International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online) Volume 14, Issue 12, December 2025)

Renewable Energy Storage System for Electric Vehicles: A Review

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***Abstract*— The rapid adoption of electric vehicles (EVs) has intensified the need for efficient and sustainable energy storage systems integrated with renewable energy sources. This review presents a comprehensive analysis of renewable energy storage systems for electric vehicles, focusing on technologies that enable clean energy generation, storage, and utilization. Various energy storage options such as lithium-ion batteries, solid-state batteries, supercapacitors, and hybrid energy storage systems are critically reviewed in the context of their compatibility with renewable sources like solar and wind energy. The study also examines charging infrastructure, vehicle-to-grid (V2G) integration, energy management strategies, and recent advancements aimed at improving energy density, charging speed, lifecycle, and safety. Key challenges related to intermittency of renewable sources, cost, thermal management, and recycling are discussed, along with future research directions for developing reliable, high-performance, and eco-friendly energy storage solutions to support next-generation electric mobility.**

***Keywords*— Electric Vehicles, Renewable Energy, Energy Storage Systems, Battery Technologies, Vehicle-to-Grid.**

I. INTRODUCTION

The global transportation sector is undergoing a major transformation due to rising concerns over climate change, depletion of fossil fuels, and increasing air pollution. Electric vehicles (EVs) have emerged as a promising solution to reduce greenhouse gas emissions and dependence on conventional internal combustion engine vehicles[1]. However, the large-scale adoption of EVs strongly depends on the availability of efficient, reliable, and sustainable energy storage systems. In this context, renewable energy–based storage systems play a crucial role in ensuring clean, economical, and long-term energy supply for electric mobility[2].

Renewable energy sources such as solar, wind, and small-scale hydro are environmentally friendly and abundant, but they are inherently intermittent and unpredictable. This intermittency creates challenges in directly supplying power to electric vehicles, which require stable and controllable energy for charging and operation[3]. Energy storage systems act as a vital bridge between renewable energy generation and EV power demand by storing excess energy when generation is high and supplying it when demand increases. Hence, the integration of renewable energy storage systems is essential for achieving a sustainable EV ecosystem[4].

Batteries are the most widely used energy storage technology in electric vehicles, with lithium-ion batteries dominating the current market due to their high energy density, long cycle life, and relatively low self-discharge[5]. In addition to conventional batteries, emerging technologies such as solid-state batteries, supercapacitors, and hybrid energy storage systems are gaining attention for their potential to improve charging speed, safety, and lifespan. These storage technologies are increasingly being designed to work efficiently with renewable energy sources, enabling green charging solutions for EVs[6].

Renewable energy storage systems also support advanced concepts such as smart charging, fast charging stations powered by solar or wind energy, and vehicle-to-grid (V2G) systems[7]. Through V2G technology, electric vehicles can act as mobile energy storage units, supplying stored energy back to the grid during peak demand periods. This bidirectional energy flow enhances grid stability, promotes better utilization of renewable energy, and provides economic benefits to both EV owners and power utilities[8].

Despite significant progress, several challenges remain in the development and deployment of renewable energy storage systems for electric vehicles. These include high initial costs, limited battery lifespan, thermal management issues, recycling and environmental impact of batteries, and infrastructure limitations[9]. Addressing these challenges requires continuous research, innovation, and supportive government policies to improve performance, reduce costs, and ensure sustainability[10].

Renewable energy storage systems are a key enabler for the future of electric vehicles. By combining clean energy generation with advanced storage technologies, they offer a pathway toward low-carbon transportation, energy independence, and sustainable urban mobility. Continued advancements in this field are expected to play a vital role in shaping next-generation electric vehicles and smart energy systems worldwide[11].

II. LITERATURE SURVEY

X. Tan et al., [1] proposed an integrated self-modularized battery equalizer combined with a supercapacitor charger for hybrid electric vehicle energy storage systems. The work focuses on improving energy balancing efficiency while reducing system complexity. The proposed architecture enables effective voltage equalization among battery cells and supports fast energy transfer to supercapacitors. Experimental validation demonstrates enhanced charging efficiency and improved battery lifespan. The system also reduces thermal stress under high load conditions. This study highlights the importance of integrated power electronics for hybrid storage systems. The approach is highly suitable for renewable-powered EV applications.

