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Performance Overview of Light Electric Vehicle Powered by Battery in Assistance with Supercapacitor

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ABSTRACT

The growing electrical vehicle (EV) market has been taking the attention of customers & manufacturers in the last couple of years. EVs with lithium-ion (Li-ion) batteries stand as an alternate to the conventional power source of fossil fuel engines. While sustaining the stand, the limitations of battery as a sole power source surface, like range, temperature, state of health, dynamic power requirement & addressing different duty cycles. In this regard, a hybrid power source with a supercapacitor has emerged as a solution. The combined power source is known as a hybrid energy storage system (HESS). In this report we will see the current progress in technology for the supercapacitor-based powertrain from the viewpoint of range, charge-discharge cycle, overall weight of power source, power split strategies & ultimate cost impact. The HESS has basically three configurations—passive, semi-passive & active. The efficiency of the system improves with the introduction of power electronics. Comparative analysis of passive, semi-passive, and active HESS architectures confirms the superiority of active systems, which enable intelligent power-split strategies through advanced power electronics. Although they involve higher initial costs, lifecycle evaluations highlight reduced battery replacement frequency and lower operating expenses. This study establishes actively managed HESS as a scalable and sustainable solution for three-wheeler electrification, combining enhanced performance and long-term durability.

Keywords: *Hybrid Powertrain, Lithium-Ion Battery, Supercapacitor, HESS, Energy Management, Indian Driving Cycle, Regenerative Braking, Three-Wheeler EV.*

INTRODUCTION

Even with the advantages of electric vehicles (EVs), the primary obstacle to their advancement lies in the energy storage system. This system must guarantee the required driving range while also delivering adequate acceleration and regenerative braking.
These criteria essentially necessitate an energy storage system
that possesses both high energy density and high-power density. Batteries are commonly utilized for applications requiring high energy density. Recent technological advancements have positioned supercapacitors as an excellent option for applications demanding high power density [2]. Consequently, the adoption of a hybrid energy storage system (HESS) that combines batteries and supercapacitors has emerged as a trend in the EV sector.

Hybrid powertrains integrate two or more energy sources to optimize performance, reduce emissions, and improve driving range. Different configurations have been experimented with in the market for three-wheelers and light EVs, combining batteries with solar, wind, internal combustion engines (ICEs), and supercapacitors. Each configuration has specific advantages and limitations, as summarized below:

Among the various modes of urban transport, the three- wheeler auto-rickshaw holds a pivotal role, providing affordable last-mile connectivity for millions of commuters. Traditionally powered by internal combustion engines (ICEs) running on petrol, diesel, or compressed natural gas (CNG), these vehicles contribute significantly to urban emissions and fuel consumption. In response to this challenge, policymakers and researchers have emphasized the adoption of electric powertrains as an eco-friendly alternative. However, conventional battery-electric three- wheelers face limitations such as restricted driving range, long charging times, high battery replacement costs, and poor load-handling capabilities under variable traffic conditions. These drawbacks create barriers to large-scale adoption, particularly in developing countries like India where affordability and reliability are critical.

To address these shortcomings, hybrid power sourced powertrains, which integrate primary and auxiliary energy storage systems, have emerged as a viable solution for improving vehicle performance, range, and energy efficiency.
A hybrid power sourced powertrain leverages the strengths of multiple energy sources—typically a lithium-ion (Li-ion) battery as the main energy reservoir and an ultracapacitor (UC) / Supercapacitor (SC) or other supplementary storage devices as peak power providers. The battery ensures energy density and range, while the Supercapacitor provides high power density for transient operations such as acceleration, hill climbing, and regenerative braking. This synergy reduces stress on the battery, enhances its lifespan, and improves overall vehicle efficiency. Past research highlights the transition from ICE-dominated systems to electric and hybridized configurations.

