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Advancing Electric Vehicle Technology: Evaluating Supercapacitors Versus Batteries

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Abstract Electric vehicles (EVs) are crucial in the global shift from fossil fuels towards sustainable transportation. However, conventional EVs alone do not fully address issues such as urban congestion, parking difficulties, battery recycling challenges, and the environmental concerns associated with battery disposal. To overcome these limitations, micromobility solutions particularly light electric vehicles offer promising advantages for short urban journeys. This paper provides an in-depth examination of two key energy storage alternatives: supercapacitors and batteries, assessing their roles and future implications for electric transport. Supercapacitors are evaluated for their superior power density and rapid energy discharge capability, making them ideal for applications involving frequent stops and regenerative braking in urban mobility. Concurrently, battery technologies, including lithium-ion and lead-acid, are critically analyzed regarding energy capacity, longevity, economic feasibility, and environmental impacts.

Additionally, this study incorporates insights from the LIFE2M project, which utilizes hybrid supercapacitor accumulators designed to significantly extend battery life, reduce environmental impact, and lower ownership costs. Ultimately, this paper underscores how the strategic integration of advanced energy storage systems and supportive infrastructure can achieve substantial reductions in energy consumption, urban pollutants, and CO_2 emissions, driving urban transport towards a greener, more inclusive future.

Keywords: Electric Vehicles (EVs), Energy Storage Technologies, Supercapacitors vs. Batteries, Urban Mobility, Sustainable Transportation, Micromobility, Energy Storage Applications

1. Introduction

Supercapacitors represent a newer energy storage technology particularly suited to urban transport applications requiring frequent acceleration, braking, and rapid energy charging capabilities (Chidembo, 2014). Due to their high-power density and quick charge/discharge cycles, supercapacitors are ideal for short-distance micromobility vehicles and urban transport scenarios involving frequent stop-and-go movements (Zorpette, 2005). However, their relatively low energy storage capacity restricts their standalone applicability for sustained energy demands, prompting interest in hybrid storage solutions combining supercapacitors and batteries.

In response to these technological challenges, the LIFE2M project aims to promote sustainable micromobility through the development of advanced hybrid energy storage solutions, utilizing hybrid supercapacitor accumulators that significantly extend battery life, reduce overall ownership costs, and eliminate battery waste. (LIFE2M, 2022) integrates hybrid SC technologies into recyclable micromobility vehicles adapted from the EU-funded H2020 LEONARDO project, combined with photovoltaic-powered fast-charging stations to enhance sustainability. Implemented in Palermo, L'Aquila, and Florence, LIFE2M introduces around 800 micro-vehicles, creates digital platforms for vehicle monitoring, develops communication campaigns, and formulates viable business and policy strategies to support scalable micromobility solutions. The project's ambitious goals include achieving reductions in energy consumption by 93%, atmospheric pollutants (NOx, COVNM, CO, PM10) by 95%, CO_2 emissions by 85%, and eliminating battery waste through hybrid SC technologies within five years after its completion.

This paper comprehensively reviews energy storage technologies highlighting their historical development, comparative performance, environmental implications, and practical applicability in micromobility and demonstrates how strategic integration of supercapacitors and batteries could profoundly influence urban mobility, making it more sustainable, efficient, and inclusive

2. Methodology

This study employs a systematic literature review approach, focusing on energy storage technologies relevant to electric vehicles (EVs), specifically examining batteries and supercapacitors. Following the SPAR-structured method, peer-reviewed literature published within the last twenty years was collected, emphasizing high-impact, well-cited sources addressing battery and supercapacitor technologies.

The review initially identified key developments and applications of lithium-ion, lead-acid, nickel-based batteries, and supercapacitors in electric and micromobility vehicles. Selected studies were evaluated based on critical performance metrics, including specific energy, power density, lifecycle durability, cost-effectiveness, environmental sustainability, and recycling considerations. Comparative analysis was conducted using quantitative data aggregated from existing literature to highlight strengths and limitations of each storage technology clearly and objectively.

Further, the integration and complementary usage of hybrid energy storage systems, combining supercapacitors and batteries, was examined in-depth. This structured approach enabled concise identification of optimal energy storage solutions, supporting informed decision-making for enhanced efficiency, sustainability, and practicality in urban EV and micromobility applications.

3. Hybrid Energy Storage System

Hybrid Energy Storage Systems (HESS), which integrate supercapacitors and batteries, offer a sophisticated and efficient solution for energy management in electric vehicles (EVs). Supercapacitors, characterized by their high-power density and rapid energy discharge capabilities, excel at handling short-term power demands such as acceleration and regenerative braking. These systems effectively capture and reuse kinetic energy, reducing energy loss and minimizing battery strain.

Conversely, batteries, especially lithium-ion technologies provide high energy density, storing ample energy necessary for extended driving ranges. However, frequent high-power demand significantly reduces battery life and performance. The integration of supercapacitors with batteries creates a balanced energy storage solution (Khalid, 2019), where supercapacitors manage peak power demands, alleviating electrical and thermal stress on the batteries. This complementary arrangement significantly reduces battery degradation, extends battery lifespan, and enhances overall system efficiency and durability (Qiu, 2016).

Hybrid Energy Storage Systems thus offer an optimized approach that combines the strengths of both storage technologies, improving vehicle performance, efficiency, sustainability, and the economic viability of EVs in urban transportation.

4. Results

The scoring scheme illustrated in Figure 1 clearly highlights the strengths and limitations of various energy storage technologies. Supercapacitors excel in power density and charge/discharge rates, making them ideal for applications involving rapid energy transfer. Lithium-ion batteries offer high specific energy and good cycle life, positioning them as preferred choices for extended-range EV applications, despite concerns related to environmental impact and safety. Nickel-based batteries deliver balanced performance across multiple criteria, while lead-acid batteries, though limited by lower energy density and recyclability concerns, remain viable primarily due to their cost-effectiveness. This visual comparison effectively underscores each technology's suitability for different EV requirements.

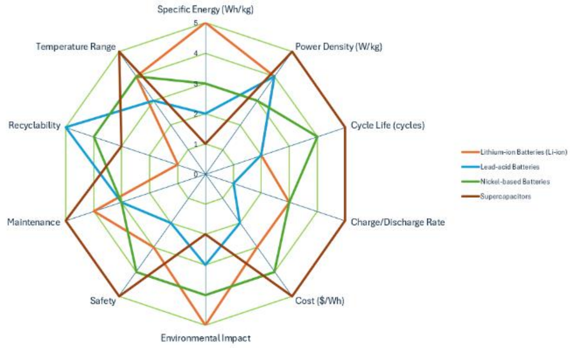

Figure 1. Comparison of energy storage systems across ten key performance metrics.

5. Conclusion

This review highlights the essential roles of advanced energy storage technologies specifically supercapacitors and various battery types (lithium-ion, lead-acid, and nickel-based) in electric vehicles (EVs). Supercapacitors are optimal for rapid energy bursts during acceleration and regenerative braking, while lithium-ion batteries provide sustained high energy density suitable for long-range driving, despite associated environmental and safety concerns.

Hybrid Energy Storage Systems (HESS), integrating these complementary technologies, significantly improve vehicle efficiency by approximately 20% and extend battery lifespan by 30–50%, reducing overall costs and environmental impact. The LIFE2M project demonstrates practical implementation by incorporating hybrid supercapacitor accumulators in recyclable micromobility vehicles, adapted from H2020 LEONARDO models, to foster sustainable urban mobility solutions.

Future advancements, including solid-state batteries, graphene-based supercapacitors, and sustainable recycling approaches, will further accelerate the transition toward greener transportation and a circular economy

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