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Comparative Analysis of Energy Storage System's Hybridization for Electric Vehicles: Evaluating Lithium-Ion Batteries, Supercapacitors, and Fuel Cells on Performance Metrics

Ravikant Nanwatkar[1,*], Deepak Watvisave[2], Aparna Bagde[3], Sonali Sabale[4], Dinesh Burande[5], Pravin Nitnaware[6]

Abstract

High-performance energy storage systems (ESS) in electrically powered cars are becoming more and more necessary as transportation options become more environmentally conscious. This research provides a thorough comparison of hybrid energy storage systems (HESS) that link fuel cell technology, supercapacitors, and batteries made of lithium ion. Critical performance metrics are assessed for each technology, including energy density, power density, efficiency, lifecycle durability, thermal performance, cost and sustainability. It summarizes the advantages as well as disadvantages of each individual ESS technologies, and explore hybrid configurations (e.g., lithium-ion battery–supercapacitor, lithium-ion battery–fuel cell, and fuel cell–supercapacitor systems). Using a combination of simulations and experimental validation, this study shows how the novel hybridization can synergistically improve energy efficiency, power transfer, and operation life while alleviating the limitations of individual systems. The choice of HESS architecture is application dependent; battery–supercapacitor systems are better in power demanding applications while battery-fuel cell pairs provide the best range and energy sustainability. The study additionally states issues in ESS hybridization such as cost trade-offs, thermal management, and infrastructure constraints. This work highlights the importance and critical need of HESS in boosting electric vehicle performance, as well as informing optimal designs of energy storage systems for varied mobility needs. Further investigation into next-gen materials, solid-state batteries and artificial intelligence–powered energy management systems would also benefit continued efforts to improve HESS efficiency and dependability.

Keywords: Battery–supercapacitor, lithium-ion battery–fuel cell, fuel cell–supercapacitor, thermal management, infrastructure constraints

***Author for Correspondence**
Ravikant Nanwatkar
E-mail: ravikant.nanwatkar@sinhgad.edu

[1]Assistant Professor, Department of Mechanical Engineering, Sinhgad Technical Education Society (STES)'s Sinhgad College of Engineering (Affiliated to Savitribai Phule Pune University), Pune, Maharashtra, India
[2]Associate Professor, Department of Mechanical Engineering, Maharshi Karve Stree Shikshan Samstha (MKSSS)'s Cummin's College of Engineering (Affiliated to Savitribai Phule Pune University), Pune, Maharashtra, India
[3]Assistant Professor, Department of Computer Engineering, Jayawant Shikshan Prasarak Mandal Narhe Technical Campus (JSPM NTC) (Affiliated to Savitribai Phule Pune University), Narhe, Pune, Maharashtra, India
[4]Research Scholar, Department of Mechanical Engineering, Sinhgad College of Engineering, Pune, Maharashtra, India.
[5]Assosicate Professor, Department of Mechanical Engineering, NBN Sinhgad Technical Institutes Campus (NBNSTIC) (Affiliated to Savitribai Phule Pune University), Ambegaon, Pune, Maharashtra, India
[6]Professor, Department of Mechanical Engineering, D Y Patil College of Engineering (DYPCOE) (Affiliated to Savitribai Phule Pune University), Akurdi, Pune, Maharashtra, India.

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INTRODUCTION

Since energy storage systems (ESS) have advanced electric vehicle (EV) technology, they serve as the foundation of sustainable transportation through efficient, reliable and clean energy. ESS are important contributors for vehicle performance, range and reliability, which has only become more prevalent as the demand for EVs around the globe increases in response to greenhouse gas emission reduction goals and a move towards energy independence from fossil fuels. Lithium-ion batteries, being the most widely used ESS technology, have transformed the EV landscape thanks to their high energy density, efficiency and relatively long lifespan. But in applications that do not require long duration performances, the existing standalone energy storage technologies are limited by insufficient power density, thermal stability and cyclic degradation. Such limitations highlight the need for alternative and complementary technologies including supercapacitors and fuel cells that offer benefits in other performance domains. Hybrid energy storage systems (HESS) have appeared as a hopeful solution to the drawbacks of individual ESS technologies and to reach the energy density–power delivery, efficiency and cost-effectiveness trade-offs [1]. Hybrid systems, which amalgamate capacities from multiple ESS classes, allow for the optimization of energy across different operation requirements. As an example, while lithium-ion batteries offer energy storage for long distances, supercapacitors provide high bursts of power for acceleration or regenerative braking. Likewise, fuel cells aid in extending the range and are being identified as a low-polluting energy source by using hydrogen. The hybridization of these technologies enables the matching of synergetic characteristics to achieve a plethora of benefits, such as enhanced performance, longer lifetimes and lowered expenses while addressing key issues, including thermal management and efficiency losses (Figure 1).

Problem Definition

Rapid electrification of vehicles as a sustainable substitute to conventional internal combustion engine vehicles has escalated the demand for ESS that are efficient and reliable. Lithium-ion represents the dominant battery type owing to its high energy density and efficiency, but also suffers from major issues including thermal instability, long recharge times, and limited lifetime. As a result, they fail to support the variety and dynamic performance demands of EVs for fast power delivery in acceleration and efficient energy recovery when braking. Conversely, while supercapacitors and fuel cells provide other unique benefits (power density and energy sustainability, respectively), each also has its own challenges as an individual device characterized by low energy density (supercapacitor) or high cost- and infrastructure-sensitive performance (i.e., the fuel cell) [2].

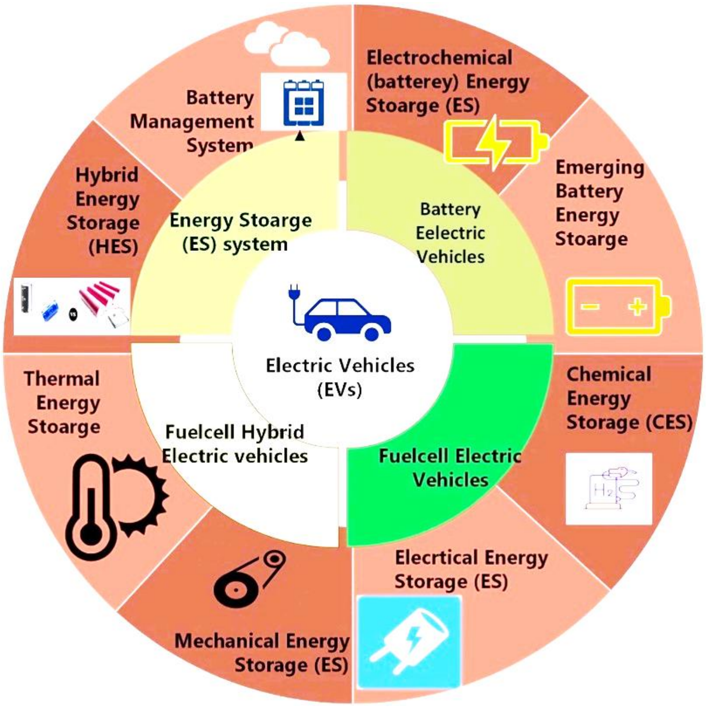


Figure 1. Strategy plan for the present research study.

The difficulty is in figuring out energy storage that can couple up to optimize critical performance metrics, including energy density, power density, efficiency, cycle life, thermal traits and price/cost. HESS, which combine two or more ESS technologies, represent a promising solution to capitalize on the complementary advantages of these systems [3]. Nevertheless, the best hybrid combinations and their matching in different EV applications have not been intensively defined yet leaving an impressive empty canvas for how trade-offs/spread-out synergies between lithium-ion batteries or supercapacitors, or even fuel cells. Moreover, control strategies, energy management systems and the scalability of hybrid systems create other levels of complexity.

Such advanced research is fundamental yet critical to identify optimal HESS configuration, and contrasting their performance with the unique demands of EVs. By compositely evaluating the merits, weaknesses, and compromises of lithium-ion batteries versus supercapacitors and fuel cells over various performance parameters as a function of peak power/energy ratio, the study hopes to yield practical guidance in designing and deploying effective yet cost-efficient energy storage systems for varying EV applications [4, 5].

Objective

- The objective of this paper is to provide a comparison between lithium-ion batteries, supercapacitors, and fuel cells for their roles in hybrid energy storage systems for EVs.
- The study aims to identify the best configurations for certain EV applications, based on an assessment of important performance metrics, including energy density, power density, efficiency, lifecycle durability, thermal performance, cost and sustainability.
- The goals include shedding lights on the trade-offs and synergies of hybrid systems, informing their practical realization, and suggesting directions for future research to leverage and sustain such gains in efficiency and reliability.
- The objective of this analysis is to set the basis for designing and implementing novel HESS, thus contributing to more capable and sustainable electric mobility.

