Hybrid energy storage system topology approaches for use in transport vehicles: A review

Mpho J. Lencwe | Shyama P. Daniel Chowdhury | Thomas O. Olwal

Abstract

High peak current for vehicle starting, recuperation of regenerative braking energy, longer battery lifespan, and more significant acceleration among others in modern transport vehicles (TVs) require increased battery size. Moreover, batteries have high energy density and low power density. Therefore, a big battery pack can weigh more, shorten its lifespan, increase vehicle total mass, and increase battery degradation costs. On the one hand, higher power energy storage systems (ESSs) such as supercapacitors, lithium-ion capacitors, and superconducting magnetic ESSs have a lower energy density, higher power density, and greater lifespan. Thus, to satisfy the requirements of modern TVs, the combination of higher energy and higher power density can provide enhanced performance and a longer battery lifespan for these vehicles. Available research publications in the literature have addressed a similar problem. However, these publications have reported the findings separately, providing various research and conclusions. Currently, no available literature has compiled an intelligible and combined analysis for addressing hybrid ESS configurations, sizing methods, and energy management strategies to create further knowledge in this domain. There is a need to consolidate a compact and insightful knowledge toward this research direction for a more significant societal and industrial impact. This paper critically reviews the hybrid higher energy density batteries and higher power density ESSs used in TVs. It discusses the integration configurations, applications, and provides sizing methods to achieve the best hybrid energy storage systems (HESSs). Also, applied control methods are described for these HESSs such that the overall system performance matches the vehicle requirements. Lastly, it provides insights and future research direction for HESS configuration, sizing, and control.

Keywords

configuration, control methods, electric vehicles, hybrid energy storage systems, performance enhancement, sizing
1 INTRODUCTION

Currently, there is a pronouncement for a decrease in the number of pollutants produced by the dominant fossil fuel combustion transportation. Thus, the transition from internal combustion engine vehicles (ICEVs) to hybrid electric vehicles (HEVs) and total electric vehicles (EVs) is obligatory.¹ Second, the fossil fuel demand will increase from 6.0 to 9.8 million barrels per day by 2040.² Hence, EVs are the future of the alternative world because of the depleting fossil fuel resources. Electrified vehicles have grown reception and transitioned the transportation to the huge sole need of energy storage system (ESS), which represents 10× better usage by energy capacity than stationary applications. The automotive battery energy storage need market will reach 0.8–3 Terra Watt-hour (TWh) by 2030.³ However, the cost, energy density, power density, and lifespan are essential to the evolution of the EV market.⁴ Automobile manufacturers such as Bavarian motor works (BMW), Mercedes Benz, Nissan, Opel, Chevrolet, Volkswagen, and others, produce fully EVs. There is a significant improvement regarding the widespread adoption of EVs; by the end of 2020, 10 million EVs have existed worldwide; by 2025, they will be 50 million, and 140 million by 2030 in the world roads.⁵,⁶ These vehicles will reduce fuel consumption and polluting emissions. However, future EVs must satisfy specific criteria. These criteria’s include high-energy-density to provide an extensive vehicle range,⁷ high-power-density to ensure high performance in terms of acceleration, deceleration, and capturing of regenerative braking energy,⁸,⁹ long lifespan to reduce cost, and fast recharge capability.¹⁰ Besides, the higher energy and power-density ESSs help reduce overall vehicle weight¹¹ in terms of EVs when using aluminum extrusion to decrease energy or electricity consumption and increase travelling distance. It is essential considering that the batteries with higher energy density are more significant than traditional ICEVs, and electricity demand may increase when EV adoption increases.¹²–¹⁵ Moreover, Yang et al.¹⁶ added that battery degradation could primarily increase the energy consumption and greenhouse gas (GHG) emission in EVs per distance traveled. However, to reduce energy consumption when EV adoption increases, ESSs with both higher energy and power density could decrease energy consumption and GHG emissions from EVs.

Electrochemical ESSs play an essential role in the evolution of EVs and renewable energy systems because of the accelerated energy and power requirements and variable renewable energy generation. Their purpose is to provide a power supply and energy buffer. Besides, to enhance efficiency and overall economy in each application, respectively, these EESSs need to be safe and tolerant to high and low temperatures. They need to be cost-effective, provide enormous power or energy density, and have a long lifespan in every aspect.¹⁷ However, batteries lose their performance over time for several reasons. The reasons include properties of the electroactive materials, conductivity, chemical stability of the current collectors, and frequent charging or discharging, respectively. Besides, they have low power density, short lifespan, and higher energy density.

The batteries’ ability to deliver specific energy and power is highly related to its performance. However, battery capacity and performance decrease over their lifespan, directly influencing the energy and power produced for a typical transport vehicle (TV) operation.¹⁸ Moreover, batteries lose their capacity because of diffusion-induced stress generated during regular charge/discharging, which leads to deformation and fracture of electrode materials, formation and growth of solid-electrolyte interphase (SEI). These stresses distribute asymmetrically through the thickness of the electrode plates; resulting in short circuits, cause deformation and fracture, and leads to the disconnection that gives active electrode materials the inability of storing positive Lithium-ions.¹⁹–²² Besides, the change of SEI during a few thousands of cycling and physical deteriorations of the negative electrode because of intrinsic volume change for graphite electrode used in lithium-ion batteries causes the loss of active material (LAM), thus, loss in capacity. Additionally, the attribute of performance loss in batteries causes increased electrode resistance of the positive electrode. Over-discharge causes battery capacity loss and significantly affect the cyclic performance during standard operating conditions.²³–²⁵

Louli et al.²⁶ propose operando pressure measurements as a criterion to assess SEI on lithium-ion batteries. This method shows a relationship between the irreversible volume expansion and loss of capacity caused by a continually thickening of SEI during cycling. Kim et al.²⁷ perform a capacity loss investigation for Lithium-Nitrate Manganese Oxide (LNMO)/graphite cell. The loss in capacity originates from Li-ion loss in LNMO, where manganese (Mn) dissolution plays a significant role in SEI layer growth. Despite many methods adopted to assess battery degradation in terms of their performance and capacity, Yang et al.²⁸ and Pastor-Fernandez et al.²⁹ evaluate battery aging mechanisms using incremental capacity analysis. During the investigation, LAM increased battery degradation and decreased Coulombic efficiency. The study further emphasizes that the battery lose its capacity and performance during the repeated charge/discharge process. Many factors cause battery degradation, which includes loss of lithium inventory (LLI), conduction loss (CL), and increase in internal resistance (IR). Figure 1 illustrates the most prominent capacity and performance loss caused by side reactions in a battery.²⁹,³⁰,³¹
At a battery pack during vehicle testing, hot and low temperatures cause battery capacity loss. \cite{32,33} Besides, at low temperatures, the electrolyte's viscosity increases and decreases the ionic conductivity, while the IR increases because of the impedance of directional migration of chemical ions. Also, lithium-plating that appears on the graphite and other carbon-based anodes lead to battery capacity loss. \cite{34} Thus, its performance degradation needs consideration during battery design steps. \cite{35,36} Also, Figure 2 shows different ESS characteristics based on a Ragone plot.

On the other hand, supercapacitors (SCs) have higher power density and low energy density. However, they are suitable candidates for high peak power demand during short periods, when the battery cannot suffice because of their excellent cycle life and high abuse tolerance, etc. \cite{38} Because of these reasons, sole higher energy density or higher power density ESSs cannot suffice the energy and power requirements of modern TVs and renewable energy generation systems. Therefore, combining different ESSs that simultaneously provide higher energy and power to meet a specific application requirement arouse great interest for many researchers and industries. However, the system's physical size needs consideration when designing the combination of ESSs.

Hybridization is a combination of different storage technologies with various characteristics to downsize the overall system and direct the unfavorable load conditions such as severe charge or discharge current fluctuations to a more sturdy ESS (i.e., SC). \cite{39,41} Massive, frequent currents, and changes of power into or out of the battery, come at a cost and reduce batteries' lifespan. \cite{42,44} Besides, hybridization helps to decrease the operating costs by avoiding frequent battery replacements and increasing battery lifespan, system efficiency, reducing energy waste, low volume, and improved performance of the overall system. \cite{1,38,45,47,48} Also, the produced heat in HESS reduces significantly because high peak currents are absorbed and provided by high power storage devices, thus reducing internal battery losses. In the future, EVs will probably adopt hybridized energy storage to enhance the battery lifespan by reducing the effect of eminent power and rapid attenuating loads. \cite{49}
Energy management systems (EMSs) play an essential function in refining and controlling the performance of battery electric vehicles (BEVs), EVs, HEVs, and plug-in hybrid electric vehicles (PHEVs), respectively. The quality of an EMS enhances the lifespan of ESSs and can increase the performance, efficiency, and fuel economy in these vehicles.\(^5^1\) How to best split the power demanded by the motor and vehicle at every time step between the battery and SC must be decided. The energy and power splitting procedure will provide enhanced battery lifespan, reduced cost, and a significant efficiency improvement.\(^5^1\) Although the initial cost of the HESS is higher compared to sole-battery systems, enormous savings in battery lifespan may compensate for this cost simultaneously. HESS provides much higher peak power and an extended range for EVs. Hence, the application of HESS can be more profitable if the price of a SC or superconducting magnetic energy storage system (SMESS) decrease significantly.\(^5^2\)

Kasimalla et al.\(^5^3\) review the energy allocation of an HEV comprising a hybrid fuel cell, battery, and SC. The study emphasizes that the EMS contains an energy administration procedure. The procedure includes calculations that select criteria at each step and power fracture among the principle control source. Wang et al.\(^5^4\) confirm the issues of control and management for HESSs of Kasimalla et al. The study discusses methods and theories for parameter state estimation. It further includes aging mechanism and life prediction methods, hybrid structural design optimization, and energy-power management distribution strategies, respectively. However, the studies draw several shortfalls with considering other HESS topologies in their investigations and how they will impact changes in their energy allocation strategy. Chong et al.\(^5^5\) later solve these research shortfalls when reviewing classical and intelligent control strategies for renewable energy power systems (REPS) comprising HESSs. The authors further deliberate on future trends with HESSs and their control. Besides, the research conducted by Chong et al. presents shortfalls because its primary concern includes renewable energy systems and ignores TV applications.

