOC [4],

motor speed, and actual speed inputs. Energy Flow: The system captures the kinetic energy in regenerative braking when the motor acts as a generator and charges the battery with the regen controller regulating the process.

## VII. BATTERY-LESS ELECTRIC VEHICLE CONCEPT USING SUPERCAPACITORS

### A. System Configuration

A battery-less electric vehicle powered by supercapacitors utilizes a supercapacitor bank as its primary energy storage unit [6]. This design effectively eliminates the need for conventional electrochemical batteries, relying solely on the electrostatic storage of the capacitor bank. The comprehensive system configuration typically integrates a high-power fast-charging station, power electronic interfaces such as DC-DC buck converters, a motor driver controller, sensing elements, and an electric traction motor. To meet specific voltage ratings and capacitance requirements for vehicle propulsion, supercapacitor cells are interconnected in tailored series-parallel combinations. A centralized control unit or microcontroller continuously monitors operating parameters like voltage and current to regulate the charging and discharging processes through real-time software. This coordinated design ensures reliable power delivery, improved dynamic response, and safe operation under varying driving conditions.

### B. Ultra-Fast Charging Concept

One of the most significant advantages of supercapacitor-based vehicles is their capacity for ultra-fast charging. Unlike chemical batteries, supercapacitors can safely accept high charging currents due to their electrostatic storage mechanism and high-power density [6]. Dedicated fast-charging infrastructure supplies controlled high-power pulses, enabling full energy replenishment within a very short duration, typically ranging from five seconds to a few minutes. This rapid charging capability substantially reduces vehicle downtime, significantly enhancing operational efficiency in high-utilization transport scenarios. Advanced power electronic converters and protective control algorithms are critical to maintaining safe operating limits, preventing over-voltage or over-current conditions, and ensuring stable performance during repeated cycles.



### C. Urban Mobility Suitability

Battery-less electric vehicles are particularly well-suited for short-range and urban mobility applications where frequent acceleration, deceleration, and stop-and-go traffic are prevalent. The high-power density and rapid energy exchange capabilities of supercapacitors allow them to efficiently handle the transient load demands typical of congested city environments. Although their relatively lower energy density limits long-distance travel, strategically located charging stations can compensate by allowing frequent energy replenishment at stops. Such vehicles are ideal for campus transportation, industrial material handling, last-mile connectivity, and smart city shuttle services. Their lightweight structure, low maintenance requirements, and environmentally friendly operation without battery replacement issues further enhance their practicality for sustainable urban transport [6].

### D. Limitations

Despite several operational benefits, battery-less supercapacitor vehicles face notable technical and economic challenges. Their relatively low energy density severely restricts driving range, necessitating frequent charging and limiting suitability for long-distance transit [6]. The development and deployment of high-power ultra-fast charging infrastructure require significant initial investment and involve complex grid integration. Furthermore, maintaining a stable output voltage during discharge requires advanced converter topologies and sophisticated energy management strategies. Thermal management, system integration complexity, and the higher costs associated with specialized materials remain critical research concerns that must be addressed for large-scale practical implementation.

## VIII. CHALLENGES AND FUTURE OUTLOOK EXISTING

### Challenges

1) Monitoring Accuracy (SOC and SOH) - The accurate calculation of the State of Charge (SOC) and State of Health (SOH) [4] of the battery remains a great challenge. The inaccuracies may result in suboptimal allocation of energy and reduced reliability. Conventional data-driven models face difficulties in accommodating the uncertainties of the capacity of the battery during regenerative processes. The rapid changes in power may cause measurement inaccuracies, which may affect the conventional models of estimation.

2) Cost and System Complexity -

The implementation of a hybrid energy storage system (HESS) [5] requires expensive bidirectional DC-DC converters to manage the large voltage range and power fluctuations between the sources. The large amount of expertise involved in the construction of the system, along with the expensive advanced materials used, such as carbon nanotubes (CNTs) and ionic liquids, makes it difficult to implement the hybrid system.

3) Electrochemical Stressor -

The critical trade-off remains a great challenge for the implementation of a hybrid energy storage system in electric vehicles [4]. The regeneration process increases the range of the vehicle but causes degradation of the battery by accelerating lithium plating and thickening of the Solid Electrolyte Interphase (SEI) layer [4].

### Future Scope

The future research directions for energy storage and associated technologies are listed as follows:

1) Advanced computer simulations -

Further research will aim at the development of more accurate computer models that can simultaneously calculate the energy recovered during braking and the rate of battery deterioration. The application of Adaptive Kalman Filters (AKF) will allow for better battery health and charge level monitoring, improving the accuracy of the simulation results over existing methods.

2) Novel and environmentally friendly materials -

In order to bridge the energy density gap associated with batteries, researchers are working towards the development of high energy density storage media like Lithium-Ion Batteries and Nanohybrid Capacitors, which have tripled energy densities. There is a strong emphasis placed on the development of associated technologies like the use of natural, plant-based materials like cellulose and lignin, aiming at making the manufacturing process of electrodes more "green."

3) Safe and green chemistry -

The energy storage sector is moving away from the traditional flammable solvents used in the manufacturing process of energy storage media towards more "green" water-based solvents, even though these have lower voltage limits.



4) Self-charging and associated technologies - The energy storage media of the future will have the ability to charge autonomously through solar, motion, or perspiration-based charging mechanisms. In the context of smart cities, IoT will allow for the development of vehicle-to-everything (V2X) communication, allowing for efficient energy distribution management.

5) Manufacturing improvements - Further research will aim at the development of advanced materials at a lower cost than traditional batteries, allowing for the development of flexible supercapacitors for wearable electronics like smart clothing and medical devices.

Constraint	Impact on System	Primary Cause
Lithium Plating	Irreversible capacity loss	Aggressive RBS charging pulses
SOH Inaccuracy	Suboptimal energy management	Measurement error during transients
Pore Blocking	Increased ESR and Capacitance fade	Electrolyte decomposition products
Gas Generation	Internal pressure and safety risk	Electrolyte boiling or over-voltage

Table 2. Critical System Constraints, their impact on system and primary cause

## IX. CONCLUSION

Supercapacitor have gain substantial attention due to their exceptional power density, rapid charge-discharge capabilities, and longer lifecycle. The review paper shedding light on their materials, technologies, and their importance in modern electric mobility was examined through application in HESS, regenerative braking and Battery-less electric vehicle concept. Despite having many advantages of using and integrating supercapacitors, factors such as low energy density, higher system cost and complex power electronic interface limits their widespread adoption. Continuous research on advanced electrode materials, smart energy management techniques, and cost-effective system integration is being under focus to enhance their performance and real-world

applicability. Overall, supercapacitors are likely to play an important role in enabling efficient, reliable, and environmentally sustainable electric transportation systems. This review serves as a reference by summarizing the existing knowledge and highlighting key future research direction. The review also highlights the growing importance of supercapacitors in modern electric mobility was examined through applications in Hybrid Energy Storage Systems (HESS), regenerative braking, and battery-less electric vehicle concepts.

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