Research Gap

While the energy storage technologies for EVs have made significant progress, there are still outstanding gaps in understanding their trade-offs, synergies, and overall performance of HESS.

Although lithium-ion batteries, supercapacitors, and fuel cells have been discussed many times individually, there is no systematic discussion about hybrid configurations of these energy storage converters in terms of performance metrics such as energy density, power density, efficiency versus cycle life stability trade-off and thermal management/cost. To our knowledge, most previous studies investigate selective hybrid architectures (e.g., lithium-ion battery + supercapacitor or fuel cell) but are less comprehensive in examining the three technologies under a unified comparison in their hybridized systems. Moreover, the majority of studies have focused on very restrictive/idealized theoretical models or experimental implementations while practical considerations for real-world applications remain largely overlooked. Objectives such as the interaction of control strategies with energy management systems and hybrid architectures dedicated to different EV applications from passenger through to heavy-duty vehicles remains largely unaddressed [6]. Moreover, there is a lack of studies that investigate how different HESS configurations can be optimized for diverse electric vehicle needs such as high acceleration, long range and regenerative energy. The lifecycle, cost-effectiveness, sustainability and infrastructure needs of hybridizing these technologies is largely unexplored. The missing overall analysis results in a limited design and implementation of optimal HESS solutions, impeding path towards higher performance, economical, and sustainable EV ESS.

Scope of Work

The objective of this study is to fill the research gaps by performing a comprehensive comparative study of HESS consisted of Li-ion batteries, supercapacitors and fuel cells for electric vehicles. The scope of work includes:

- *Performance evaluation:* Evaluating the performance alone and in combination of lithium–ion batteries, supercapacitors and fuel cells in terms of energy/power density, efficiency, thermal stability, cycle life/robustness, and cost. Suitability comparison of hybrid configurations (e.g., lithium-ion battery–supercapacitor, lithium-ion battery–fuel cell, and fuel cell–supercapacitor for different EV applications [7].
- *System optimization:* Trade-offs and synergies in hybrid systems for design — the trade-off between a series plant, performance needs (speed versus range), or rapid power delivery capability and potential energy recovery during braking.
- *Energy management and control strategies:* Evaluating higher-level control algorithms and energy management systems to enhance hybrid configurations performance against dynamic operating environments.
- *Environmental and economic assessment:* Hybrid system lifecycle (cost, sustainability, recyclability) analysis.
- *Practical implementation:* Example of appropriate experimental results from actual case studies that prove the feasibility of implementation for hybrid systems in EV applications.
- *Future directions:* Finding integration avenues into hybrid energy storage systems for new technologies, such as solid-sate batteries, developments in hydrogen storage and artificial intelligence (AI)-powered energy management.

Such a detailed analysis can help researchers, manufacturers, and policymakers design, implement, and adopt efficient low-cost sustainable hybrid energy storage technologies for the upcoming generation of electric vehicles [8].

LITERATURE REVIEW

The battery technologies for EVs such as lithium-ion batteries, supercapacitors, and fuel cells have been a core topic of extensive research in recent years representing unambiguous ESS. Due to their high energy density, reasonable speed and efficiency, and long cycle life, lithium-ion battery technology has been nearly ubiquitous in the EV space since both were commercially introduced around the turn of the twenty-first century; providing steady energy for range is a requirement for sustained high-power usage. Nevertheless, they have disadvantages, including thermal instability, time dependent loss of capacity, and relatively low charging rates that limit their response to the power demand fluctuation of EVs.

Conversely, while supercapacitors are able to provide high bursts of power quickly and have a much improved cycle life over batteries, their low energy density disqualifies them as standalone ESS for EVs. Fuel cells convert hydrogen to produce electricity, and they are excellent sources of sustainable and clean energy with minimum environmental impact. However, the high initial cost of fuel cell systems and the still developing hydrogen infrastructure create major barriers to their acceptance as a stand-alone technology contributing significantly to global energy demand [9–11].

To overcome the isolation of each individual ESS technology, HESS has appeared as a potential solution, which takes the most advantage of different energy storage technologies. Common configurations of HESS suitable for EV applications include lithium-ion battery–supercapacitor systems, with adequate energy density and rapid power delivery, and lithium-ion battery–fuel cell systems, accounting for the extended range capabilities associated with fuel cells combined with the reliability commonly found in batteries. Other research has explored combinations of fuel cells with supercapacitors, which can improve transient response and potentially decrease required battery system volume. Not only do these hybrid approaches boost overall performance, but they also overcome key issues like energy consumption, heat management, and longevity—factors that are vital in making EVs practical and affordable. HESS can dynamically distribute energy between components to maximize performance under different operating conditions by incorporating advanced energy management systems and control strategies, thus improving efficiency and vehicle life [12].

But there are still considerable research and development gaps in HESS. Although individual hybrid configurations have been studied, comparative analyses assessing two or more type of hybrids (e.g. lithium-ion battery-supercapacitor versus lithium-ion battery-fuel cell systems versus fuel cell-supercapacitor systems) using a single set of metrics are still lacking. Additionally, the literature primarily emphasizes theoretical models or certain types of EV uses with limited studies on practical evidence of actual implementations. It is not clear how hybrid configurations scale and adapt to different EV needs in passenger cars or even buses, or heavy-duty vehicles. Moreover, the long-term economic and environmental consequences of hybridization (e.g., lifecycle costs, recyclability, and infrastructure availability) have not been adequately addressed. This knowledge gap indicates the need of systematic valuations on HESS to capture optimal configurations of HESS and facilitate their deployments in practicality with evolvement of nature of EVs [13].

ENERGY STORAGE SYSTEMS AND HYBRIDIZATION CONFIGURATIONS

Energy Storage Systems Overview

Lithium-ion batteries have long been considered the cornerstone of contemporary EVs, due to their high energy density, efficiency and cycle life. These batteries can store large amounts of energy in small, light packages, which was needed to provide the long ranges EV customers are seeking. They have high efficiency and allow lower losses in charge-discharge cycles, which is crucial for applications that always need stable energy supply. But for all these benefits, lithium-ion batteries suffer from a number of severe drawbacks [14]. The most significant one is thermal management because lithium-ion batteries tend to overheat during high charge-discharge rates or continuous use, leading to performance loss or safety risks in extreme cases. They are also limited in terms of lifespan due to capacity fading after many cycles, particularly during harsher operation conditions. This requires expensive battery replacements and can undermine EVs' long-term economics. New materials, as well as thermal management systems, are developed to address these problems but performance has always been a trade for lifetime and safety (Figure 2).

Supercapacitors are an orthogonal energy storage technology, with also the highest power density of any available means and very fast charge/discharge rates. Supercapacitors are also unique in that they store energy electrostatically (as opposed to chemically in lithium-ion batteries), which enables high-power bursts ideal for EV applications like acceleration and regenerative braking. They have a very long cycle life, they can withstand millions of charge–discharge cycles with only negligible degradation so represent a highly stable element within energy storage systems. Their energy density is lower than lithium-ion batteries and the amount of energy they can store cannot take an EV a long distance, so they will not be used on their own. This constraint limits supercapacitors to hybrid arrangements, where they can assist batteries or fuel cells in improving power delivery and system efficiency [15]. Theoretical approaches have demonstrated possibilities to enhance the energy density of supercapacitors, such as graphene and other advanced materials but indispensable design for high-performance devices remains elusive (Figure 3).

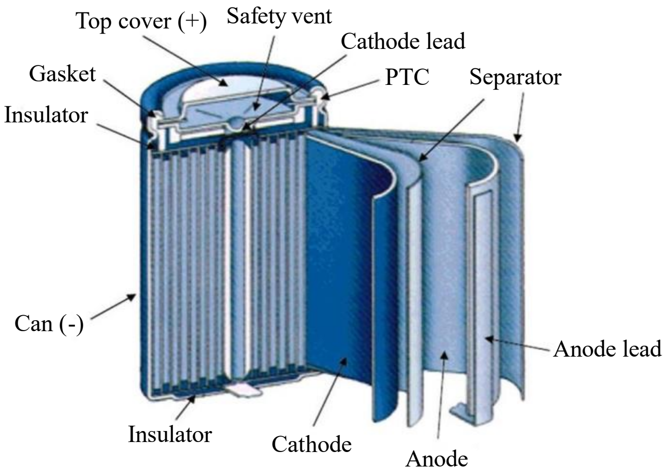


Figure 2. Lithium-ion cell structure.