Silva et al.\(^5^6\) conduct a study to elaborate on the advantages and disadvantages of different HESS systems, including passive and active topologies. The systems are simulated using a Matlab/Simulink tool and comprise a battery-only and battery-SC system. Zhang et al.\(^5^7\) confirm the validity of Silva et al. in their comprehensive review of electrochemical ESSs used in electrified vehicle applications. This review discusses HESS, configuration topologies, DC-to-DC converter design, and energy management strategies. In addition, Farhadi et al.\(^5^8\) discusses various high-power ESSs, including their developments, higher power-dense batteries (i.e. Li-ion), and compared them in terms of their energy, power, cost, life, and performance, respectively. Besides, it discusses these systems applications and their limitations in TVs. Yet, these investigations present various deficits with HESSs. Hannan et al.\(^5^9\) solve these deficits by reviewing battery ESSs. They discuss their technologies, optimal sizing, associated constraints, their optimization models, and the limitations of their optimization approaches. However, these studies present various shortfalls in conducting limited case studies for HESS topologies, direct focus on battery ESS as a single source with no hybridization with other ESSs. Besides, they lack a detailed discussion of available higher-power technologies such as lithium-ion capacitors.

In addition to previous studies, Xiong et al.\(^6^0\) review smarter HESS comprising a battery and a SC. The authors discuss the HESS configuration schemes and their different energy management control strategies. Ostadi et al.\(^6^1\) confirm the validity of Xiong et al. by conducting a review on battery and SC HESS for vehicle applications. The paper reviews the different hybrid schemes, including passive, semi-active, cascaded, and fully active parallel topology approaches. In addition, it includes these topologies energy management strategies. Yet, these reviews further draw various shortfalls, including discussing a fully functional parallel topology approach based on a Z-source converter. Besides, they lack discussion about sizing methodologies for these HESSs. Hajiaghasi et al.\(^6^2\) later solve these research shortfalls by conducting a comprehensive review in HESSs for microgrid (MG) applications. The study discusses the types of HESSs in microgrids, capacity sizing methods, converter topologies for HESS schemes, architectures, energy management control strategies, economic analysis with their methodology, and future trends, respectively. However, the study focuses on MGs. The capacity sizing techniques discussed in this study may differ depending on applications. Besides, it addresses the HESS configurations as converter topologies, which contradicts the discussion of the type of converter utilized for such applications. Hemmati and Saboori\(^6^3\) solve the shortfalls found in Hajiaghasi et al. by discussing HESSs used in renewable energy and transport applications. They discuss a few concepts of HESSs, the hybridization principles, HESS schemes, their electronic power integration, energy management control strategies, and applications. However, the authors elaborate more on topologies, including passive, cascaded, and fully active parallel. They omit to elaborate on semi-active parallel topologies.

Lukastskaya et al.\(^6^4\) review different types of electrical energy storage technologies, provide techniques to avoid current limitations and future trends toward the next generation of ESSs. Although the study includes hybrid schemes of battery and SC ESSs, it analyzes these configurations at the cell level, not from a module/system level of application. Ren et al.\(^6^5\) confirm the indications adopted.
by Lukastkaya et al. to avoid current limitations in various energy storage technologies for TV applications, including batteries, SMESS, flywheels, SCs, and HESS. The study discusses these ESSs for vehicles with a new propulsion system comprising linear engines, and however, it lacks detailed discussions of HESS schemes for possible adoption in these vehicles. Zimmermann et al. later solved these deficits by discussing different hybrid topologies regarding their usable voltage window, stored energy utilization, interface to the vehicle power train, and the necessary power electronic devices (PEDs). Consequently, they discuss the configuration of these ESSs at the cell level and module level with no PEDs and suggest new HESS topologies. Besides, the study does not cover HESS sizing.

The existing proposed solutions exist in separate contributing publications. However, they have not compiled a comparative analysis and synthesis of the keys in a single review. A detailed review of hybrid energy storage topologies, their sizing, and control techniques is lacking. This deficit in available literature presents a research shortfall in terms of HESSs. Besides, the shortfall includes ESS design integration topology approaches, detailed HESS sizing, energy and power management control methods, and current research trends. Therefore, this research contributes to the body of knowledge in closing the gap of detailed HESS configuration, sizing, and control techniques for use in TVs or renewable energy generation applications.

This paper review and test the HESS configurations, their sizing critically, and energy and power management control for proper energy/power splitting applied in TVs or renewable energy generation. The HESS configuration, sizing, and energy/power control improve the overall EVs’ efficiency, reduce costs, extend vehicle range, and enhance battery lifespan. The study includes passive, battery semi-active, SC semi-active, and fully active parallel topologies. Besides, it contains a cascaded battery semi-active, cascaded SC semi-active, cascaded fully operational, and Z-source converter fully-functional similar topologies. The contribution includes a review of conventional and recent HESS design configurations, detailed HESS sizing techniques, thorough energy and power management control methods, current research trends, and a future research direction based on the assessed review. It presents comprehensive design considerations, opportunities, and solutions to be used by future researchers in this domain to develop HESS configurations, sizing methods, and power and energy management. Such a focus has received little or no attention in the existing literature. Also, to the best of our knowledge, no similar work has contributed to the current research trends and future of the HESS configuration, sizing, and energy and power management control. The main goal of this paper is to undergo a comprehensive research literature survey, which seeks to fill in the research gaps as mentioned earlier with novelty.

Henceforth, the paper encompasses Section 2, which describes the comparative energy storage market analysis by application; Section 3, the state-of-the-art research for HESS schemes; Section 4, the overview of different HESS schemes, their merits, and demerits; Section 5 discusses the HESS sizing, including energy and power management strategies; Section 6 summarizes HESS sizing and their energy/power management strategies, followed by Section 7, which discusses the research trends and future recommendations. Section 8 provides the conclusion of the research work conducted here.

2 COMPARATIVE ESS MARKET ANALYSES BY APPLICATION

This section discusses various ESS market analyses by application. The world energy storage market contains Lead-acid, Lithium-ion, flow Nickel-metal hydride batteries etc. According to Nestar research report named “Global Renewable Battery Storage Market 2021-2028”, Li-ion batteries dominates the market with $1066.21 Million in 2021. These batteries have a higher energy density, exceptional temperature tolerance, safety, and rapid charging capability, unlike other ESSs, which plays a significant role in their market growth. The study’s outcome estimates that by the end of 2028, this segment will generate revenue of $9928.25 million from an income of $888.48 million in 2019. These batteries have broad applications, including power systems, renewable energy sources, transportation, and telecommunications. For a typical example, in South Africa, diverse businesses are interested in using renewable energy supply because of constant load shedding, which affects the businesses’ daily operations and revenue.

At the end of 2020, the energy storage (i.e., Batteries) capacity remained at 17 GW. That year (i.e., 2021), the battery installation grew by 50% compared to 2019. Currently, the world has added 5 GW of storage capacity, led by China and the United States (US), each recording 1 GW plus from the original. The energy generation installation continued to lead the market, accounting for 2/3 of the additional capacity. ESSs have broad applications, including renewable energy integration, intelligent grid support, creating a dynamic electricity market, providing ancillary services, grid resilience, energy self-sufficiency, and transportation. Market drivers for these applications have to do with the reduction in battery cost and performance improvement, modernization of the grid, global adaptation of renewable energy sources, participation of electricity customers in the wholesale market, government financial incentives,
phase-out of feed-in-tariffs, the need for self-sufficiency, and national policies, respectively. Figure 3 shows the battery energy storage capacity by its primary use globally.

3 | STATE-OF-THE-ART ANALYSIS

A combination of different ESSs in a hybrid involves various approaches. This section discusses different topology approaches for HESSs. Classification of these topologies is as follows:

- **Passive-parallel topology approach**: In this topology, the battery and SC connect directly in parallel and to the DC-bus voltage link.

- **Active-parallel topology approach**: This topology connects the battery and SC to their individual DC-to-DC power electronic converters. Thus, the output of

- **Semi-active-parallel topology approach**: The battery or SC connects to the DC-bus voltage link through a power electronic DC-to-DC converter. This configuration allows ESSs to be controlled based on their associated current, voltage, or state-of-charge (SoC), thus regulating their energy and power flow. Moreover, the widely used topologies, including cascaded, are in the literature compared to the ones described in Figure 3(C) and (D). These topologies are battery semi-active topology, semi-active SC topology, battery semi-active (uni-directional converter), and battery semi-active (bi-directional converter) topology, respectively.

**FIGURE 3** The world battery energy storage represents current capacity by application.
these converters connects to the DC-bus voltage link. Multi-input fully active can achieve similar topology by using a single DC-to-DC power electronic converter with multiple inputs. The study refers to these topologies as fully functional topology approaches.

Figure 4 shows different hybrid topology approaches for battery and SC sources. Figure 4(A) offers a passive-active topology approach. It presents a direct connection of the battery and SC to the DC-bus link. Figure 4(B) shows a battery semi-active topology. In this topology, the battery connects to the DC-bus link through a DC-to-DC converter. This converter can be uni-directional or bi-directional. The SC terminals connect directly to the DC-bus link in this topology. The power electronic converter limits the current flowing to/from the battery. Figure 4(C) represents a semi-active SC topology. This topology connects the SC to the DC-bus link through a bi-directional power electronic DC-to-DC converter. The battery connects directly to the DC-bus link. Figure 4(D) shows a fully active topology. This topology shows the battery and SC click to the DC-bus link through their electronic power converters. The battery converter used in this topology is uni-directional or bi-directional. The SC connects through a bi-directional converter to allow varying voltage within a desirable range. Figure 4(D) can form a multi-input converter topology. This topology is like a fully active topology. However, the multi-input topology uses one casing to reduce space and wiring for the converters. Figure 4 provides different topologies for the development of battery-SC HESS approaches. It allows simple consideration in structure, complexity and volume, respectively.