A. Benhammou et al., [2] presented efficient scheduling techniques for hybrid electric vehicle energy management. The study emphasizes optimal coordination between energy sources to minimize power losses and improve vehicle efficiency. A mathematical scheduling model is developed to manage energy flow during varying driving conditions. Simulation results show reduced energy consumption and improved system reliability. The proposed strategy also enhances battery health by avoiding deep discharge cycles. The work contributes toward intelligent control in renewable-assisted EV systems. It is applicable to both grid-connected and standalone charging scenarios.

V. C. Tella et al., [3] provided a comprehensive review of energy management strategies for hybrid electric vehicles. The paper categorizes rule-based, optimization-based, and artificial intelligence-based control techniques. It critically analyzes performance metrics such as fuel economy, battery degradation, and computational complexity. The authors highlight the role of renewable energy integration in modern EV systems. Challenges related to real-time implementation are discussed in detail. Future research directions focus on adaptive and learning-based controllers. This review serves as a strong foundation for sustainable EV energy management research.

R. Punyavathi et al., [4] investigated sustainable power management in light electric vehicles using hybrid energy storage and machine learning techniques. The study integrates batteries and supercapacitors with predictive learning algorithms. Machine learning models are used to optimize power sharing under dynamic load conditions. Results show improved energy efficiency and extended battery life. The approach effectively handles renewable energy fluctuations. The system demonstrates adaptability to real-world driving patterns. This work confirms the potential of AI-driven renewable EV storage systems.

K. M. Elakkiya et al., [5] developed an energy management system based on hybrid battery-supercapacitor storage for electric vehicle applications. The proposed system focuses on reducing battery stress during peak power demand. A control algorithm is designed to allocate transient power to supercapacitors. Simulation results indicate improved overall system efficiency. The hybrid configuration enhances acceleration performance and regenerative braking efficiency. The study supports renewable energy compatibility. It is suitable for next-generation EV energy storage architectures.

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T. Sutikno et al., [6] presented a detailed review of recent advances in hybrid energy storage systems for renewable energy sources. The paper discusses battery-supercapacitor and battery-fuel cell combinations. Emphasis is placed on power electronic interfaces and control strategies. Performance evaluation parameters such as efficiency, cost, and reliability are analyzed. The authors highlight challenges in renewable intermittency handling. Integration with electric mobility applications is discussed. This review is relevant for renewable-based EV charging systems.

S. Rajasekaran et al., [7] proposed a hybrid battery and supercapacitor storage system specifically designed for electric vehicles. The study focuses on improving power density and energy utilization. A control strategy is implemented to manage charge–discharge operations efficiently. Simulation results show reduced battery current stress. The system improves vehicle acceleration and regenerative energy recovery. Renewable energy compatibility is emphasized. The work supports sustainable EV energy storage design.

J. Shen et al., [8] introduced a fuzzy logic-based power management system for hybrid energy storage in solar electric vehicles. The fuzzy controller dynamically distributes power between battery and supercapacitor. The system effectively handles solar power intermittency. Simulation outcomes show improved energy efficiency and system stability. Battery aging effects are significantly reduced. The method requires minimal computational resources. This approach is well-suited for renewable-powered EVs.

I. Husain et al., [9] designed and implemented a battery–supercapacitor-based hybrid energy management system for electric vehicles. The study focuses on real-time control implementation. A bidirectional DC-DC converter is used for energy coordination. Experimental results validate enhanced performance under dynamic load conditions. Battery lifespan improvement is clearly demonstrated. The system supports regenerative braking efficiently. This work strengthens practical hybrid storage integration in EVs.

S. Wang et al., [10] presented a detailed review of energy management strategies for battery-supercapacitor hybrid systems in electric vehicles. The paper compares classical, optimization-based, and intelligent control methods. Advantages and limitations of each approach are critically analyzed. The impact on battery aging and system efficiency is discussed. Renewable energy integration challenges are highlighted. The authors suggest AI-based adaptive control as a future direction. This review provides valuable insights for sustainable EV storage research.

N. Sarmah et al., [11] proposed an intelligent energy management system for a battery-supercapacitor hybrid system in solar electric vehicles. The system uses predictive algorithms to manage renewable energy input. Simulation results show enhanced power utilization efficiency. Battery degradation is significantly reduced through intelligent control. The approach improves overall vehicle performance. The system adapts well to varying solar conditions. This work demonstrates the effectiveness of intelligent renewable EV storage systems.