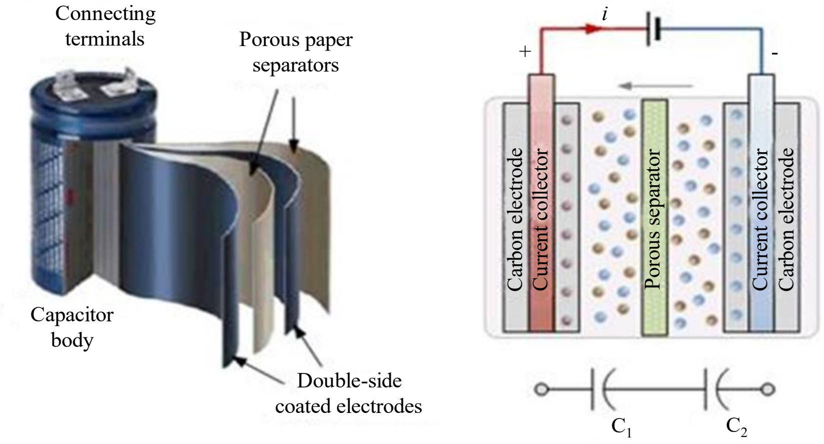


Figure 3. Supercapacitor cell structure.

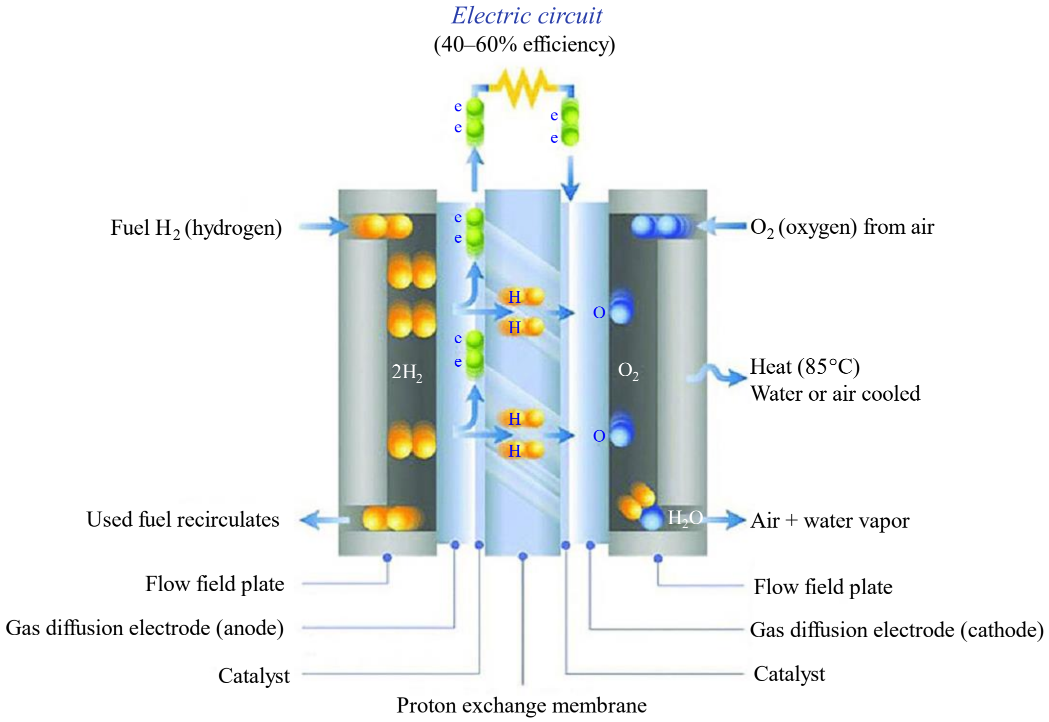


Figure 4. Fuel cell structure.

Fuel cells are a different concept of storage and production of energy as they work with the process of conversion from hydrogen gas into electricity through an electrochemical reaction. Their big edge is energy sustainability and eco-friendliness since they have zero emissions at point of use, with water being the sole by product. It makes them a suitable option for EVs looking to target long-range use cases as well as environmentally-sustainable focused markets. In addition, they can stay powered indefinitely with a good supply of hydrogen, removing battery charge time limitations. Yet a minimum fuel cell may hold up major inroads on roadways (Figure 4). The hurdle, however, has been the high cost of manufacturing and operating using ultra-expensive materials like platinum as a catalyst. Also, as long as hydrogen production, storage, and distribution infrastructure are not yet well developed, their practical application becomes impossible in regions with insufficient investment in clean hydrogen technology. To unleash the full potential of fuel cells in EV applications, however, these challenges must be overcome requiring innovations across the catalyst design, scalable hydrogen production and infrastructure landscape [16].

Hybridization Configurations

Lithium-ion battery + supercapacitor hybrid systems utilize the energy storage capacity of lithium-ion batteries in conjunction with the power density and fast charge-discharge capabilities of supercapacitors, providing an equilibrium between sufficiently high energy demands at a sustained rate. Thus, hybrid systems are advantageous for supplying dynamic EV loads. In these arrangements, the lithium-ion battery is a far more significant source of energy, supplying maximum energy during long-range operations and allowing the supercapacitor to bulk up on brief periods of high-power demand for acceleration or regenerative braking. By sharing the workload, it eases stress on the battery itself and prolongs its lifespan due to avoiding high-power bursts (which can lead to faster degradation).

In addition, the rapid energy absorption and release property of the supercapacitor also increases the efficiency of the overall system throughout different situations such as energy recovery during braking [17, 18]. This is extremely advantageous in the context of urban EVs, where frequent stop-and-go driving causes significant power variations.

Lithium-ion batteries coupled with fuel cell hybrid systems, which combine the inherent merits of both technologies and tackle-lifetime limitations by decreasing reliance on frequent recharging. Here, the stack is the primary energy source, producing power to run the vehicle and charge a battery that acts as an auxiliary energy buffer. This setup enables the fuel cell system to provide long-range performance, while the battery caters for peak power requirements and transient loads. With the combination of these technologies, engaging in continuous operation with overall improved efficiency is a possibility for the system. In addition, the hybrid system shrinks the necessary battery size giving upfront cost and mass benefits. These setups are recommended for long-haul and commercial EVs with range and less downtime being the key operational challenges [19].

The section on *fuel cell + supercapacitor hybrid systems* deals with improving transient response and performance by taking advantage of the fast power delivery characteristic of supercapacitors while allowing for continued energy generation from the fuel cell. In this arrangement, the supercapacitor responds to instantaneous power demands including during acceleration and also smoothens transient power fluctuations which allows for optimal operating parameters for the fuel cell. Lowering the stress on the fuel cell will make it more efficient and last longer. By the way, during regenerative braking, it captures and stores energy to be reused by the vehicle's supercapacitor for subsequent high-power demands. In addition, this combination is specifically appealing for high-power and heavy-duty EVs the types of applications that see frequent load variations (buses or long-haul delivery vehicles) where optimal power availability and energy efficiency are key to advancing e-mobility in the right direction [20].

The effectiveness of HESS depends not only on the component selection but also on their configuration, control procedures, and energy management systems. Series, parallel, or a combination of the two configurations can be further optimized depending upon the practical applications and performance metrics required. In series, the energy flow is typically sequential and although it can simplify the control strategy, it may restrict simultaneous power delivery. In contrast, parallel configurations enable several energy sources to operate simultaneously, which is more flexible and efficient but necessitates intricate control systems. To optimize the energy management between the different hybrid components, advanced control strategies (i.e., rule-based, fuzzy logic or model predictive control (MPC)) are usually required. The strategies charge or discharge energy from primary and/or auxiliary storage systems as needed to satisfy performance constraints on specific metrics including system efficiency, power transfer, and battery lifetime. Energy management systems (EMS) are indispensable in coordinating the operation of HESS, since they observe current state information, forecast future energy loads, and control optimal energy allocation. A good EMS needs to face issues like power sharing, SoC (state of charge) balancing, thermal management, and fault detection. As an example, if the hybrids consist of a lithium-ion battery–supercapacitor pair, the EMS should be able to manage it so that at short durations when high-power demand occurs, it is always and only provided by supercapacitor while at longer durations where sustained energy need exists has to be tackled by battery. In lithium-ion battery–fuel cell systems, the EMS must maximize the usage of fuel cells in steady-state power demand conditions while keeping lithium-ion battery available as an auxiliary power source. Likewise in fuel cell–supercapacitor systems, EMS need to control the rapid charge-discharge cycles of the supercapacitors to provide support for a stable energy output from the fuel cells. AI and machine learning (ML)-based algorithms, which are being increasingly incorporated in EMS for online optimization, predictive maintenance, adaptive control etc., will provide new directions to improve HESS performance that could translate into more reliable EV configurations [21, 22].