3.1 Passive-parallel topology

This section discusses the passive-parallel topology approach for a hybrid ESS used in TVs. It also discusses the challenges of using this topology in TVs, as stated in other literature. This topology directly connects the battery and SC to the DC-bus voltage link. The HESS configuration is the simplest, cost-effective, less weight, and requires no control for energy/power-sharing. The ESS IRs determine the energy/power-sharing. However, during regenerative braking, the battery is subjected to a high current peak, which affects their lifespan and the efficiency of the TVs. Also, it effectively underutilizes SC. Various studies report the application of the passive-parallel topology.

Grüner et al. investigate the direct connection between hybrid lithium-SC ESSs. The investigation tests whether a direct link of dissimilar ESSs can improve lifespan, power, and energy density compared to a single ESS. The results show that the energy and power density of the hybrid system highly depend on the voltage-level matching of both ESS. The system can reduce a load of Li-ion battery by 15%–30% compared to a single battery of the same weight and volume. Goussian et al. and Barcellona et al. confirm the validity of Grüner et al. by conducting behavior analysis of passive hybrid Li-ion battery and SC on various EVs under different driving cycles and temperatures. The results show that integrating SC with battery can help EV start at shallow temperatures. However, the results do not quantify how good the results are for the significant utilization of Li-ion or SC. This shortfall is later solved in Dezza et al. when authors compare the passive-parallel topology approach with semi-active topology to hybridize battery-SC ESSs of forklifts. The passive-parallel topology’s purpose is to split the power flow between the ESSs. The study uses passive topology to achieve the best overall performance of the HESS in terms of efficiency, capacity, and lifespan. However, the results show many typical voltage profiles for the two ESSs during discharge. Besides, the topology used causes limited usable energy of the SC during admissible voltage fluctuation of lead-acid batteries (LABs). The research presented a nonquantified achieved range. Zhang et al. first describe additional shortfall in conjunction with passive parallel topology and emphasize that close to 64% of the SC’s stored total energy is unused. Second, the SC size is usually significant compared to other HESS topology approaches. Last, the SC voltage follows the battery voltage. The passive scheme causes a limited usable SC high-power density characteristic.

Chong et al. compare an islanded photovoltaic (PV) system comprising battery and SC hybrid and battery-only ESS for a typical rural household. The study uses the passive-parallel and semi-active-parallel schemes for comparison. Authors in Chong et al. confirm the conclusions drawn by Chong et al. and deliberate corporate concerns of stand-alone renewable energy power systems comprising passive, semi-active, and active-parallel schemes. In addition, they discuss the decision matrix to investigate the technical and economic feasibilities for various technologies of ESS in renewable energy power systems. Although the passive parallel topology is simple, provides high reliability, low cost, and less weight, it provides a minor performance improvement because of uncontrollable power flow. In addition, various studies show that the direct integration of battery and SC is feasible and applicable for use in TVs. Nevertheless, it lacks full utilization of SC and harms the overall system performance, insignificant current profile, low volumetric efficiency, low design flexibility, and uncontrollable power flow, respectively. Moreover, it has no protection for ESS against faults. Figure 5 shows a passive-parallel configuration for a hybrid battery and SC
3.2 | Semi-active-parallel topology

This section reviews the semi-active topology for hybrid ESSs used in EVs. Besides, it describes the advantages and disadvantages of using these topologies in TVS, thus helping the automotive industry select the suitable hybrid topology approach for TVs. This topology uses a single DC-to-DC converter connected to one of the individual ESSs, whereas the other ESS is connected directly to the DC-bus. An additional power electronic system adds cost and requires more space. However, this scheme can control and release the energy needed for applications, as stated in Hajighasemi et al.62

Golchoubian et al.51 use a semi-active SC approach for proposing real-time nonlinear model predictive control (NMPC) of battery-SC HESS. The authors connect the SC to the battery through a bi-directional DC-to-DC converter. The topology directly connects the battery to the DC-bus voltage link. Such a connection forces the DC-bus voltage to be nearly constant. The authors in Castaings et al.79 confirm the validity of using the same approach to enhance battery lifespan and EV performance. However, the study did not consider the implications of system operation and efficiency under variable bus voltage. The authors in Wegmann et al.80 later solve this drawback by using a similar topology to investigate the size and function of lithium-ion battery and lithium-capacitor HESS in EVs using stochastic and deterministic dynamic programming. The authors first evaluate a hybrid system before sizing for a range. The study concludes that the topology offers a good trade-off between cost, weight, and control complexity and provides adequate energy-to-power performance, correspondingly. Besides, it emphasizes that the energy of the HESS must satisfy the load requirement. Consequently, the power of the battery pack used is enough to meet the acceleration performance of EVs. The results show that the HESS reduces the micro-cycles on the higher-energy-density battery.

Wang et al.81 use a battery semi-active topology approach with a boost converter to develop an estimator adaptive sliding mode control (e-ASMC) strategy for a boost converter battery-SC HESS. The created e-ASMC provides robust current control in practical applications. It must guarantee battery safety by designing a sturdy current tracking control. Keil et al.82 confirm the validity of Wang et al.’s topology by investigating a lithium-ion
battery with a lithium-ion capacitor to evaluate the HESS performance at low temperatures. This study allows a smaller size of an electronic power converter. Besides, it compares the HESS with a sole battery system. The results show that at −20°C, the isolated battery system cannot meet the power demand profile of a typical driving cycle. However, the HESS with higher energy density and a higher power battery provides the demanded load power demand at this temperature and extend the vehicle range as compared to HESS-based SCs. It also shows that the volume ratio of the individual ESS hybridized needs to be the same to meet the load power demand of the vehicle for a particular driving cycle. However, the topology approach used cannot guarantee optimal battery SoC. Also, because the SC is directly connected to the DC-bus link and naturally has a varying voltage, this voltage can be elevated to undesirable limits and cause damage to connected loads. Chung et al. later addressed these research shortfalls when they proposed a lithium-ion and lead-acid battery HESS using a lead-acid battery semi-active scheme for a utility light EV. The developed HESS has competitive costs like a sole lead-acid battery system and sustains the performance benefits of conventional lithium-ion ESSs. The results show that the system obtains a 17% range enhancement and efficiency increase a continuous 24 km/h cycle of 23%. Nevertheless, the batteries in nature have slow dynamic characteristics; thus, hybridizing batteries may offer low efficiency for providing and absorbing rapid peak currents for vehicle acceleration and recuperation of regenerative braking energy.

Sun et al. use a semi-active SC topology approach for an adaptive power split strategy of a battery-SC HESS used in EVs. The authors tested the effectiveness of the HESS by directing damaging loads to the SC. Nguyen et al. confirm and adopt the same topology approach as Sun et al. to assess the adaptive Pontryagin’s minimum principle (APMP) strategy for effective energy sharing. Despite using the adaptive power splitting strategy, these studies present various shortfalls regarding the topology, and the battery lifespan could shorten significantly. Therefore, Chung et al. later solved this problem by adopting the same HESS topology and developing a real-time charge-discharge rate management strategy based on an adaptive algorithm for EVs to enhance battery lifespan by considering their physical dynamics and operation history. The physical dynamics that affect the battery’s charge/discharge rate (e.g., regenerative braking) can cause peak currents, thus affecting battery lifespan significantly. The results show that the battery lifespan improves by up to 37.7% with a small added cost compared to a sole battery system. Hussain et al. also solve this similar problem. The study develops a strategy to ease the power density shortage in electrochemical ESSs. The results show that the EMS reduces the battery’s stress, temperature, and power loss. However, the results did not quantify reduced power loss and enhanced battery lifespan.

Previous studies report mainly on battery temperature reduction for a holistic lifespan improvement. Although it is crucial to monitor battery temperature, it is also necessary to evaluate the temperature performance of the overall HESS system to increase its operating lifetime. Mesbani et al. propose an advanced model, which integrates the HESS thermal behavior and enable easy investigation of ESS aging effects comprising lithium-ion battery and SC for an urban EV. This model incorporates the electrothermal behaviors of the HESS, which allows easy analysis of progressive degradation of HESS performance. The results show that the model performance is good. Li et al. validate the findings of Mesbani et al. by extending their previous study to improve the battery lifespan by hybridizing...
superconducting magnetic energy storage (SMES) with a battery using SMES semi-active scheme. SMES is employed to reduce battery short-term power cycling and peak discharge currents in an off-grid wind energy system to improve the battery lifespan. The results show a reduced battery cycling and the lower peak released currents from the battery in a renewable energy system. However, these researches present various shortfalls with HESS topology and the adopted model. The model assumes that the HESS temperature variation is like the battery’s. Also, Mesbani et al. assess the topology in a different application. Hence, Ruan et al. solve this drawback by proposing a multispeed electrified power train with a battery and SC topology to improve the energy efficiency, dynamic performance, and EV range without increasing battery size. The SC combines multispeed transmission to enhance the vehicle driving range and increase battery lifespan in this configuration. The study results show that the HESS reduces battery capacity fade significantly. The authors in Song et al. adopt a SC semi-active topology approach to analyze the influence of different temperatures and battery prices on an integrated optimization of HESS. It includes sizing the SC and EMS for EV applications. The authors achieve this by conducting an analysis based on a comprehensive battery price range. The results show that the optimized ESS price of 12% less compared to the sole-battery systems.

