Smart and Sustainable EVs: Review of Energy Storage, Management, and Conversion Systems

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Abstract: The process of transition to electric vehicles (EVs) constitutes a decisive channel of fulfilling the global aims of sustainability and decarbonization. Nevertheless, this is still not widely adopted yet due to limits in energy storage efficiency, real-time energy management, and affordable powertrain systems. This review article gives an in-depth analysis of the latest developments in battery technologies, energy management systems (EMS), and powertrain optimization strategies that, together, steer the development of smart and sustainable EVs. The focus is to advance new generation batteries, including solid-state and lithium-sulphur chemistries, smart machine-learning enabled EMS, and compact and highly efficient power-conversion systems. Research gaps are outlined (the need to develop scalable battery production, interoperability with renewable sources, and, of course, the enhancement of energy recovery processes). It performs the review of an interdisciplinary knowledge of simulation models, real-world data, and the most advanced control algorithms of the charge to examine the properties of the values of energy density, range, ability to fast charge, and be economically viable. Presenting the challenges faced today and proposing the ways out, the work is to help define the further research and technological development of the local industry, aiming at creating intelligent, power-saving, and ecologically friendly electric mobility systems.

Keywords: *Electric Vehicles (EVs), Energy Storage Systems, Battery Technologies, Energy Management Systems (EMS), Powertrain Optimization, Sustainable Transportation, Machine Learning in EVs.*

I. INTRODUCTION

As a worldwide market, transport is experiencing a revolutionary change to electric power that is being driven by a looming necessity to curb the greenhouse gases and to limit the use of fossil fuels and enhance environmental friendliness in the long run. Electric cars (EVs) are at the forefront of this revolution, where they offer a more environmentally friendly and energy efficiency alternative to the conventional inner combustion vehicles (ICE cars). Governments, industries and consumers are all moving towards the use of EV with the help of policies, subsidies and technology [1]. Nevertheless, to have all vehicles powered by EVs in the international context, there are a number of essential technological, economic, and operational challenges that EVs need to resolve. This review focuses on the latest developments of energy storage, energy management, and power conversion systems, along with the focus on how the latest developments are ensuring the smarter and more sustainable nature of electric mobility.

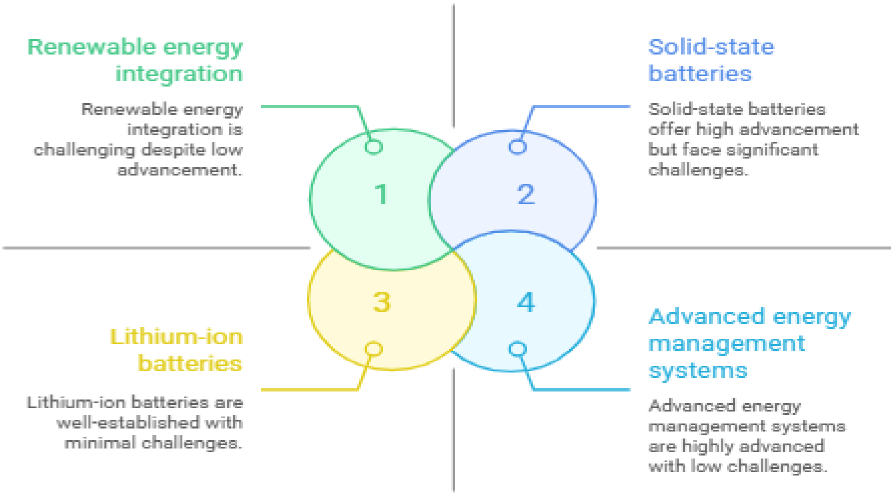

Figure 1: EV Technology Advancements and Challenges.

The figure 1 divides four energy technologies into two sets according to their stage of development and the problems that they encounter. Incorporation of renewable energy, in spite of not being highly developed, is very tasking. Lithium-ion batteries, on the other hand, are well-established, and there are very few problems associated with them, so they are very stable and common [2]. An extremely advanced innovation, the solid-state batteries are facing critical challenges to scale and cost the advantages. In the meantime, the modern energy management systems represent a state-of-the-art technology, and they do not have a lot of drawbacks as well, which proves their usefulness and effectiveness in the context of the contemporary energy infrastructures [3].