SIMULATION AND PERFORMANCE METRICS FOR EVALUATION

Simulation

Simulink is MATLAB’s simulation software which has been used widely to analyze HESS for electric vehicles. The program uses a modular and dynamic environment that enables researchers to simulate, design, and evaluate multiple configurations of lithium-ion batteries, supercapacitors and fuel cells. Simulink allows for accurate modeling of electrical, thermal, and control phenomena that help understand how the system behaves in real-world operating scenarios. It comes with libraries for the energy storage components and the control system built in to enable implementations of advanced energy management strategies to optimize performance metrics of interest (e.g., efficiency, power density, and lifetime). MATLAB Simulink enables efficient, scalable and versatile comparison of hybrid systems for different EV applications, which is an important contribution towards future HESS research [23].

- *Energy density versus power density* — Lithium-ion batteries are superior when it comes to energy density (providing sustained energy output over a longer duration to support commercial long-range applications). Supercapacitors on the other hand provide better power density (i.e., they can charge/discharge rapidly). Fuel cells can be a compromise between energy density and constant power output, where they can run for hours. Hybrid systems will optimize these trade-offs, combining the best of both.
- *Efficiency*: Hybrid configurations can enhance energy conversion efficiency through the dynamic assignment of energy tasks. Thus, supercapacitors deal with transient loads while batteries or fuel cells exploit the steady energy requirements to reduce energy losses.
- *Increased life cycle and longevity:* By removing stress from individual systems hybridization is able to prolong the life of various components. Supercapacitors take on high-power duties to prevent wear and rip on a battery, while fuel cell hybrids smooth out operational loads for longer service life.
- *Cost*: Standalone systems present independent cost challenges, with capital-intensive lithium-ion batteries and fuel cells. While HESS have the potential to drive down long-term costs by utilizing each component more effectively, initial setup costs of the control systems can be quite high when compared with simpler, stand-alone ESS [24].
- *Thermal management:* There is heat generation in lithium-ion batteries and fuel cells. A hybrid system spreads its thermal loads around, allowing for better heat dissipation and reducing the risk of overheating.
- *Sustainability:* Lithium-ion batteries and fuel cells have a recycling issue, whereas supercapacitors are easier to reuse. Hybridization can reduce environmental impact by improving energy use and reducing resource needs for maintenance and replacement.

Critical Assumptions and Parameters

1. *Energy and power measures:* Wh/kg, W/kg (stand-alone and hybrid systems)
2. *Conversion and utilization efficiency (%):* Under dynamic and steady state operations.
3. *Lifecycle:* Charge-discharge cycles and associated degradation rates for each technology [25].
4. *Price:* Initial capital investment, operational costs, and long-term maintenance costs of the system.
5. *Seebeck driven thermal performance:* Heat production rates (W) and rejection capability at different load conditions.
6. *Sustainability:* Emissions, recyclability rates and environmental impacts
7. *Stand operating conditions:* Assumes typical EV application with defined load profiles, SoC ranges and ambient temperatures.
8. *Control strategies:* Same energy management strategies used to guarantee fair comparison between hybrid configurations [26].

Methods for Comparing Things

1. *Modeling:* Creating simulation and mathematical models using MATLAB Simulink to replicate energy flow, thermal behavior, and cycle impacts.
2. *Data collection:* Acquiring data from previous experiments or field studies, or utilize a prototype to test and validate the performance of different ESS configurations.
3. *Simulations:* Computer-based tests to determine how the system behaves under a variety of conditions, such as load cycles, thermal extremes, and efficiency benchmarks.

4. *Performance measures:* A comparison of milimeter-level metrics, including range, energy use, response time and degradation trends between technologies
5. *Sensitivity analysis:* Determine how changes in values of parameters (such as SoC limits or load peaks) affect performance and cost [27].

Here, we have used MATLAB/ Simulink for simulating the results of hybridization of different energy storage systems. Case 1 indicates HESS of two different batteries whereas case 2 indicates HESS of battery and supercapacitor (Figure 5).

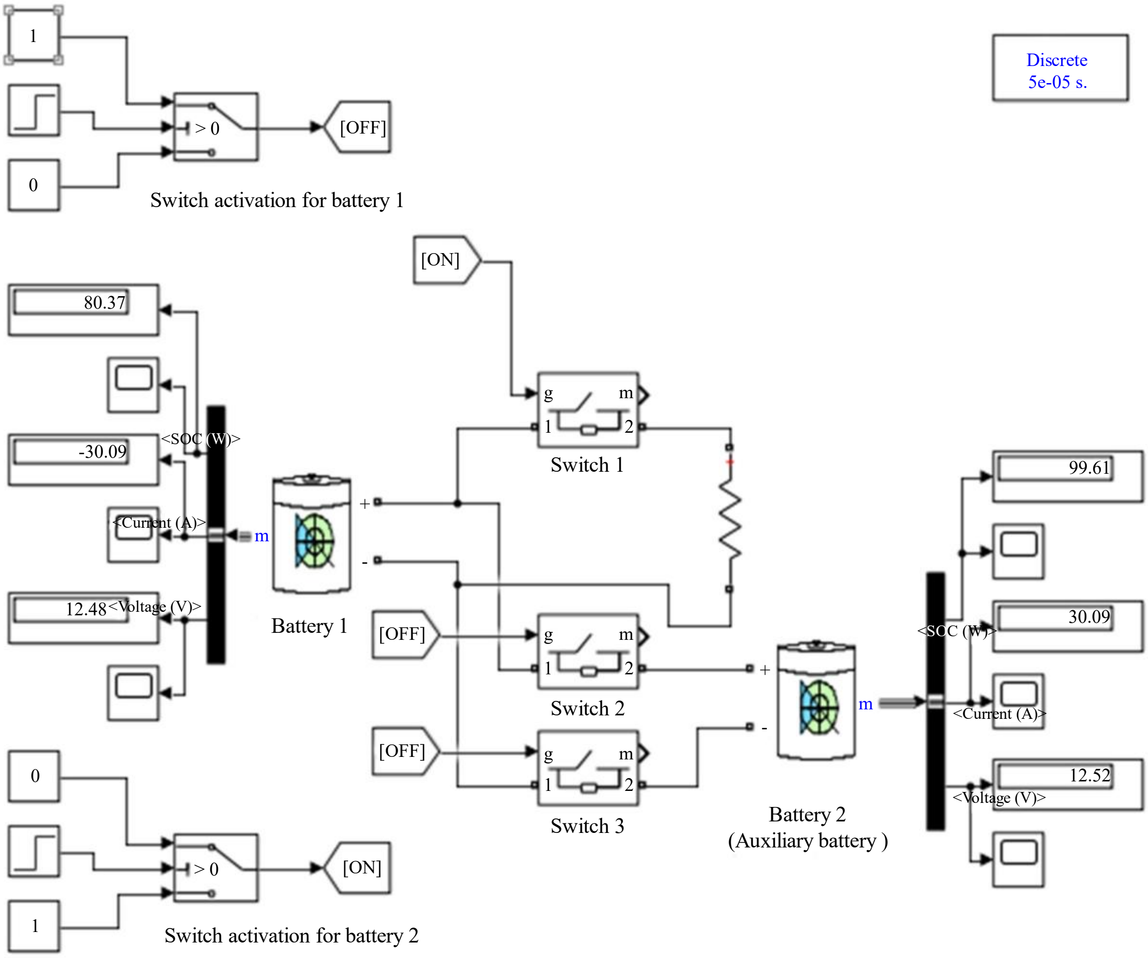


Figure 5. Simulink circuit for battery charging using auxiliary source (battery).

Case 1: Application Based Simulation of Batteries (Time of simulation 10 s with step size of 4 s)

Here simulation is performed to analyze the results of more than one energy storage systems, to check and verify the effects on system performance parameters. Here battery is used as auxiliary source and in further simulation is will be supercapacitor.

Case 2: Simulation of Battery and Supercapacitor

Here the effect of supercapacitor as a second energy storage device to battery as a primary device is evaluated using a Simulink circuit. Lithium-ion battery of nominal voltage 11.1 V, rated capacity 20 Ah and initial SoC of 80%, whereas EDLC (electric double layer capacitor) supercapacitor of rates capacitance 100 F and rated voltage 13.5, is taken for this study. Results were evaluated for approximately 20 seconds, considering discharge time of each supercapacitor as 3.6 seconds (Figure 6).

RESULTS AND DISCUSSION

The current and voltage of lithium-ion battery and EDLC supercapacitor remains same whereas there is change in both SoCs (Figure 7).

- Battery SoC is reduced from 80% to 78.67 after 4 seconds.
- Battery current is constant up to 4 seconds, at the same time it raises to its peak value and its starts reducing to zero with respect to time (Figure 8).
- Battery voltage is constant up to 4 seconds, at the same time it reduces to its 8 V (nominal value) and its starts increasing to rated capacity with respect to time [28–30].
- Supercapacitor shows increase in current after 4 seconds, whereas voltage and SoC show approximately 10 units (Table 1).