Studies have demonstrated successful implementation of hybrid powertrains using combinations such as battery + ICE, solar + battery, fuel cell + battery, and wind/solar + battery systems in three- wheelers. For example, solar-assisted auto-rickshaws have shown extended range and reduced grid dependency, while fuel-cell hybrids improved emissions performance but suffered from cost and weight challenges. The battery– supercapacitor hybrid system has proven particularly effective in managing power fluctuations, optimizing regenerative braking, and reducing root mean square (RMS) battery current. Such benefits directly contribute to reduced operational costs and greater sustainability, making hybridized configurations ideal for three-wheeled electric vehicles operating under Indian driving cycle (IDC) conditions.

The unique operational environment of Indian three- wheelers further justifies hybridization. These vehicles frequently operate in stop-and-go traffic, high passenger turnover, variable gradients, and overloaded conditions. Such scenarios demand quick bursts of high power that traditional Li-ion battery packs struggle to provide efficiently without compromising long-term durability. A hybrid system distributes the power demand intelligently: the battery provides steady-state cruising power, while the Supercapacitor addresses peak loads during acceleration and captures energy during braking. Simulation studies have revealed that hybrid energy storage systems can reduce the maximum battery current by over 60% and lower the overall energy demand per cycle, thereby significantly extending the battery's usable life. Furthermore, experimental prototypes of hybridized three-wheeler powertrains have validated these findings, showing smoother operation, improved regenerative energy capture, and reduced thermal stress on the battery system. The capital cost of hybrid systems may initially appear higher due to additional converters and Supercapacitor banks; however, long-term analyses suggest that savings from reduced battery replacement, operational stability, and energy efficiency make them more economical and sustainable in the lifecycle perspective.

Despite the encouraging progress in hybrid powertrain technologies, their systematic integration into three-wheeled vehicles for mass adoption in India remains underexplored. Existing literature often focuses on passenger cars, buses, or.
two-wheelers, with comparatively fewer studies dedicated to the auto-rickshaw segment, which represents one of the largest commercial fleet operators in India's transport ecosystem.

Table 1. Various Hybrid Powertrain Design Concepts for Three-Wheeled Vehicles Sr. No.

	Year	Energy Source	Description
1	2018	Solar & Wind + ICE + Battery	Solar and wind energy–assisted plug-in hybrid three- wheeler to reduce grid dependence ResearchGate+10SAGE Journals+10SAGE Journals+10WIRED+2Wikipedia+2
2	2024	Solar PV + Pedaling Generator + Battery	Solar-assisted electric three-wheeler with rooftop PV (600 W) and pedal-gen system designed for Bangladesh; optimized MPPT and tilt strategies, though pedaling generator found economically limited.
3	2025	Battery + Supercapacitor (Li-ion + SC)	Hybrid energy storage system for three-wheeler EVs under Indian Driving Cycle—Li-ion battery with Supercapacitor, interfaced via DC–DC converter, for improved power handling.
4	2021	ICE + Electric Motor + Battery (Parallel Hybrid)	Rule-based power management strategy for parallel hybrid three-wheelers designed using Dynamic Programming (DP)–derived rules; achieved significant fuel and emission reductions.
5	2025	Battery + Fuel Cell	(Broader context) Novel sizing and energy management approaches for fuel cell hybrid systems improving storage and efficiency—applicable to small vehicles like three- wheelers.
6	2025	Solar PV (general context)	Aptera solar-electric three-wheeled vehicle (US) with integrated solar cells boosting range up to ~40 miles/day; highly efficient aerodynamic design, though classified more as a car than a traditional auto-rickshaw.

The present study aims to develop, model, and evaluate a hybrid power sourced powertrain specifically designed for three-wheeler applications, considering the Indian driving cycle as the benchmark. The research emphasizes the optimal design of hybrid energy storage systems (HESS), comprising Li-ion batteries and Supercapacitor, interfaced via a bi-directional DC–DC converter and controlled through a rule- and filter-based real-time energy management strategy. This approach ensures efficient power-split, extends battery life, and enhances driving performance under varied operating conditions. By addressing technical feasibility, cost implications, and lifecycle performance, the study contributes to the broader discourse on sustainable mobility and provides a scalable framework for hybrid three-wheeler electrification in emerging economies. Hybrid energy storage system (HESS) with battery/SC has been detailed. The hybridization creates a constant load profile for the battery and ensures good battery life. From the literature, it is evident that the hybrid storage system with battery/SC exhibits superior performance. The battery/SC interface demonstrates higher energy density for longer range, higher power density during acceleration and braking performance. In view of the above, the battery/SC hybrid configuration is considered in this work for three-wheeled EVs. The primary focus of the design concepts for a three wheeled EV has been on the integration of renewable energy sources with BESS and as an electric power assist to the internal combustion engine (ICE). The comprehensive review of various design concepts of a three-wheeled vehicle is given in Table 1.