In another study, the authors use a SC semi-active topology approach to test energy management control strategies, including lambda-control and rule-based control in real-time for EVs. These EVs comprise hybrid battery-SC ESS. Zhang et al. use these control strategies on a new proposed semi-active topology approach for HESS to efficiently manage the battery current. The battery accepts regenerative braking energy when the SC charges fully. Besides, it offers a low cost compared to existing topologies reported in the literature. This topology is unique because of two additional uni-directional or bi-directional electronic power converter switches. Xiang et al. confirm and validate the proposed topology as in Castaings et al., but compared to Zhang’s et al.’s topology, it does not comprise a capacitor to filter out the ripples on the DC-bus voltage. However, they have low charging efficiency because of the energy consumption of power electronic converter. Naseri et al. address this drawback by proposing an efficient regenerative braking system for full EVs, HEVs, and PHEVs. The HESS has different operating modes. The controlled DC-to-DC converter maintains the SC voltage higher than the battery voltage. The results show an improved efficiency of the regenerative braking system by 20%, and vehicle driving range increased by five cycles. Also, Zhao et al. further propose a solution by investigating the energy transfer and distribution strategy of an HESS comprising battery and SC to improve the recovery and utilization efficiency of the regenerative braking energy. The analysis evaluates the in-depth energy loss and recovery flow path during driving and braking scenarios. The results show that the HESS with proper control strategy can eliminate excessive output power of the battery, thus enhancing its lifespan.

Kollmeyer et al. introduce a hybrid Li-ion battery, and Li-ion capacitor configured in a semi-active parallel scheme for a PHEV. In this configuration, the lithium-ion capacitor connects directly to the DC-bus of the motor inverter. The study aims to ensure an optimum power split between the ESS and optimize variables, including reducing ESS losses, increasing regenerative braking recovery, and reducing the motoring power limitations. Soltani et al. confirm and adopt the same HESS to protect the battery against damaging power fluctuations during cycling, extend range, and enhance the battery lifespan of a pure electric bus. The results show that the battery lifespan improves by 16%, and the battery-only system’s size decreases by 30% when using the proposed HESS. However, this HESS configuration underutilizes the lithium-ion capacitor and causes system instability because of wide voltage variation during operation.

Zhang et al. carry an experimental analysis for a semi-active SC scheme. The topology decouples the SC from the DC-bus voltage link through a bi-directional electronic power converter. Because it provides full utilization of the SC, this topology approach provides a trade-off between control and performance of the system compared to passive and wholly active topology approaches. Vulturescu et al. confirm, implement, and test an HESS topology used by Zhang et al. comprising a nickel-cadmium battery and a SC for an electric bus. The study analyzes whether there is an improvement in bus range extension, vehicle dynamic performance enhancement, and battery stress, respectively. The results show that the system reduced the battery root mean square (RMS) current and the overheating by a factor of 2, which offer lifespan extension. However, the study presents several shortfalls, including battery subjected to high DC-bus voltage fluctuation, affecting its operating lifespan. Yaïci et al. solve this drawback by evaluating the benefits of using the same adopted topology by Zhang et al. and Vulturescu et al. showing how workable it is to use the proposed method topology on EVs by simulation. The results show a significant reduction in battery charging time intervals. The SC contributes substantial power, and the vehicle range extended by 21.5% under the United States high acceleration aggressive driving cycle (US06) conditions. The authors further emphasize that integrating battery and SC can reduce the size of the EV energy source. Figure 6 below shows two conventional semi-active topology approaches for battery-SC
HESS. Figure 6(A) shows a battery semi-active topology approach, Figure 6(B) shows a SC semi-active topology approach, Figure 6(C) illustrates a battery semi-active cascaded topology, and Figure 6(D) shows a SC semi-active cascaded configuration, respectively.

3.3 Semi-active (uni-/bi-directional converter)

This section discusses the newly proposed semi-active parallel topology for a battery-SC HESS used in EVs, as discussed in Section 3.2 above. The battery and SC connect through a uni-directional or bi-directional electronic power converter. This topology added a switch between the battery sources and the load. The topology is simple, easy to implement, and cost-effective. However, it has low charging efficiency because of the energy consumption of power electronic converter. These topologies need bi-directional switches. Besides, they cannot provide complete control of battery SoC variation. There is a need for performance tests of these topologies against the conventional topologies in terms of charge efficiency. Figure 7 shows the new hybrid topologies. Figure 7(A) presents a new battery semi-active topology approach with a uni-directional converter and a single switch. Figure 7(B) shows a new battery semi-active topology approach with a bi-directional DC-to-DC converter and single control. Figure 7(C) represents the new battery semi-active topology approach with a uni-directional DC-to-DC converter and two switches. These switches are bi-directional to allow battery and SC recharge by regenerative operating mode, using specific criteria depending on ESSs’ SoC. The recent literature discusses these topologies, and to the best of our knowledge, recent literature reviews have not reported these topologies in a single thought.

Song et al. compare different semi-active parallel schemes of HESS for EVs. These different approaches are used specifically for an electric city bus. The study used the China bus driving cycle to investigate the performance of varying HESS topologies. The performance test includes operation cost, initial cost, and DC-bus voltage regulation. The study further elaborates that topology (A) in Figure 7 increases efficiency, decreases converter cost, and utilizes a simple control strategy. However, its limitation includes no degree-of-freedom for traction mode control, high DC-bus voltage fluctuation, and high operating cost, correspondingly. In terms of topology (B) in Figure 7, it has advantages, including the reduced power level of the DC-to-DC converter. Song et al. confirm the validity of the topology as used in Song et al. for use in EVs to achieve a high HESS efficiency and fewer systems costs. The achieved objective utilizes a small uni-directional DC-to-DC converter. However, this topology has limitations of an uncontrollable system when the SC voltage reduces to the battery voltage. Besides, it has limited SC operation and varying DC bus voltage, respectively. Fang et al. solve this drawback by proposing and demonstrating this HESS topology in virtual synchronous generators (VSGs) in renewable energy power systems. The HESS ensures frequency regulation by emulating the conventional synchronous generator applications in a power system and operating as an inertia coefficient, droop control, speed governor, and VSG turbine. The results show

![FIGURE 7 Recent semi-active hybrid topology approach. (A) Additional switch uni-directional topology, (B) Additional switch bi-directional topology, and (C) Two other buttons uni-directional topology. Courtesy: Cong Zhang, Dai Wang, Bin Wang, and Fan Tong](image-url)
that the HESS reduces the power variation and its C_rate. Furthermore, an experimental study validates the system application.

### 3.4 The fully active parallel topology

This section discusses the fully active parallel topology approach for a battery-SC HESS used in EVs. It provides advantages and disadvantages of using this topology approach. These advantages and disadvantages apply to the multi-input, fully active, and fully functional cascaded parallel topology approach. The structure is similar in both topologies. Therefore, a separate section for a multi-input, fully dynamic topology approach is unnecessary. The fully operational topology provides improved system efficiency, flexible control, etc. Also, it allows the effective use of SCs. However, it has a high cost because of the increased number of DC-to-DC converters. This topology decouples both ESSs from the DC-bus link through their power electronic DC-to-DC converter. Therefore, because power electronic components are becoming cheaper than ever before, it is simple to provide appropriate matching and size with the topology at a reasonable cost.

In Ref. 101, the authors adopt a fully active topology for the power management strategy of pure EVs. This approach stabilizes the voltages of the energy storage sources by realizing an effective load current split in a buck or boost converter mode of operation. Zhang et al.\(^\text{102}\) confirm the validity of the authors in Ref. 101 by using the same topology to improve the power flow from or into the battery. Besides, it protects the battery from high peak currents during charge or discharge cycles in EVs. Yet, these investigations draw several shortfalls with effective load current splitting because rule-based strategies cannot offer quality control. Hence, the authors in Ref. 103 solve this drawback by adopting a similar topology approach for an optimally controlled HESS. This topology minimizes the effect of peak current demand on the battery under a single-pulse electric vehicle (NEV) driving cycle. The authors conduct the study by hypothesizing that the hybrid can lower operating costs for a NEV. This low operating cost may offer lower energy losses and enhanced battery lifespan. The results show the reduced peak current drawn from the battery. If the peak current matters in determining the battery usable capacity per single charge and the length of battery lifespan, then the vehicle operating cost can relate to lower energy losses. However, the study lacks an explicit explanation of the control method applied.

Sellali et al.\(^\text{104}\) use the parallel-active topology to develop hybrid battery-SC ESS in EVs. This topology has an increased number of degree-of-freedom. Reduced energy source’s lifespan can be possible if the ESSs connect directly to the DC-bus voltage link. Castiglione et al.\(^\text{105}\) agree and also adopt this topology of Sellali et al. for a power management system of battery and SC HESS in E-mobility usage. The aim is to provide both eminent energy and power for the vehicles. Besides, Sellali et al.,\(^\text{106}\) in another study, confirm the validity of Sellali et al. and Castiglione et al. to assess the novel power management strategy based on real-time fuzzy logic control of a battery and SC HESS. Although the system is expensive and provides less efficiency, Zhang and Li\(^\text{107}\) solve this problem using the same topology approach for an HESS integration. It is an ideal candidate for achieving the most flexible control. The results show that the topology effectively saves battery power with feedback regulation. Fadil et al.\(^\text{108}\) provide a different solution to add value to the investigation conducted by Zhang and Li. The authors develop a model for the HESS scheme while considering its nonlinear control for a fuel cell and SC HESS used in EVs. Besides, they use nonlinear control to regulate the DC-bus voltage at a very tight oscillation, track the SC current, and ensure an asymptotic of the closed-loop control system. Figure 8 shows the configuration of the active parallel topology approach.