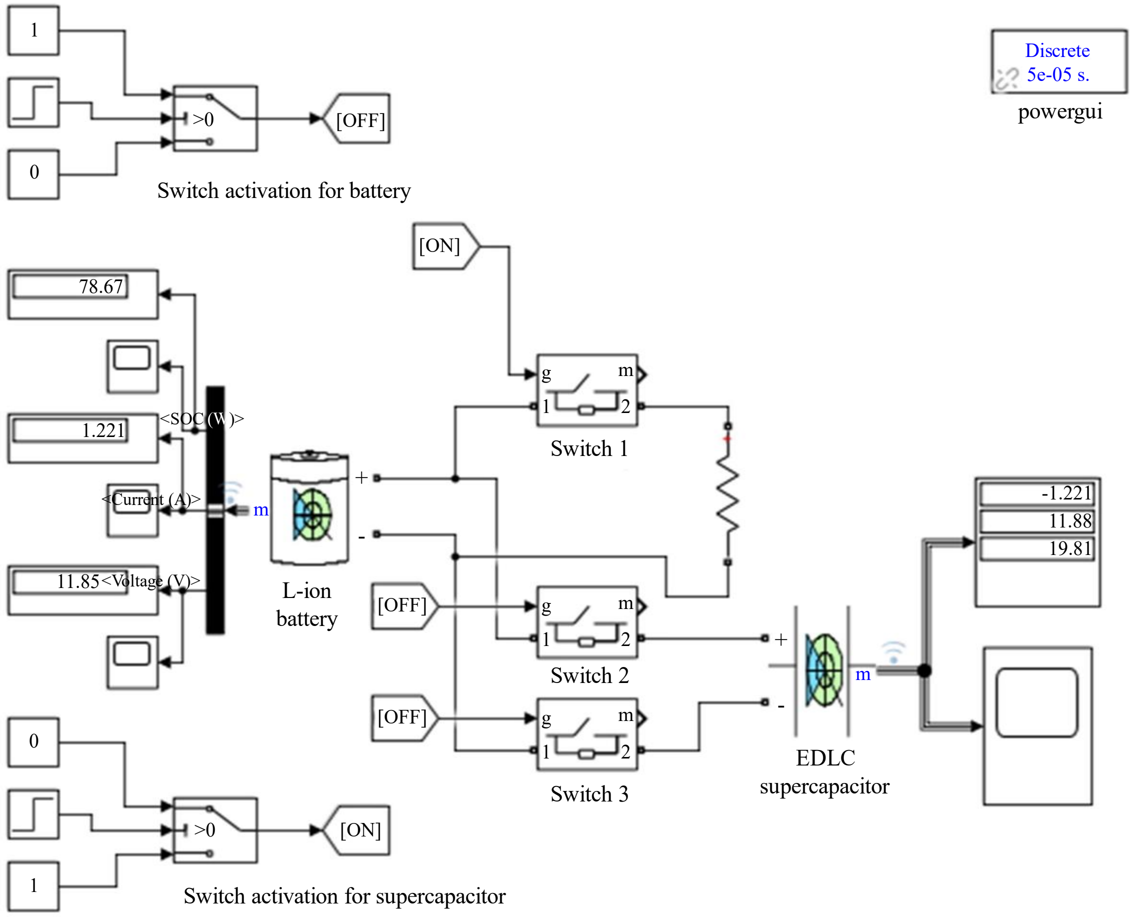
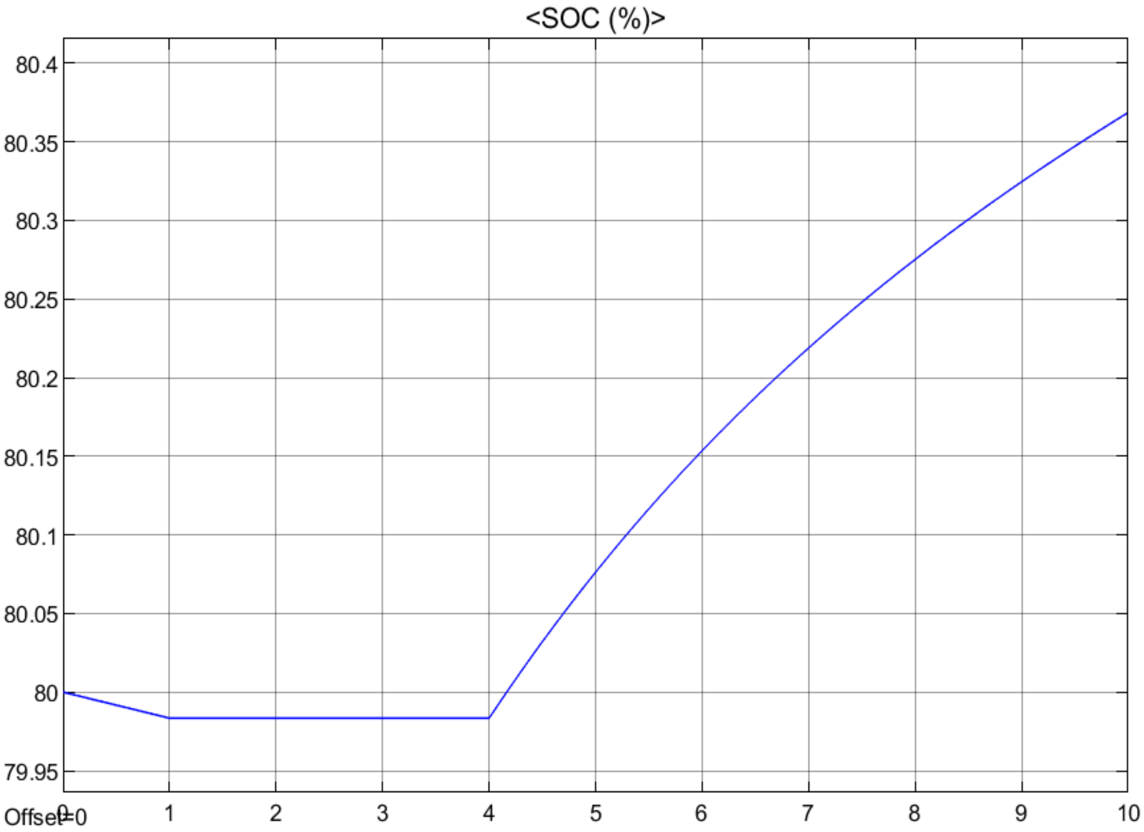


Figure 6. Simulink circuit for battery charging using auxiliary source (supercapacitor).

For working battery versus auxiliary battery/supercapacitor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2
3
4
5
6
7
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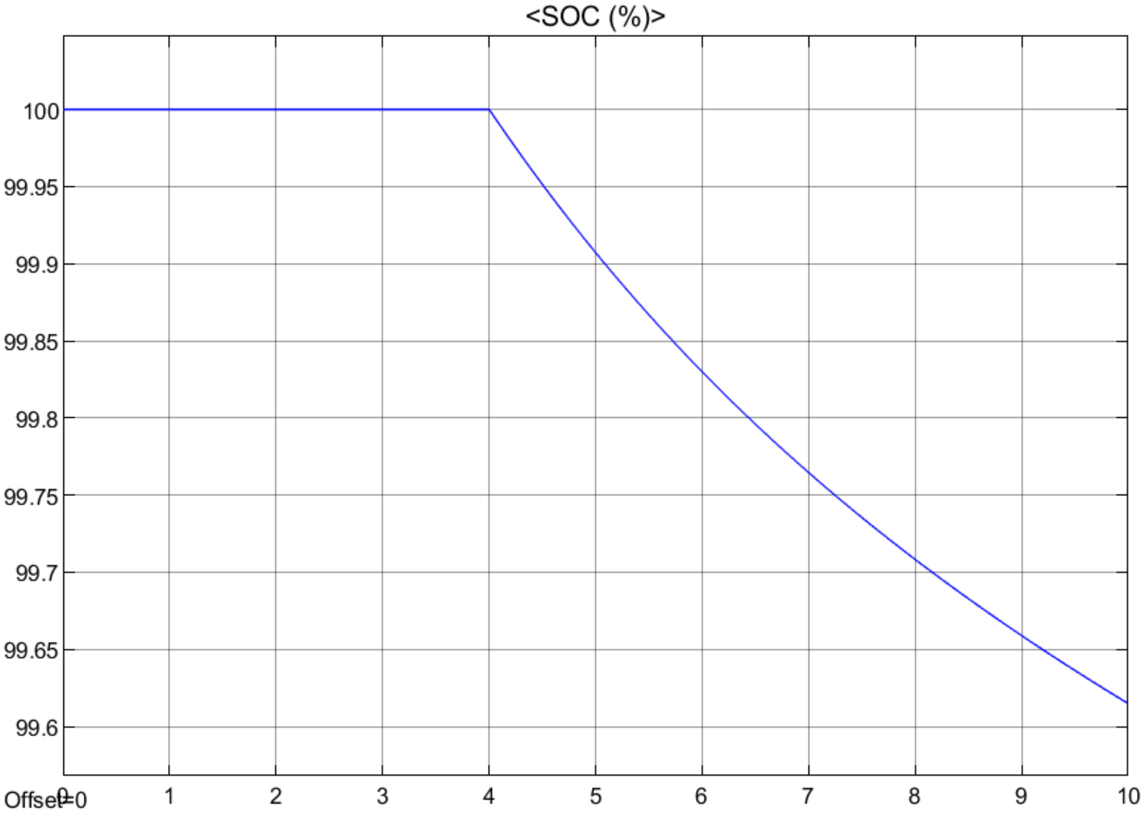
9
10