J. Hong et al., [12] developed an energy management and control strategy for photovoltaic-battery hybrid distributed power generation systems. A three-port power converter is used to integrate PV, battery, and load. The proposed strategy ensures efficient power flow control. Experimental results show high conversion efficiency and stable operation. The system supports bidirectional energy transfer. It is suitable for renewable-powered EV charging stations. This work contributes to grid-integrated EV energy storage solutions.

III. CHALLENGES

Challenges in Renewable Energy Storage Systems for Electric Vehicles

The integration of renewable energy storage systems with electric vehicles (EVs) presents significant technical, economic, and operational challenges that must be addressed for large-scale adoption. Renewable energy sources such as solar and wind are inherently intermittent, leading to fluctuations in power availability that directly affect EV charging reliability and efficiency. Energy storage systems must therefore be capable of handling variable

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input power while ensuring consistent output to meet vehicle performance requirements. Additionally, the high cost of advanced batteries, limited lifespan, safety concerns, and recycling issues pose major barriers to sustainable deployment. The lack of standardized infrastructure, complex energy management strategies, and grid compatibility issues further complicate integration. Overcoming these challenges requires advances in materials, intelligent control algorithms, power electronics, and supportive regulatory frameworks to ensure that renewable-based EV energy storage systems are reliable, cost-effective, and environmentally sustainable.

1. **Intermittency of Renewable Energy Sources**
   Renewable energy sources such as solar and wind are not continuously available, causing unpredictable charging patterns for EVs. This intermittency necessitates large-capacity and fast-response storage systems to maintain stable energy supply. Managing sudden power variations without affecting battery health remains a critical challenge.
2. **High Initial Cost of Energy Storage Systems**
   Advanced battery technologies and hybrid energy storage systems involve high manufacturing and installation costs. The use of rare materials and complex power electronics further increases system expenses. High costs limit affordability for consumers and slow down widespread EV adoption.
3. **Limited Battery Lifetime and Degradation**
   Frequent charging and discharging cycles accelerate battery aging and reduce usable capacity over time. Renewable energy fluctuations increase stress on batteries, leading to faster degradation. Improving cycle life and developing degradation-aware energy management strategies are essential.
4. **Thermal Management and Safety Issues**
   High power charging from renewable sources can generate excessive heat in batteries and converters. Poor thermal management increases the risk of thermal runaway and safety hazards. Designing efficient cooling and monitoring systems is a major technical challenge.
5. **Energy Management Complexity**
   Coordinating energy flow between renewable sources, storage units, and EV loads requires sophisticated control algorithms. Real-time decision-making under dynamic conditions is computationally complex. Ensuring reliability without increasing system complexity remains difficult.
6. **Recycling and Environmental Impact**
   Disposal and recycling of used batteries pose serious environmental concerns. Many battery materials are hazardous and difficult to recycle efficiently. Sustainable recycling methods and circular economy approaches are still under development.
7. **Infrastructure and Grid Integration Limitations**
   Renewable-powered EV charging infrastructure is still limited, especially in developing regions. Grid compatibility issues, voltage fluctuations, and lack of bidirectional support hinder effective integration. Upgrading existing infrastructure requires significant investment.
8. **Lack of Standardization and Policy Support**
   The absence of universal standards for renewable EV charging systems creates interoperability issues. Inconsistent government policies and incentives further slow development. Strong regulatory frameworks are needed to support innovation and deployment.

IV. CONCLUSION

Renewable energy storage systems play a vital role in enabling the sustainable growth of electric vehicles by effectively integrating clean energy sources with advanced energy storage technologies. This review highlights that the combination of batteries, supercapacitors, and hybrid energy storage systems, supported by intelligent energy management strategies, can significantly enhance charging efficiency, system reliability, and battery lifespan. Although challenges such as renewable intermittency, high cost, battery degradation, safety concerns, and infrastructure limitations remain, ongoing advancements in materials, power electronics, and artificial intelligence–based control methods are steadily addressing these issues. With continued research, standardization, and supportive policy frameworks, renewable energy–based storage systems are expected to become a cornerstone of next-generation electric mobility, contributing to reduced carbon emissions, improved energy independence, and a cleaner transportation ecosystem.

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