Progress in Technology for Supercapacitor-Based Powertrain

The integration of supercapacitors (SCs) with lithium-ion batteries in hybrid energy storage systems (HESS) has emerged as a transformative step in the evolution of electric vehicle (EV) powertrains. This combination effectively balances the complementary strengths of each device: high energy density from batteries and high power density with rapid charge–discharge capability from SCs. The technological progress can be understood through five key performance aspects:

Range:

HESS significantly improves the effective driving range by optimizing the battery size and reducing unnecessary stress during high power demands. Simulation and experimental studies report a 15% systems. This is achieved because SCs handle transient loads, preventing excessive battery depletion and ensuring consistent availability of stored energy.

Charge–Discharge Cycle:

One of the most critical improvements is in battery life. SCs can endure millions of charge–discharge cycles without significant degradation. By absorbing frequent high-current spikes during acceleration and releasing energy during regenerative braking, they reduce the frequency and depth of battery cycling. As a result, battery lifespan is extended by 2–3 times, lowering replacement costs and improving reliability.

Overall Weight:

Although the inclusion of SC modules adds mass, optimized HESS configurations allow for downsizing of the primary battery pack, since the SC provides the necessary peak power. This trade-off leads to a net curb weight reduction, making vehicles lighter, more efficient, and capable of carrying additional payloads without performance penalties.

Power Split Strategies:

Efficient distribution of energy between battery and SC is essential for maximizing benefits:

i. Passive HESS: Direct connection, simple and inexpensive, but inefficient in dynamic load conditions.
ii. Semi-passive HESS: Incorporates unidirectional converters, offering better control and moderate efficiency gains.
iii. Active HESS: Uses bidirectional DC–DC converters, enabling adaptive control and optimized power split. Active systems deliver the best results in terms of battery State of Charge (SOC) balance, State of Health (SOH) preservation, and overall efficiency, though they involve higher cost and complexity.

Concept of Cyber-Physical System:

The information control system and the main HESS equipment are integrated via the CPS. To gather data on the condition of HESS, the system uses sensors and a communication network. The cyber layer computes and creates precise energy allocation plans for the HESS using the information gathered from the physical layer. The first component of CPS is a physical system that functions in accordance with physical rules and has an immediate impact on actual equipment. The physical layer in this section consists of bidirectional DC/DC converters, Li-ion, and supercapacitors. The cyber layer is an additional component that senses, communicates, and evaluates physical data across all physical device components. The physical layer receives control directives from the control instructions produced by the cyber layer. The cyber layer comprises monitoring sensors that are employed to gather the SOC of Li-ion and supercapacitors, along with a multi-objective optimization control module and PI controllers, among others.

A control system for a battery-supercapacitor hybrid energy storage system, utilizing multi-objective optimization based on Cyber-Physical Systems (CPS), has been developed. A low-pass filter scheme that employs multi-objective optimization (MOP) is introduced to effectively manage the energy flow by designating the supercapacitor utilization rate as a key control objective. This approach allows the supercapacitor to handle a greater proportion of high- frequency components, thereby reducing power fluctuations and minimizing the depth of discharge in the battery system, ultimately extending its lifespan.

Rule based Power Split Strategies:

The Indian driving cycle has below mode of operations –

i) Starting - Acceleration mode, ii) Cruise-constant speed mode, iii) Braking-deceleration mode

The first mode of vehicle starting and acceleration demands maximum power where both battery and supercapacitor provides power demanded by vehicle system.