(a)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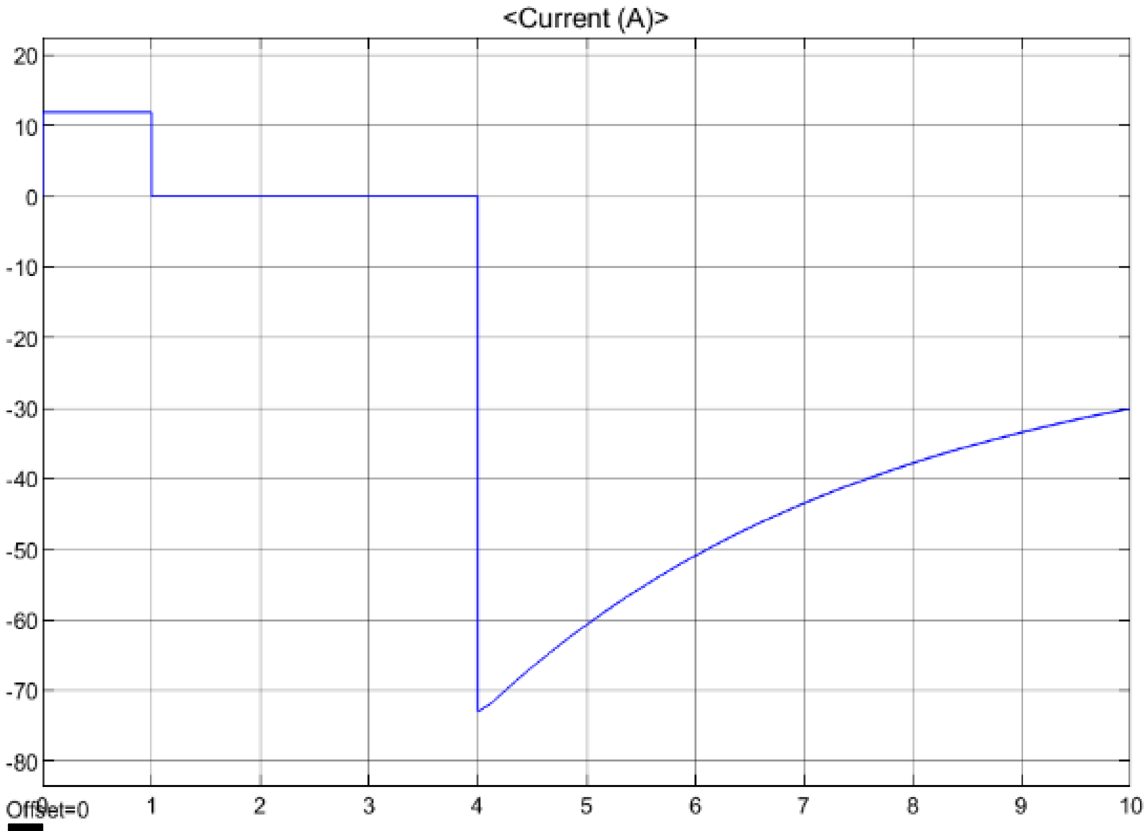
(b)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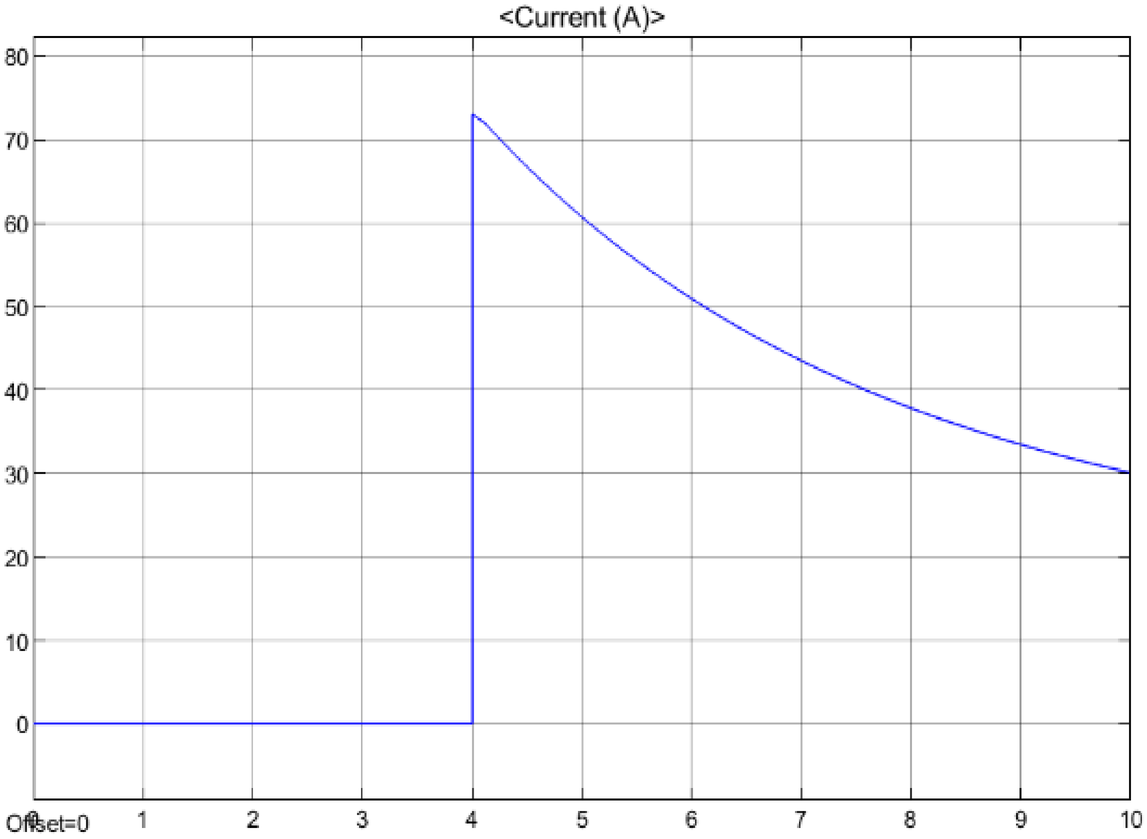
(c)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(d)