### 3.4.1 Z-source active converter topology

This subsection describes an active-parallel topology approach based on Z-source converter configuration. This scheme integrates the ESSs converter with a traction motor inverter and offers a bi-directional power flow of the two hybridized ESSs depending on the operation. It has better performance at a reduced cost than previously discussed conventional fully active parallel schemes in Section 3.4 because there is no need for an individual battery or SC converter. In addition, it effectively utilizes the ESS like the fully active topology. Figure 9 shows a fully functional parallel SMES and battery HESS. The SC can replace the SMES. As indicated in Figure 9, the Z-source network incorporates the battery using an easy DC-to-DC chopper circuit. This circuit offers a system with less cost and increased performance. Besides, the system allows independent control of DC-bus link voltage. The Z-source scheme comprises capacitors \(C_1\) and \(C_2\), inductors \(L_1, L_2\), switch \(SW_1\) with an antiparallel diode to enable bi-directional energy/power flow between the two ESSs and the load. A piece of detailed operational information about this topology is discussed in Refs. 109-112.

Hu et al.\(^\text{111}\) propose a hybrid battery and SC based on EVs’ asymmetric Z-source converter topology. The topology effectively uses the SC, and the network impedance of the Z-source converter allows individual
ESS to exchange power. In another study, the authors confirmed the validity of Hu et al. and adopted the topology by applying a quasi Z-source converter for an HESS. The frequency control optimizes the energy/power management of the HESS system. Omran and Mosallanejad validate Hu et al.’s topology by offering a hybrid SMES and a battery using the same topology. This topology improves the overall HESS performance. Besides, it offers less weight, is cost-effective, has improved reliability, has effective battery/SC voltage regulation, and is simple to design.

![Fully active parallel topology](image1)

**FIGURE 8** Fully active parallel topology. (A) Fully active parallel scheme and (B) Fully active cascaded scheme

![Fully active parallel hybrid SMES and battery energy storage system](image2)

**FIGURE 9** Fully active parallel hybrid SMES and battery energy storage system

| Hybrid battery-supercapacitor topologies | Advantages | Disadvantages |
|-----------------------------------------|------------|--------------|
| Passive-parallel                        | • Simple, easy to implement\(^{11,41}\)  
  • Requires no DC-to-DC converter and control\(^{90,116}\)  
  | No control\(^9\)  
  • No effective use of SC, No optimal energy/power sharing\(^{43,90,96,116}\) |
| Semi-active parallel                    | • Provide trade-off between other two approaches\(^{16,43,53}\)  
  • Provide a good compromise between performance and cost\(^{79,91}\)  
  • Adequate degree-of-freedom\(^{90}\)  
  | Complex energy management strategies. Wide range of DC bus voltage\(^{90,96}\) |
| Cascaded semi-active parallel           | • Wide SC voltage swing & utilization factor\(^{117}\)  
  | Generate more energy throughput, high battery degradation\(^{18}\)  
  It requires cell balancing at high voltages & low stability\(^{43}\) |
| Active-parallel                         | • It has good flexibility of power management control. Provide full control of individual ESS. It allows wide SC voltage variation. Battery voltage can be lower than DC-link. Effective use of SC stored energy, lower conversion losses\(^{31,90,96,103,119}\)  
  | Compromises cost and efficiency. Very complex. High converter losses reduce the global efficiency of the ESS under various operating conditions. Bulky\(^{38,43,90,96}\) |
4 | OVERVIEW OF HYBRID ENERGY STORAGE TOPOLOGIES

The reviewed literature shows different hybrid topologies comprising the integration of hybrid battery-SC topology. Passive topology is simple and easy to implement compared to any other topology. However, it cannot effectively split the power between the energy sources. Controlled power cannot sustain long periods of vehicle acceleration because the control method is determined/influenced by the IR of the individual ESSs. Also, it is challenging to utilize SC effectively for maximum efficiency. The semi-active topology approach is a choice for most researchers because it offers an excellent compromise between cost and performance. It provides a good trade-off between the passive and wholly active topology approaches. However, this topology causes a wide variation of the DC-bus voltage link, affecting motor or vehicle efficiency.

The new semi-active topologies with a single switch are likely to have similar challenges to conventional topologies. These topologies connect the SC directly to the DC-bus voltage link. The new semi-active topology has two additional switches. It shows enhanced performance based on switching operations on specific rules to protect the ESSs. Quality performance tests in terms of efficiency need consideration and comparison to existing topologies. A fully active topology approach provides practical and flexible energy and power flow control between ESSs. However, it is costly and complex because it requires two additional converters with separate control rules. Based on the analysis, the semi-active topology approach has wide adaptation in many studies in the recent literature. It provides many benefits as compared to other topologies. Therefore, it is imperative to test the required standard of an application before choosing the desired topology approach. This assessment is essential, especially in EVs where performance, cost, and weight are crucial. Therefore, Table 1 compares and summarizes different hybrid battery-SC topology approaches, their advantages, and disadvantages based on the literature. Also, Section 4.1 below summarizes the literature reviewed for these topologies’ strengths, weaknesses, opportunities, and threats. Figure 10 shows detailed HESS topology applications in various industries.

4.1 | SWOT analysis of HESS topologies

This section summarizes the strengths, weaknesses, opportunities, and threats of different topologies based on the existing literature.

4.1.1 | Passive

**Strength:** It has a reduced degree-of-freedom, \(^{42}\) reduces battery load by 10%–30%, \(^{71,72}\) provides battery degradation mitigation, \(^{73}\) and provide peak-shaving function, \(^{11}\) respectively.

**Weakness:** This topology is less effective on high-power demand\(^{42}\); how does the SC leakage current affect the system?\(^{72}\) Battery lifespan is similar to a single ESS.\(^{71}\)
There is no practical use of SC and guaranteed performance. The battery limits SC voltage variation, and there is no optimal energy sharing.

**Opportunity:** There is a need to show how well the distribution of energy/power is among the ESSs, a need for battery energy use results and validation of effects presented by the SC leakage current. There is a requirement for consistent presentation of results to increase energy and power density for modern TVs. There is a requirement for a simple cell balancing system, measurable benefit in terms of vehicle range, consider inhomogeneous developments of battery parameters over their service life, with capacity and resistance being relevant.

**Threat:** External environmental conditions could affect the performance of the HESS; the upper and lower voltage level of the ESS components restricts operational voltage range, battery voltage constrains the HESS, and 64% of the stored SC energy is unused. There is no vehicle range extension because HESS achieves the same lifespan and performance as a sole ESS.

### 4.1.2 | Battery semi-active

**Strength:** EMS effectively ensures battery safety and system stability and extends battery lifespan.

**Weakness:** SC has a low energy density. It requires a large enough DC-to-DC converter, which leads to increased cost. Boost converter experiences a complete discharged battery’s capacity. It increases battery degradation.

**Opportunity:** There is a need to use a bi-directional DC-to-DC converter instead of a boost converter to enhance battery charging capability during regenerative braking and improve energy efficiency during braking.

**Threat:** Boost converter experiences a complete discharged battery’s capacity. It increases battery degradation.

### 4.1.3 | Supercapacitor semi-active

**Strength:** In this topology, the SC supports the battery to reduce degradation. The HESS is suitable for city cars than other types of TVs. This topology is applicable in harsh environmental conditions. HESS is influential in EV applications, maintains constant DC-Bus Voltage. It provides an adequate degree of freedom, it has a reduced weight, and it ensures effective use of the SC.

**Weakness:** The HESS has a lower impact, and it has increased energy losses, frequent charging actions, reduced battery lifespan and requires a large converter size. The harvested regenerative braking energy is low in the SC, and it requires complicated modulation techniques, respectively.

**Opportunity:** There is a need for thermal management and the effect of higher energy density ESS for improved lifespan; reduction of power electronics cost could reduce the cost of the HESS and its bulkiness. There is a need to coordinate optimal power flow between ESSs.

**Threat:** If battery price reduces significantly, HESS benefits EVs, and SCs cannot be a primary energy source.

### 4.1.4 | Fully active

**Strength:** It takes full advantage of the SC, improves system efficiency while enhancing battery lifespan and allows constant DC bus voltage. Besides, regenerative braking charges the battery and the SC, there is superior losses, flexible technical design, and provides adequate scaling of energy and power.

**Weakness:** High cost because of additional DC-to-DC converter, and complex.

**Opportunity:** There is a need to provide a matching and sizing method for HESS, battery lifespan improvement, effective SC voltage regulation, which allows the system to respond to future power demand by having SC charged optimally.

**Threat:** HESS efficiency relies on battery and SC technologies.

### 5 | HESS SIZING

Recent TVs utilize higher energy density storage systems with long enough discharge to simultaneously enhance system efficiency and minimize cost, weight, and volume. Sole-battery systems in modern TVs endure detrimental effects because of higher peak power, current, regenerative braking energy, etc. These effects cause battery degradation, which shortens their lifespan. Therefore, a HESS is crucial in reducing these adverse effects on batteries. Allocation of higher peak power demands to a robust ESS such as SC, superconducting magnetic energy storage, lithium-ion capacitor, and flywheel could minimize these adverse effects. Even though these sturdy ESSs have low energy density than batteries, they have higher power density and more extensive lifespan, absorb regenerative braking energy, and increase acceleration power.

In contrast, batteries have higher energy density and are suitable for more minor power vehicle application requirements. However, because of limited space available in modern TVs and restriction of permissible weight required, it is essential to size the HESS adopted in these vehicles to provide satisfactory performance as required by the vehicles customers or automotive manufacturers and...
renewable energy power systems. Moreover, sizing HESS alone without considering their energy management strategies may cause an unreliable system. Therefore, many researchers have focused on integrated HESS sizing with their energy management strategy approach, which forces the research direction on multi-objective optimization approaches. Hence, this section discusses different HESS sizing techniques available in the literature. Figure 11 below describes other methods applied in sizing HESSs.