The second mode of cruising where the vehicle has more or the less constant speed the primary source of power that is battery must take all power demand. In most of the studies its been mentioned that battery will also charge supercapacitor in this mode if SoC of supercapacitor drops below its maximum value. In third mode, braking-deceleration; the energy which is regenerated used to charge supercapacitor & battery based on their SoC status and requirement.

In above mentioned mode of operation in constant speed, where battery takes complete load and also charges supercapacitor, this strategy although looks good but its effect overall system efficiency by numerus charge- discharge cycle leading to minimize the contribution of hybridization factor of range extension. So, the battery alone system will have longer range in single charge against HESS system with above power-split, power regeneration charge discharge strategy. This issue needs to address by altering the rules to get better results for range extension & to improve overall efficiency of HESS system

Cost Impact:

While SC integration increases the initial capital cost due to additional power electronics and SC banks, the lifecycle economics are favorable. Reduced battery replacements, improved energy efficiency, and longer system durability translate into significant savings over the vehicle’s operational lifetime. Long-term analyses consistently show that HESS configurations achieve a lower total cost of ownership compared to battery-only systems. Refer below

Table 2: Quantitative comparison of HESS topologies

HESS Topology	Approx. System Efficiency (%)	Battery RMS Current Reduction (%)	Regen Energy Capture Efficiency (%)	Power Electronics / Control Complexity	Relative Cost	Notes
Passive	85–90	30	50	Low	Low	Simple coupling; limited control, lowest cost
Semi-passive	90–93	45	70	Medium	Medium	Unidirectional converter; improved efficiency
Active	93–96	60	85	High	High	Bidirectional DC–DC; best SOC/SOH & range

Table 2 highlights the relative performance of passive, semi- passive, and active hybrid energy storage systems. Passive systems are the simplest and cheapest, achieving 85–90% efficiency but offering only moderate current reduction and limited regenerative energy recovery. Semi-passive designs, with unidirectional converters, provide better control, raising efficiency to 90–93% and capturing about 70% of braking energy, though at moderate cost and complexity. Active HESS topologies clearly outperform both, reaching 93–96% efficiency, reducing battery RMS current by up to 60%, and capturing 85% of regenerative energy. Although cost and control complexity are higher, the active approach ensures superior SOC/SOH management, making it the most sustainable and technically robust configuration.

CONCLUSION

The present study reaffirms that the integration of supercapacitors with lithium-ion batteries in hybrid energy storage systems (HESS) represents a transformative approach for electric vehicle (EV) powertrains. By combining the high energy density of batteries with the high power density and rapid response of supercapacitors, HESS effectively addresses the shortcomings of battery-only systems, particularly in stop-and-go traffic and variable load conditions such as those represented by the Indian Driving Cycle.

The findings indicate that optimum weight distribution and sizing are critical for achieving both improved efficiency and reduced curb weight. Supercapacitors absorb transient peak loads, allowing batteries to be downsized without sacrificing performance. This balance not only reduces overall vehicle mass but also enhances driving range.

Simulation and experimental evidence further confirm that hybrid configurations can extend battery lifespan by reducing deep discharge cycles and mitigating thermal and current stresses.

From an economic perspective, while the adoption of HESS introduces additional upfront costs due to power electronics and capacitor modules, the lifecycle cost advantage is evident. Reduced frequency of battery replacements, lower maintenance requirements, and enhanced operational efficiency make hybrid systems more cost-effective in the long term compared to conventional battery-only configurations.

In terms of architecture, the comparative analysis of passive, semi-passive, and active HESS topologies highlights the superiority of active configurations**.** With advanced power electronics and intelligent control and power split strategies like rule based and CPS; such active systems ensure optimized power split, balanced State of Charge (SOC), and improved State of Health (SOH) of the battery.

This directly translates to better range performance, stability, and reliability of the EV powertrain.

In conclusion, the research establishes that an actively managed HESS with optimized battery–supercapacitor sizing is the most viable pathway for the future of EV powertrains. It combines performance improvements, cost- effectiveness, and sustainability, thereby offering a scalable solution for the widespread adoption of electric mobility in both urban and regional contexts.

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