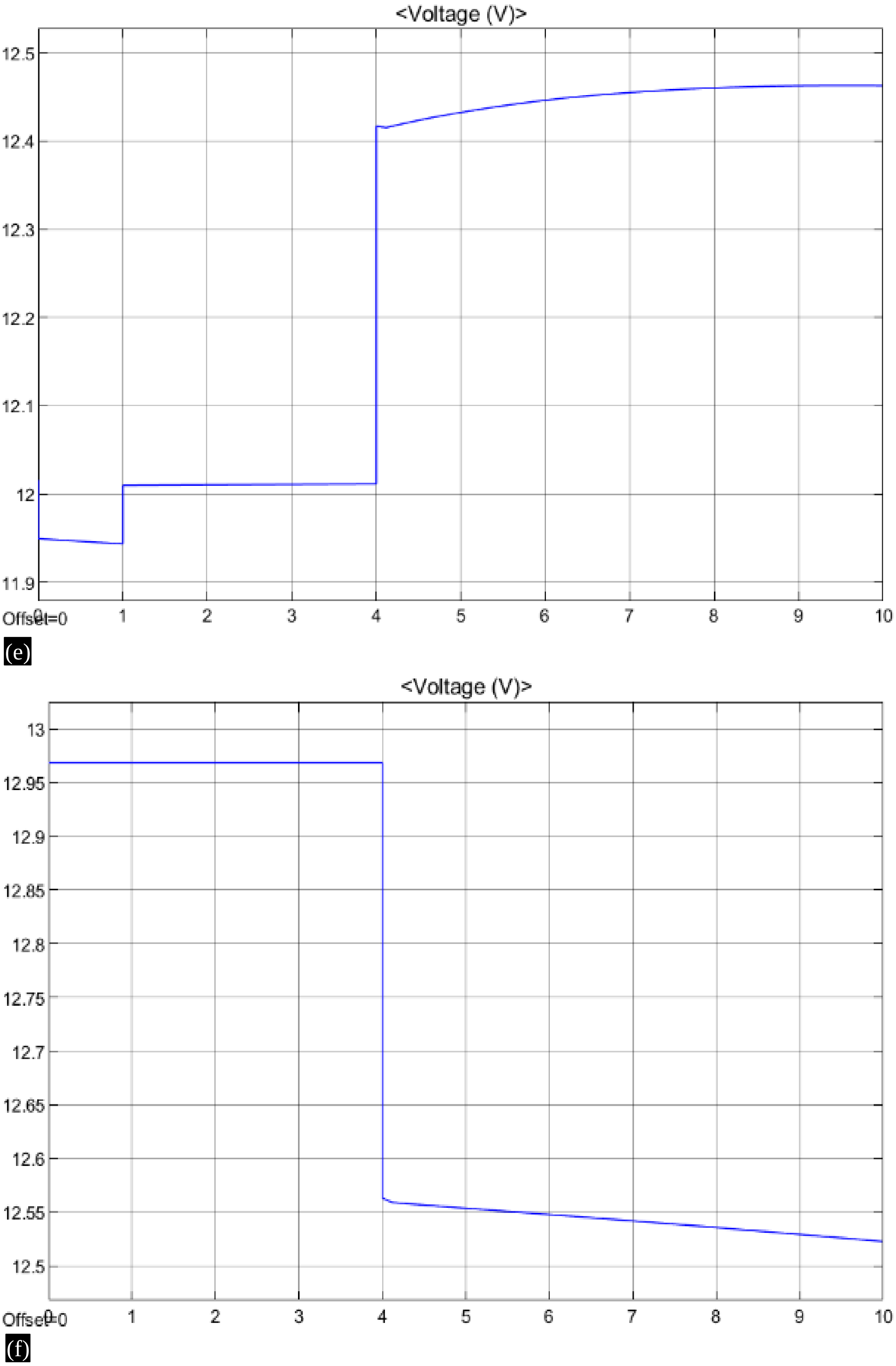
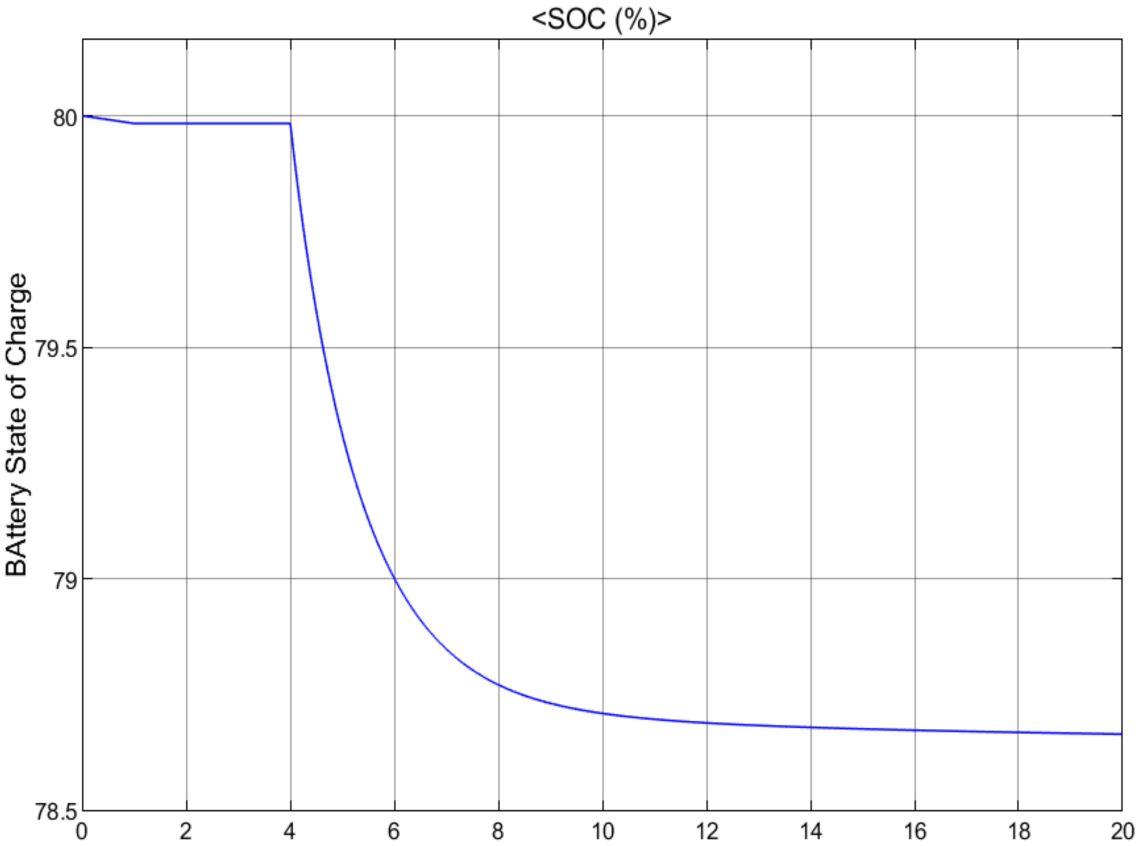


Figure 7. (a–f) Simulink circuit results for battery charging using auxiliary source.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4
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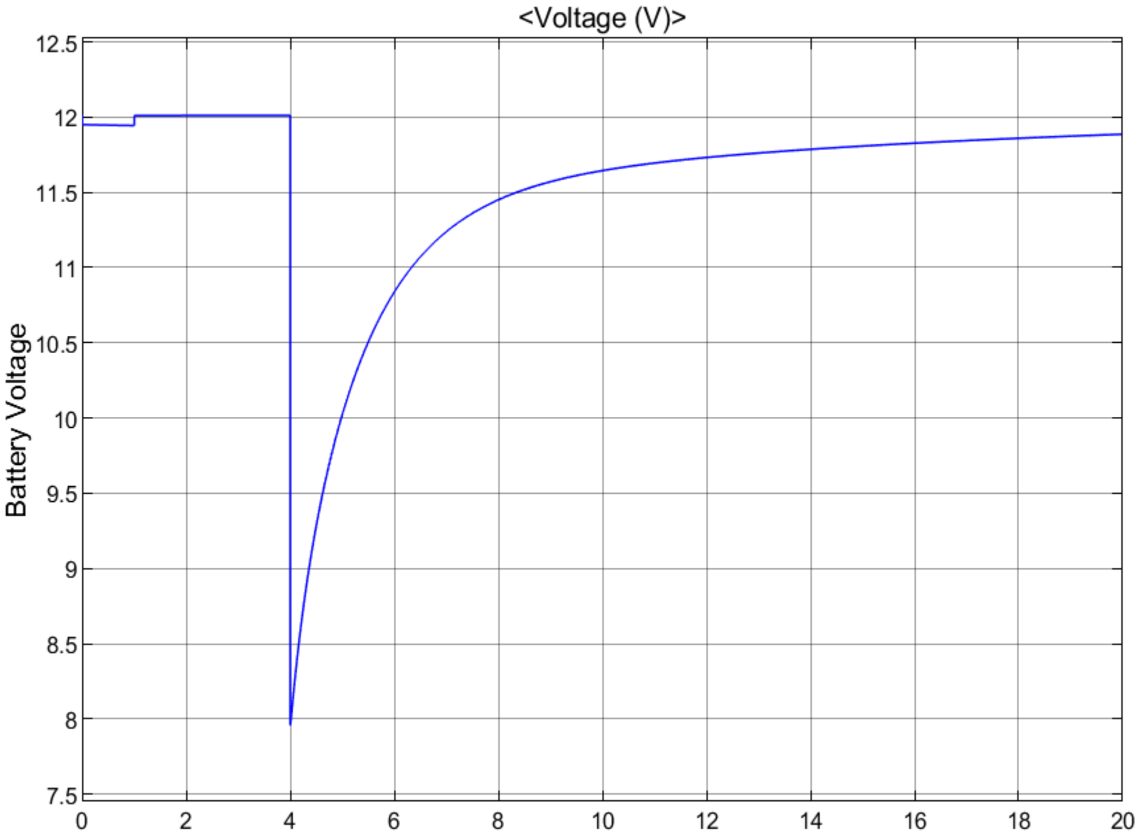
8
10
12
14
16
18
20