5.1 Optimization techniques

Optimization or numerical methods are crucial in decision science and analyzing physical systems. In terms of ESSs, these methods use a quantitative measure to analyze the system’s performance and size of the system’s components. The modeling process identifies the systems objective, variables, and constraints for a sizing problem when using optimization methods. Based on Refs. 120 and 121, selecting an algorithm for a particular situation depends solely on the user because of many existing algorithms in the literature. This selection of an algorithm is vital because it determines whether the solution to the problem happens slowly, fast and if the algorithm obtains the results entirely. The optimization technique should find the solution based on conditions to evaluate the obtained variables. In many cases, sensitivity analysis could help in finding optimal solutions.

Convex programming provides an optimal global solution and can show arbitrary initialization of the objective function. This technique offers a global solution only if the objective function and the feasible region are convex. Moreover, to describe whether a particular case of constrained optimization exists, the objective function is convex, the equality constraints are linear, and inequality constraints functions are concave. Hu et al.\textsuperscript{122,123} suggest convex programming as an optimization technique to simultaneously size the battery and SC HESS and obtain the best energy management solution for power-sharing of the ESS utilized in a fuel cell EV bus. The authors conduct this study to evaluate the impact of the battery exchange strategy on the economy of the bus and the HESS, and the study adopts a battery state-of-health (SoH) model. In Ref. 87, the authors confirm their method’s validity by quickly and effortlessly optimizing the size and energy/power splitting strategy of a hybrid fuel cell system and battery for use in a hybrid electric bus. Besides, to analyze the driving cycle impact on the optimization performance. Wu et al.\textsuperscript{124} follow and adopt the same technique and hybrid topology as Hu et al. to optimize the power splitting control and energy source parameters. Besides, it reduces the energy and power cost while meeting the TV energy/power and battery SoH requirements. The results show a minimized battery SoC of 20%. However, all the studies analyzed a system with a fuel cell semi-active topology approach, which may provide the battery with enormous peak power, thus shortening the battery lifespan.

**FIGURE 11** Hybrid energy storage system sizing methods
Besides, it increases battery replacement costs. These drawbacks are later partially solved by Hu et al.\textsuperscript{125} in their other study comparing the optimized sizes of ESSs and energy management strategy considering battery-only, SC-only, and HESS. Also, the study sizes these ESSs in terms of their energy and power capacity. The results show that optimized HESS leads to less total systems cost than battery/SC-only systems. It minimizes the cost by 13.7%. However, the study did not consider battery aging to assess its influence on the price. Besides, the authors claim that adding a SC improves battery efficiency significantly. Nevertheless, there exists no information regarding the assessment of battery efficiency.

Shen et al.\textsuperscript{117} propose a multi-objective optimization using a sample-based derivative-free direct rectangles algorithm to reduce the entire size of the HESS and increase battery cycle lifespan for use in middle-sized EVs. The study utilizes a battery cycle-life degradation model to evaluate the improved battery lifespan. Also, it uses an urban dynamometer driving cycle (UDDC) to demonstrate the system’s performance. The results show an enhanced battery cycle lifespan and an optimized HESS size of 76% and 72 SC cells. The study claims to have verified the results through the hardware-in-the-loop (HIL) testing; however, no presented results for the HIL test.

Ostadi et al.\textsuperscript{126} use an altered particle swarm optimization (PSO) method to size different ESSs for use in a plug-in electric city bus. These schemes include sole-battery, sole-SC, and hybrid battery and SC systems. The study conducts a comparative analysis of these schemes to satisfy the required energy and power of the plug-in electric city bus using ESS price. The results show that the technique applied can reduce the size of the HESS and maintain variables such as SoC and voltage within desirable ranges. Consequently, Sarma and Ganguly\textsuperscript{127} and Sadeghi et al.\textsuperscript{128} agree with the validity of PSO as applied by Ostadi et al. in designing a hybrid fuel cell and battery for providing a similar tractive effort as the diesel locomotive used to haul passenger coaches. The study results show that the HESS size depends on the energy management type, driving pattern, and the railroad gradient. However, several shortfalls arise in these studies because PSO is trapped in the local minima, thus not guaranteeing the optimal global solution for the HESS size and optimized EMS parameters. Mesbah et al.\textsuperscript{129} solved these demerits later by joining the conventional PSO and Nelder-Mead (PSO-NM) algorithm to evaluate the parameters affecting the size and energy management control of HESS used in urban TVVs. The authors use frequency control for energy/power management. The results show that the hybrid PSO-NM has the best performance compared to genetic algorithm (GA) and conventional PSO in terms of computation speed and eliminating trapping in local minima.

Abbassi et al.\textsuperscript{130} propose dynamic programming (DP) as an optimization technique for sizing passive hybrid battery with SC ESS employed in an autonomous PV/Wind hybrid power system. Besides, the authors use a statistical method to evaluate the distribution of HESS capacity in the power system and evaluate its energy and power flow. They further propose a frequency control to analyze the power-sharing between the ESSs and distinguish the power as slow and fast dynamic. Besides, the hysteresis control maintains the HESS power and SoC within the required limits. Also, minimize the power peaks associated with the load consumption. The results show that the SC has a massive impact on improving power-sharing, assisting in battery lifespan extension, and significantly enhancing system performance. Song et al.\textsuperscript{131} use a similar technique as Abbassi et al. to determine the best HESS scheme while considering energy splitting strategies for a battery and SC operated in an electric city bus. The difference with the previous studies is that the authors adopt a SC semi-active parallel topology approach. The study optimizes the battery size by assessing the required traveling mileage of the vehicle while evaluating SC size using a DP method. Besides, to determine the HESS life cycle cost, a precise cost function is used on a dynamic degradation model of the battery. The results show that the HESS life-cycle cost significantly decreased with a SC. Also, the rate of this decrease is significant when the number of SCs used increases. However, the study conducted by Abbassi et al. provides no apparent reason for using statistical methods instead of other techniques. In the study by Song et al., factors chosen during battery and SC sizing are not justified. Zhu et al.\textsuperscript{118} later solved these drawbacks by adopting the same sizing method with sensitivity analysis in light passenger EVs. The sizing aims to reduce the cost of operation over the vehicle lifespan. The study sizes the HESS while considering the energy/power management strategy influence on vehicle performance, which forms a multi-objective optimization problem. The optimization framework developed is based on a three-dimensional form. It utilizes different input factors for sensitivity analysis, including vehicle driving cycle, range, HESS scheme, DC-bus voltage, DC-to-DC conversion efficiency, and component price. The results show that battery degradation accounts for 89% of HESS cost. Among these sensitivity factors, vehicle range has a relative impact on the cost of HESS, with a degree of influence being 1.243.

Proper sizing of HESS in TV application is vital to ensure improved travelling distance, required engine starting current in terms of Start/Off engine functionality, enhanced battery lifespan, etc. Zhang et al.\textsuperscript{132} propose a multi-objective nonsorting genetic algorithm (NSGA-II) to optimally size the HESS comprising battery and SC for use in EVs, with an overall aim of reducing the ESSs
cost simultaneously enhancing battery lifespan. Besides, to effectively evaluate the impact of component sizing on battery lifespan, the authors adopt the battery SoH model. On the other hand, it uses a waveform transformation algorithm for power management between the battery and SC. At the same time, Yu et al.\textsuperscript{133} confirm the validity of the same technique utilized by Zhang et al. to size a HESS comprising Li-ion battery and SC to get an optimal-sized HESS employed in EVs. A different EMS method (i.e., fuzzy logic control) uses this control with a real-time power management strategy. The NSGA-II solves the sizing and power management simultaneously. The authors conduct the sizing and control of the HESS to lower the operating cost and minimize the environmental impact of battery waste for a race EV. The study results show that the vehicle provides improved range and enhanced battery lifespan. However, positive performance outcomes obtained using the NSGA-II sizing technique show that it could enhance overall system performance if all factors are included, such as driving cycles. Because of these shortfalls in previous studies, Eldeeb et al.\textsuperscript{134} later address it by adopting the NSGA-II to size a battery and SC HESS for plug-in HEVs. Besides, the implemented optimization method reduces the HESS cost, mass, and capacity, and enhances the battery cycle lifespan. To comprehensively solve the HESS problem, the authors include energy/power-sharing management of the ESS in the study. Also, they utilize discrete waveform transformation and power splitting ratio techniques. The study employs a UDDC to analyze the effectiveness of the optimization approach. Then the authors use the results to test the optimization approach using highway fuel-economy test driving cycles (HWFTDCs). The results show that sizing HESS using an optimal power management strategy provides less weight and meets EV’s driving and functioning necessities.

Herrera et al.\textsuperscript{135,136} size the HESS comprising battery and SC using optimization parameters obtained from energy management strategy based on GA for use in a light rail vehicle. The sizing is determined to evaluate the vehicles’ daily operating costs. Besides, the study determines the daily operating cost of the car by considering the battery and SC degradation model. Also, Silva et al.\textsuperscript{137} confirm the validity of Herrera et al. by using the same technique to minimize the size of an HESS and improve the driving distance by optimizing the HESS power-sharing management for EVs. The study uses the parameters, including the urban driving cycle, vehicle drivetrain, HESS apparatuses, and their control, respectively, to assess the performance of the multi-objective GA. The results show that the hybrid ESS performs the same in all operations. Although these techniques’ performance is applied successfully, several drawbacks arise in obtaining EMS parameters. GA generally has a high computational cost. Besides, Herrera et al.\textsuperscript{138} later address these drawbacks when defining a conventional GA for adaptive and non-adaptive energy management using fuzzy and rule-based control for a hybrid ESS comprising battery and SC utilized in an electric bus. The energy management evaluates the performance of the regime. Besides, it optimizes the ESS sizing to achieve operational targets of economy, saving fuel, and efficiency. Also, it considers economic and aging models to inform the minimization of the cycling cost, replacement of ESSs along the vehicle operating lifetime, and fuel consumption. The study results show that the fuzzy logic control strategy reduces the operating cost of the car by 15% and the fuel consumption by 19% compared with the nonadaptive rule-based controller. The solution explores two optimization techniques proposed by Masih-Tehrani et al.\textsuperscript{139} GA sizes a hybrid battery and SC and develops its energy management strategy based on a forward dynamic programming algorithm in a series hybrid electric vehicle (SHEV) bus. The dynamic programming is a multi-objective problem as it assesses the battery replacement using the battery life model as a capacity loss and initial cost. Besides, the energy management strategy is optimized to improve battery lifespan. The results show an improved battery lifespan by adding a SC to form a hybrid system, and the fuel consumption improved by 26% in 10 years. However, the study does not consider HESS topology.