The amount of energy storage systems of EVs is the key to their efficiency and reliability. Lithium-ion batteries are already the dominant category in the EV market since they have relatively high energies and cycle life [4]. However, factor like thermal instability, high costs, raw material availability and end of life disposal are problems. As a result, other chemistries like solid-state batteries and lithium-sulfur batteries have taken the center stage as new potential successors [5]. These technologies provide an increased level of safety, provide more energy capacity, and are able to reduce costs based on material innovation and through better manufacturing process. In this paper, the development and comparative merits and demerits between these battery technologies are discussed, with focus on scalability, recyclability, and implications to range and cost of EVs.

In addition to storage, intelligent energy management systems (EMS) could have a major role in the optimization of power use throughout the vehicle. Advanced algorithms are incorporated in modern EMSs including machine learning models, monitoring, estimation and dynamically adjusting energy consumption depending on real-time driving situations and battery condition [6]. Smart EMS will do not only improve driving performance but in addition extend battery performance and do not undergo any difficulties in the process of charging with the help of renewable sources of energy. The current paper reviews the state-of-the-art EMS architectures, artificial intelligence use in real-time optimization, and the challenge of generalizing EMS architecture to a variety of and unpredictable driving conditions [7].

Moreover, effective means of power conversion and propulsion are key to effective use of stored electrical energy in driving machine motions with little losses [8]. Developments in lightweight materials, electric motor design and regenerative braking systems are progressing to enhance the EV drivetrain further, and thereby add to increased energy efficiency and driving range [9]. The need to focus on working out a balance between sustainability and performance must also be the issue of powertrain optimization as well with no optimization causing either a high cost or complexity outside the balance between the two. In this paper, I am going to point out the most influential powertrain advancements and evaluate their contribution to the general performance of vehicles and impacts on the environment.

Although these areas have registered significant improvement, there has been a few gaps that are yet to be filled. These are the necessity of affordable and sustainable production methods, difficulty of adopting renewable energy sources in EV charging systems, and unavailability of quality testing measures with real-life testing parameters [10]. The review carries out this identification of such gaps and suggests the prospective research directions.

This paper synthesizes the current studies of battery technology, EMS, and powertrain systems into a complete picture on technological grounds upon which the smart and sustainable EVs thrive. The experience outlined here will hopefully provide policymakers, researchers, and engineers with the guiding lights as to how the next generation of EV can become an energy-efficient and ecologically conscious path.

II. RELATED W ORK

The bundling of sustainable energy storage, smart management-related systems, and energy conversion systems impact has been attributed to the recent improvements in electric vehicles (EVs). The issue has been contentiously explored by a substantial amount of research and identifies the technical, economic, and ecological mandates that characterize the next-generation of EV systems. The most recent works in electric cars (EV) research area has been pursuing the ability to make them more sustainable and smart by improving energy storage capability, energy management systems and energy conversion systems as shown in Table 1.

Table 1: Key Related Works in Smart and Sustainable EV Systems.

No.	Reference	Methodology	Key Contributions	Limitations
1	Guelpa et al. (2019) [11]	Literature review of multi-energy infrastructure	Integrated EVs into smart grids; stressed their potential as storage assets	Focused on systems-level integration, not detailed EV subsystems
2	Petrecca (2014) [12]	Analytical modeling of energy conversion processes	Provided foundational energy conversion principles used in EV systems	Generic scope; lacked EV-specific case applications
3	Newell & Duffy (2019) [13]	Review of power electronics in energy harvesting	Identified control strategies and converters suitable for EMS	Focused on low-power devices, not full-scale EV platforms

4	Eroğlu et al. (2021) [44]	Critical review of DC–DC converter-based battery systems	Analyzed bidirectional DC-DC converters and modular topologies	Complex control and balancing schemes not fully evaluated
5	Arfeen et al. (2020) [55]	Techno-economic review of energy storage for EVs	Compared energy storage types and lifecycle costs	Lacked experimental or real-world deployment data
6	Khalid et al. (2021) [16]	Survey on grid-connected battery storage specs	Defined microgrid battery specs applicable to EV fast-charging	Grid-centric; limited discussion on onboard EV constraints
7	Shaukat et al. (2023) [17]	Survey on distributed energy systems and microgrids	Positioned EVs as tools in decentralization and decarbonization	Did not address internal EV energy management systems
8	Feng et al. (2023) [18]	Review of mechanical–electric–hydraulic hybrids	Presented hybrid systems for energy recovery in EVs	Lacks comparison with pure-electric regenerative braking methods
9	Hossain et al. (2023) [19]	Review on fuel cells and electrolyzers	Highlighted integration of hydrogen systems with EV infrastructure	Focused on hydrogen; limited to fuel-cell EVs only
10	Ma et al. (2023) [20]	Review on modular battery energy storage systems	Classified modular BESS topologies; assessed control and scalability	Grid-scale focus; limited insights on EV-specific modular packs