(a)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12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
0
2
4
6
8
10
12
14
16
18
20

(b)

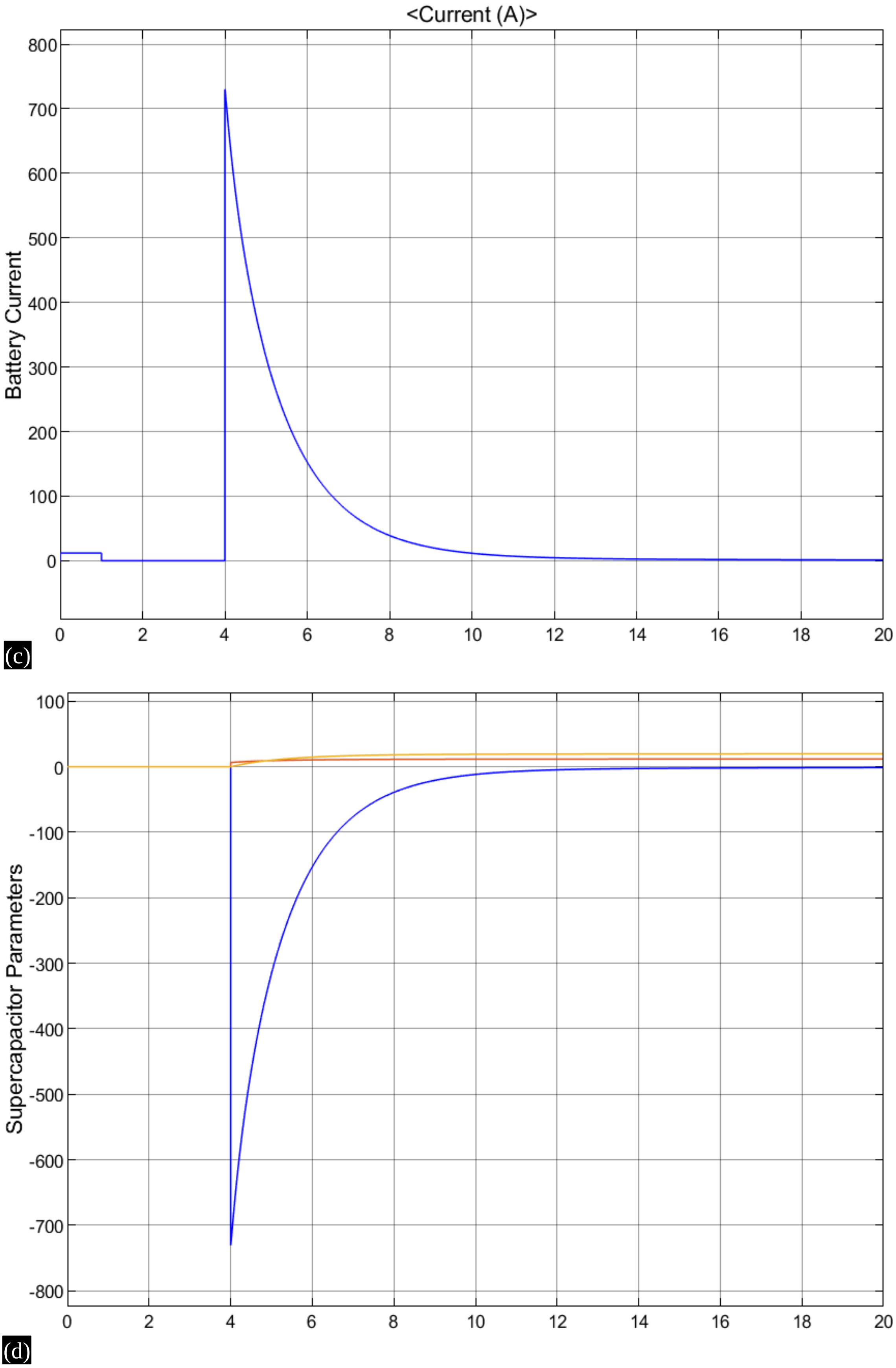

Figure 8. (a–d) Simulink circuit results for battery charging using auxiliary source (supercapacitor).

Table 1. Comparative analysis of energy storage systems.

Aspect	Individual Technologies	Hybrid Configurations	Advantages and Limitations for Applications	Trade-offs and Synergies	Optimal Configurations
Energy density	High for lithium-ion batteries (LIBs); low for supercapacitors; moderate for fuel cells	Balanced energy delivery combining high-density storage with rapid power availability	LIB–supercapacitor: suitable for passenger cars (urban areas). LIB–fuel cell: long-range buses. Fuel cell–supercapacitor: heavy vehicles requiring peak power.	Synergy: combines energy density of LIBs/fuel cells with supercapacitors' power. Trade-off: Increased complexity and cost.	LIB + supercapacitor for urban vehicles; LIB + fuel cell for long-range; fuel cell + supercapacitor for high-load heavy vehicles.
Power density	High for supercapacitors; moderate for fuel cells; moderate for LIBs	Enhanced with supercapacitors in hybrid systems	Supercapacitor hybrids deliver quick acceleration (passenger cars, buses).	Synergy: improves transient response in hybrids. Trade-off: limited energy capacity with standalone supercapacitors.	Supercapacitors essential for applications needing frequent power surges (e.g., buses, delivery vehicles).
Efficiency	High efficiency in LIBs and supercapacitors; moderate for fuel cells	Improved overall efficiency through energy management systems	Hybrid systems maximize efficiency by matching technologies to load profiles.	Synergy: efficient energy use in hybrid configurations. Trade-off: energy management system (EMS) complexity.	All hybrids benefit from advanced EMS for optimal efficiency.
Lifecycle and durability	Long lifecycle for supercapacitors; moderate for LIBs; variable for fuel cells	Prolonged by reducing load stress through task division	Hybrids reduce stress on primary energy storage system (ESS), extending lifecycle.	Synergy: increased durability. Trade-off: higher initial setup cost.	LIB + supercapacitor hybrids extend battery life in high-power demand scenarios.
Cost	High for LIBs and fuel cells; low for supercapacitors	Reduced operational costs through optimized component usage	Initial costs high, but lifecycle cost savings possible in hybrids.	Trade-off: high capital expense; Synergy: long-term savings from reduced wear on individual components.	Fuel cell + LIB for premium applications; LIB + supercapacitor for cost-sensitive urban uses.
Thermal performance	Challenging for LIBs and fuel cells; minimal for supercapacitors	Better thermal stability through load sharing	Hybrids distribute thermal loads, improving safety.	Synergy: reduced heat stress. Trade-off: more complex thermal management systems.	Hybrid configurations with advanced thermal management are optimal for extreme conditions.
Sustainability	Recycling challenges for LIBs and fuel cells; supercapacitors more environmentally friendly	Lower environmental impact due to efficiency improvements	Fuel cell + supercapacitor hybrids offer minimal emissions for heavy-duty vehicles.	Synergy: reduced emissions and resource use; Trade-off: dependency on hydrogen infrastructure for fuel cells.	Fuel cell + supercapacitor hybrids for green heavy-duty transport; LIB + supercapacitor for compact electric vehicles (EVs).

CONCLUSION AND FUTURE DIRECTIONS

1. Different ESS have different technological characteristics that complicate the design and management when they are used in combination. The initially high costs and integration problems drive up the cost of this process. It needs elaborate control systems designed to handle this energy and power competition.
2. Hydrogen cannot be stored in any container, so it necessitates the use of special infrastructure — expensive and scarce. Limitations and complexities of these underlying battery recycling processes have hindered sustainability at the cell level. Green energy storage technologies should be backed up with policies.
3. Solid-state batteries are healthier and offer a better energy density than traditional ones. Energy flow between the various storage components is optimized by AI-driven energy management to enhance efficiency and performance.
4. There are opportunities where lithium-ion batteries can be combined with supercapacitors, or solid-state batteries can be developed further for dual-use purposes. Improvement in hybrid system efficacy from AI and multilevel energy management.
5. They have high energy density but low-power output lithium-ion batteries. Supercapacitors offer fast power delivery, but with limited energy density. With hydrogen storage limitations, fuel cells are also optimal for long-range due to their high efficiency.
6. Lithium-ion batteries, paired with supercapacitors, are a good compromise for EVs. However, fuel cells and banks can be used together for extended distances vehicles. Management information system (MIS) help improve performance through optimization of energy management systems.
7. Continued research is essential to make energy storage more efficient and cheaper, to build better performing electric vehicles. In achieving hybrid ESS, it may find solutions to the barriers of merely storage technologies that can provide more sustainable transport options.

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