Li et al.\textsuperscript{140} use a grey wolf optimization (GWO) technique as a multi-objective algorithm to obtain the Pareto optimal solutions for sizing the HESS and EMS control parameters using the grey wolf optimizer DP objective function. Moreover, the authors evaluate the control rules of the EMS using the random forests algorithm. This technique minimizes HESS system cost and enhances battery lifespan. However, systems’ cost and battery lifespan enhancement are conflicting objectives. Thus, the study uses DP to get optimal parameters for the best energy/power-sharing strategy between the battery and SC. The authors use a driving pattern to get these parameters. They obtain the driving pattern using driving pattern recognition developed utilizing a support vector machine (SVM). The results show that compared to DP and conventional random forests, the adaptive random forests EMS control is near-optimal to DP. Besides, the system decreases the HESS energy loss up to 0.74%–9.49% and battery ampere-hour throughput by 0.5%–19.83%. Sukumar et al.\textsuperscript{141} and El-Bidairi et al.\textsuperscript{142} follow the same technique used by Li et al. to size the battery ESSs for a microgrid. They compare GWO with other meta-heuristic methods such as PSO, ant-bee colony algorithm (ABCA), gravitational search algorithm (GSA), and GA, respectively. The results show that GWO performs better in generating optimal global solutions.
However, several drawbacks arise in the previous studies, including no comparison with other techniques and a sizing battery-only system without hybridization. Liu et al. later addressed these demerits by applying the same optimization technique with CPLEX solver to size the HESS and improve the energy/power management strategy for use in high-speed railway traction substation system. The study utilizes the battery degradation model and replacement cost to size HESS. The results show that cost saving is prominent when using the HESS comprising battery and SC with a fixed tariff of 25.5% and time-of-use 30.95%. Besides, using a SC demonstrates that the battery lifespan can significantly improve and minimize the replacement cost.

Song et al. propose an integrated sizing of HESS with their energy/power management strategy using a two-dimensional Pontryagin’s minimum principle (PMP) as an optimization technique. The technique develops a suitable component size and the best energy/power-sharing approach for battery and SC PHEVs. Besides, the study utilizes PMP to enhance battery lifespan and reduce vehicle operating costs. The energy/power-sharing of the PHEV is among the engine, battery, and SC based on the battery degradation model. The study results show that the PMP and DP provide similar results; however, the computational burden of DP is high. The operating cost is reduced by more than 20%. Du et al. confirm the validity of the technique adopted in Song et al. by developing an optimized energy/power splitting control of HESS to minimize the life-cycle operating cost of the battery used in a plug-in hybrid electric bus. However, several shortfalls, including HESS sizing, is not considered, and PMP may trap at local minima. Besides, Liu and Liu also use the same technique to size and optimize the energy/power management control of a fuel cell HEV. This method enhances battery lifespan, simultaneously reducing battery energy loss, fuel consumption, and operating cost. The results show that the battery SoC and energy loss have declined to 0.23% and 5.6% when using battery current constraints. Also, battery lifespan and fuel consumption have increased by 0.417% and 0.068%.

Optimization methods approach to sizing hybrid ESSs plays a vital role because they can obtain and maintain systems operational limits such as SoC, voltages, and current. The sizing of HESS and its energy management are interdependent, and the most critical parameter to ensure the system’s effectiveness is the driving pattern and road geometry. Optimization techniques can help in improving energy/power-sharing between ESSs, vehicle daily operating cost; distance traveled, fuel economy, ESS lifespan, HESS cycle life, and reducing HESS energy loss. Moreover, a proper system optimization model help improve the above-stated parameters.

5.2 Statistical-based and pinch analysis methods

There exist general techniques for sizing HESSs in renewable energy power systems. These methods have gained little attraction in the TV applications. However, they still seem necessary for exploration. The authors in Ref. 42 propose a statistical method for sizing passive hybrid lithium-ion batteries and lithium capacitor for an electric motorcycle. Besides, Li et al. use an analysis speed-based energy distribution strategy for a hybrid ESS based on a battery and SC. The process is applied to improve a four-wheel-drive vehicle’s regenerative energy recovery efficiency. The results show full utilization of SC to meet the vehicle power demand, enhance vehicle performance in recovering regenerative energy, and protect the battery against peak currents, respectively. Jacob et al. offer a pinch analysis to size the HESS for use in an islanded PV-based microgrid built on accessible resources and load profile. This method uses a time-domain emulation of the procedure whereby the power generation consistently exceeds the required demand. It derives the design space from integrating short-, medium-, and long-term storage sizes. Besides, in this study, it is enhanced to get the optimum minimum cost of the system. Therefore, oversizing batteries in modern TVs could cause overcharging, adversely affecting their health and high cycle systems costs. Hence, adequate HESS sizing is necessary to minimize the aforesaid adverse effects.

6 SUMMARY FOR HESS SIZING

This section summarizes the HESS sizing and approaches available in the literature. Most research reveals that sizing HESS without an energy management strategy could result in system deficiency in meeting the operational requirements of modern TVs, microgrids, and railway system applications. Therefore, nonoptimization techniques are not suitable for sizing HESSs. Hence, current literature utilizes optimization methods as a multi-objective approach to realize optimum HESS size and obtain the energy management control variables that ensure that the system can meet the operational requirement as intended. Based on the analysis, Table 2 describes the advantages and disadvantages of different methods utilized for HESS sizing, control and applications, whereas Table 3 provides the control methods that integrate with HESS sizing methods to fulfill energy and power requirements of modern transport, railway, and renewable energy power systems.

Moreover, a battery degradation model is generally utilized in the optimization criteria to size the hybrid battery and SC ESS. The reason is that 80% of battery
loss in capacity relates directly to battery end-of-life for EVs; hence, it directly relates to the total ampere-hour battery throughput. Battery life capacity means that a battery can deliver charge before its capacity loss reaches 20% from the initial 100% SoC. The Arrhenius equation represents the battery capacity loss for cycling performance. It also depends on the pre-exponential battery value, the activation energy, operating temperature, constant gas value, and the ampere-hour throughput as shown in Equation (1);

$$Q_{loss} = -Be\left(\frac{E_a}{RT_a}\right)(Ah)^z$$  \hspace{1cm} (1)

where $B$ is the pre-exponential factor, $E_a$ represents the battery activation energy, $R$ is the gas constant of 8.314, $T_a$ is the absolute temperature in Kelvin, and $A_h$ stands for the ampere-hour throughput or the amount of charge delivered during cycling, and $z$ is the power-law factor.

The HESS could operate less efficiently when sizing it without considering any energy/power-sharing mechanism. The combination of sizing and energy/power management could enhance the search space of the optimization technique to obtain better optimality of the results. Besides, the parameters of the EMS design are crucial for further optimization and practical application purposes. The integration of sizing and energy management control is essential because the power and energy control could provide insights into the size of the battery and SC to meet the power and energy requirement of the TV. Table 2 compares different HESS sizing techniques and their applications. Besides, Table 3 describes the energy/power management strategies used in conjunction with the sizing techniques for better results.

**TABLE 2  Comparison of different techniques for HESS sizing and applications (2012–2021)**

| Sizing technique               | Advantages                                                                 | Disadvantages                                                                 | Applications                          |
|-------------------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------------|---------------------------------------|
| Dynamic programming 118,130,131,139 | It provides a globally optimal solution 139                              | It requires prior knowledge & no real-time application 118                   | City buses 131                        |
|                               | Accurate 130                                                              | High computational cost 131                                                  | Electric vehicles 118                |
| Convex programming 122        | Computationally efficient & no "curse of dimensionality" 122              | —                                                                             | Fuel cell hybrid electric vehicles 122 |
| Dividing rectangle algorithm 117 | Flexible & easily adaptable 117                                         | No practical application                                                     | Electric vehicles 117                |
| Genetic algorithm 135,137,138,139,148 | Provide a globally optimal solution 135                                   | —                                                                             | Series HEVs 138,139                  |
|                               | Ensure correct vehicle performance 135                                    | High computational complexity 140                                            | Light-rail vehicles 135              |
| Non-sorting genetic algorithm (NSGA-II) 132-134 | Provide multiple Pareto-optimal solutions, no high computational complexity, no control parameter tuning 132  | —                                                                             | Electric vehicles 132                |
|                               |                                                                           | Electric race car 134                                                       | PHEVs 134                            |
| Grey wolf optimization (GWO) 140,143 | Trace non-convex problems, better convergence performance 143              | —                                                                             | Electric vehicles 140                |
|                               |                                                                           | Traction substations 143                                                    |                                       |
| Pontryagin’s minimum principle (PMP) 144 | Flexible than DP, it provides a globally optimal solution, less computational effort, and possible real-time control 144 | Complex Hamiltonian function 144                                             | PHEVs 144                            |
| Pinch analysis 149             | Simple, flexible & low computational effort 149                           | —                                                                             | PV microgrids 149                    |
| Particle swarm optimization 126 | Highly flexible, accept various component data, provide a globally optimal solution 126 | Traps at local minima 126                                                   | City buses 126                       |

7 | **RESEARCH TRENDS AND FUTURE RECOMMENDATIONS**

Based on the state-of-the-art analysis, the combination of battery and SC in a HESSs has seen widespread application attention for use in TVs. This widespread attention is because of the continually decreasing prices of their cost—moreover, the rapid development of various electrode materials for better future energy storage systems. The scientific problems that face the current energy storage systems (i.e., batteries) have short lifespan, less power density for enhancing vehicle performance in terms of acceleration, rapidly recovering regenerative braking energy, and environmental climate conditions.
The research trend demonstrates that when developing HESSs, the energy and power density highly depend on the voltage matching of the individual energy storage system, especially when considering utilizing a passive parallel topology approach to powering a typical TV. Although this topology is feasible for applications in TVs, it has negligible performance improvement of battery lifespan because of uncontrollable energy/power flow between the ESSs. Therefore, this topology could find applications in providing starting, lighting, and ignition function for ICE vehicles, thus reducing the high starting battery current frequently needed to enhance battery lifespan with the support of a SC in the future.

In terms of considering a semi-active parallel topology approach in developing HESS for application in TVs or renewable energy power systems, additional PED adds cost and needs more space. Various energy/power management control strategies such as nonlinear model predictive control (NMPC), estimator adaptive sliding mode control (e-ASMC), adaptive Pontryagin’s minimum principle (APMP), and lambda control have seen wide application in the utilization of this topology. However, the literature emphasizes that energy/power management control helps in reducing battery stress, temperature variations, and power loss in HESSs. Additionally, it can eliminate excessive output power of the battery, leading to enhanced battery lifespan. Therefore, the critical research question that researchers could address is how do various energy/power control strategies be assessed to ensure desirable vehicle power provided by the battery does not harm its lifespan?

Furthermore, HESS temperature variation is holistically related to battery temperature change to consider the HESS life cycle. There is a need to evaluate the HESS life cycle while considering SC and PEDs temperature variation. The key question could be how can the HESS temperature evolution be linked to all integrated components to assess the systems life cycle? Consequently, when dissecting through the state of the art analysis, batteries in nature have slow dynamic response characteristics. If hybridized, they may provide low efficiency in giving/absorbing rapid peak currents for vehicle starting, acceleration, and recovery regenerative braking energy. Hence, the central future scientific research question is: What methods could be applicable in hybridizing electrochemical ESSs (i.e., batteries) to improve their slow dynamic response. Besides, what could be the most effective way to ensure high systems performance and efficiency in providing high current peaks for vehicle starting, acceleration,
recapturing regenerative braking energy during deceleration without damaging the battery?

In the case of a fully active parallel topology approach, the hybridization scheme has a higher cost than the previously discussed topologies because additional DC-to-DC converters and different control strategies are needed. However, the system protects and ensures that individual energy storage systems operate within their desirable limits. However, this topology has fewer energy/power management strategies, including real-time fuzzy logic control and nonlinear control. Therefore, it could be interesting if other authorities such as MPC, APMP, SMC, and wavelet transform could form part of the HESS topologies analysis to improve system’s performance. A similar approach will interest researchers to investigate Z-source active topology because currently, the control utilized includes only frequency control for energy/power management.

For the HESS sizing, numerical methods have proven their importance in this application. However, using the optimization method to only size the HESS does not prove effective because energy/power-sharing control for individual ESS plays a crucial role in the system’s performance. Hence, the integrated optimization technique to size the HESS and optimize the energy/management control strategy has attracted researchers immensely. Nevertheless, when applying optimization methods to size and enhance the control strategy for energy/power management, it is critical to develop a proper HESS model for optimization. Various HESS performance assessment models exist, such as the battery SoH model, dynamic degradation model, SC dynamic degradation model, and battery cycle-life degradation model. Optimization methods include convex programming, sample-based derivative-free direct rectangle algorithms, particle swarm, genetic algorithm, nonsorting genetic algorithm, dynamic programming, grey wolf, and 2-dimensional Pontryagin’s minimum principle. These techniques have attracted researchers in sizing and assessing HESS performance. The assessment includes reducing systems operating costs, increasing battery lifespan, and reducing fuel consumption. One of the studies while using the optimization method envisaged that adding a SC improves battery efficiency. However, an excellent research question that needs attention in the future is how does the battery efficiency improve with a SC, and how much will the battery efficiency improve?

Various energy/power control strategies have comprehensively investigated optimized HESS sizing. The existing optimized control methods while sizing HESS include frequency control, waveform transform algorithm fuzzy logic control, power splitting ratio, rule-based control, PSO, and adaptive random forest. These control strategies need further investigation compared with MPC, SMC, Neural Network, reinforcement learning, etc. In addition, the HESS size depends on the energy/power management control strategy. One way to obtain optimal size for HESS based on its energy/power management control is to integrate optimization techniques such as PSO with other algorithms to eliminate trapping at local minima. Therefore, there is a need in the future to compare different energy/power management control strategies for optimal HESS size and performance. The future research direction will assist both the transportation and power sector industries in designing and providing optimal systems for better performance of individual commodities, which they provide for the betterment of the society.

8 | CONCLUSIONS

As used in modern TVs, current energy storage systems alone face dangerous failures because of enhanced requirements such as start/stop functionality, providing burst power during acceleration, recapturing regenerative braking energy, among others. Therefore, alternative energy sources must meet the necessary demand for modern TVs. Hence, hybridization of the different energy storage systems is of interest to assist and meet TVs’ energy and power requirements. This paper has critically reviewed the hybridization of various energy storage systems, including batteries with high-powerESSs such as SCs, superconducting magnetic energy storage systems, lithium-ion capacitors, and flywheels, respectively. Besides, to hybridize the energy storage systems, different configurations exist. Hence, this paper also discusses the passive parallel active topology, semi-active parallel topology, semi-active cascaded topology, fully active parallel topology, fully active cascaded, and z-source fully active similar topology independently. Configuring the hybridization without properly sizing the HESS could lead to an expensive and inefficient system. Hence, properly sizing the HESS is necessary such that the system fulfills the energy and power requirements of the TV application. Consequently, this paper discusses different sizing methods for modern TVs’ energy and power requirements. Although sizing alone seems not to provide an efficient system effectively, energy and power management control of the HESS plays a vital role in providing a suitable design for its application.

SC semi-active parallel cascaded topology has attracted most researchers and applications in experimental laboratories. Although this HESS scheme provides a trade-off between performance and cost, the battery may endure high fluctuating currents because it is directly connected to the DC-bus voltage, thus affecting the battery lifespan. In this scenario, a fully active parallel topology is suitable for providing a system with protection for all the ESSs.
against harsh variables, which may negatively affect their performance. However, this topology performance drops because of two fully utilized DC-to-DC converters, which influences the overall system's efficiency, and its cost is high. Z-source fully active converter parallel topology has recently attracted some researchers, and it has not seen extensive application in TVs. This topology provides a suitable system with a reduced size, integrates the motor inverter with the ESSs, and is easy to control. Also, the SME could be adopted in the future HESS if its price can fall in the upcoming years. HESSs could be suitable as a virtual synchronous generator for frequency regulation in renewable energy sources.

Regarding HESS sizing, optimization methods have seen widespread attention from researchers as adoption to size HESSs, reduce their costs, enhance their operating life cycle, among others. Besides, they provide multi-objective global optimum solutions as compared to conventional techniques. Integrated sizing with energy/power management control could increase the search space for optimality. Also, parametric real-time energy and power management system development is essential for further optimization and practical applications. Furthermore, optimal EMS could ensure the proper system performance to meet the needs of TVs while fulfilling the application requirements and operating constraints of the overall system. However, in many optimization methods applied, they have shown great effectiveness. However, they perform better when they recognize parameters such as driving cycles prior. The majority of the sizing methods consider the battery degradation model to achieve its objective, such as enhancing battery lifespan, vehicle range, and reducing operating costs. Rule-based control methods such as fuzzy logic and frequency filter have widespread application because of their easy implementation, possible practicability, and low computational effort. Besides, many optimization techniques such as PSO also have seen wide applications in solving the sizing problem of HESSs. However, size and energy management strategy are interdependent.

This research reveals that integrated analysis of HESS sizing, their energy and power management is on the rise because optimization can solve both sizing and provide control parameters to increase its performance based on the vehicle requirements. In the future, more research to evaluate other optimization techniques and control methods in comparison to existing ones already reported in this research are required. It would be interesting if control methods such as model predictive control, neural network, reinforcement learning, among others, could assess the performance of the HESS. Prediction of future operating control parameters can benefit vehicle operating requirements such as enhanced battery lifespan, providing peak currents during vehicle starting, and recapturing regenerative braking. Also, the commercial availability of HESS is essential for the widespread adoption of EVs in the world to reduce climate change and support the world sustainable development goals. Integrated optimization-based methods will be helpful to solve the multi-objective problems for vehicles, such as increasing vehicle range, battery lifespan, reducing the overall HESS systems cost. Consequently, enhancement of future transportation systems' energy density and power density (i.e. 20–30 Wh/kg).

Recent research has focused on integrating lithium-ion batteries and SC/lithium-ion capacitors for better energy storage systems. However, the price of these energy storage systems is still high, thus increasing the total vehicle cost of ownership. Considering this fact, lead-acid batteries still significantly impact the automotive industry because of their low cost and maturity. They have received little attention in the hybridization research. Therefore, there is a need to evaluate their performance in terms of lifespan enhancement in modern TV applications through hybridization with high power energy storage systems such as SC and superconducting magnetic energy storage systems.

The system comprises DC-to-DC converters considering fully active topology in HESS safety. These primary converters responsibility is to ensure that the individual energy storage systems operate within their safe, desirable limits to avoid overcharging, which may cause hazardous risk of fire in terms of Lithium-ion batteries. However, the environmental operating temperature of HESS needs to align with batteries because the SC can handle any harsh conditions. Therefore, in the future, the cooling method of HESS will be of critical importance.

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ORCID
Mpho J. Lencwe © https://orcid.org/0000-0002-3596-9730

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