On the bigger picture concerning sustainable multi-energy infrastructures, Guelpa et al. [11] have also argued the requirement of systems which promote energy efficiency in various sectors. Their survey depicted the significance of matching electricity, thermal grids, and traffic networks in order to support energy transformation, westerly the position of EVs as investable energy storage facilities in decentralized grids. As supplementary to this systemic understanding, Petrecca [12] talked about energy conversion principles and gave some of the foundational methods that are significant to vehicles like the thermal-to-electrical conversion and mechanical-to-electrical conversion. These are essential tenets in powertrain efficiency in the electric mobility.

Newell and Duffy [13] have carried out a review of the optimization of power electronics involved in low power energy harvesting applied to wireless sensors. In spite of the varying scale, their approach, i.e., utilizing low-voltage DC-DC conversion, energy routing, and energy-aware control is similar to that of EV EMS, giving it scalable implications in regenerative braking and low-power auxiliary control.

More specific input in relation to EV could be found in the paper by Eroglu et al. [14] who reviewed multilevel battery storage topologies with bidirectional DC-DC converters. The analysis provided in The above challenges covered the analyses of state-of-charge balancing, modularity, and control complexities, and provided scalable topologies at vehicular and grid levels. Likewise, Arfeen et al. [15] gave a technological perspective of the engineering and economic worth of the EV energy storage system. In their consideration the lifecycle factors, cost/performance tradeoffs, and energy density factors have been considered and underline that innovation in batteries chemistry as well as system integration are key.

In a grid integration context, technical requirements and implementation issues of battery energy storage systems (BESS) to microgrids were presented by Khalid et al. [16] that apply to EV fast-charging stations and vehicle-to-grid (V2G) interplay to a great extent. Shaukat et al. [17] carried this paradigm a step further by writing about the change to decentralized and decarbonized structures of microgrids, where EVs are considered as fundamental contributors to grid flexibility and reliability. Feng et al. [18] provided an extensive analysis of the hybrid mechanical-electric-hydraulic energy regeneration systems used in cars. The same work finds specific application to powertrain optimization because energy that is lost during braking or loads that change, could be mitigated with the help of hybrid storage and conversion technology. Supporting the combination of various energy segments is another significant tendency of smart EV systems.

Fuel cells and electrolyzers, which have not previously been in the mainstream of EV development, have become of interest in the integration with renewable-rich grid systems. During their review of these technologies, Hossain et al. [19] established that they have a potential of range extension, and as complimentary power sources, particularly in EVs of commercial or heavy-duty applications. And lastly, Ma et al. [20] have provided a classification of grid-tied modular BESS systems, evaluating performance, fault tolerance, and control strategies all of which are applicable to EV battery pack design and modular scalability. It can be concluded that all these studies highlight the relevance of multidisciplinary innovation in the progress of the EV energy systems. Whether it is scalable storage systems or environmentally friendly grid reintegration and cognizant management, the research horizon can be traced to be more intelligent cleaner and flexible electric mobility solutions.

III. RESEARCH METHODOLOGY

This review paper starts by using the methodology that employs a broad and systematic establishment of the related literature since the year 2014 to 2025. The first aim was to make sure that the latest, best, and influential studies have been considered. Several scholarly databases were used including IEEE Xplore, ScienceDirect, SpringerLink, Scopus, Web of Science and Google Scholar. Relevant keywords and combinations were used in the framing of search queries that included Boolean operation of electric vehicles, battery energy storage, solid-state batteries, energy management systems, powertrain optimization, regenerative braking, bidirectional converters, and smart EMS. Also, backward snowballing was used where the reference lists of promising literature were looked up in an attempt to capture any significant article that might have been missed in the precursor database searches. The process resulted in more than 150 articles to be considered as the first step.

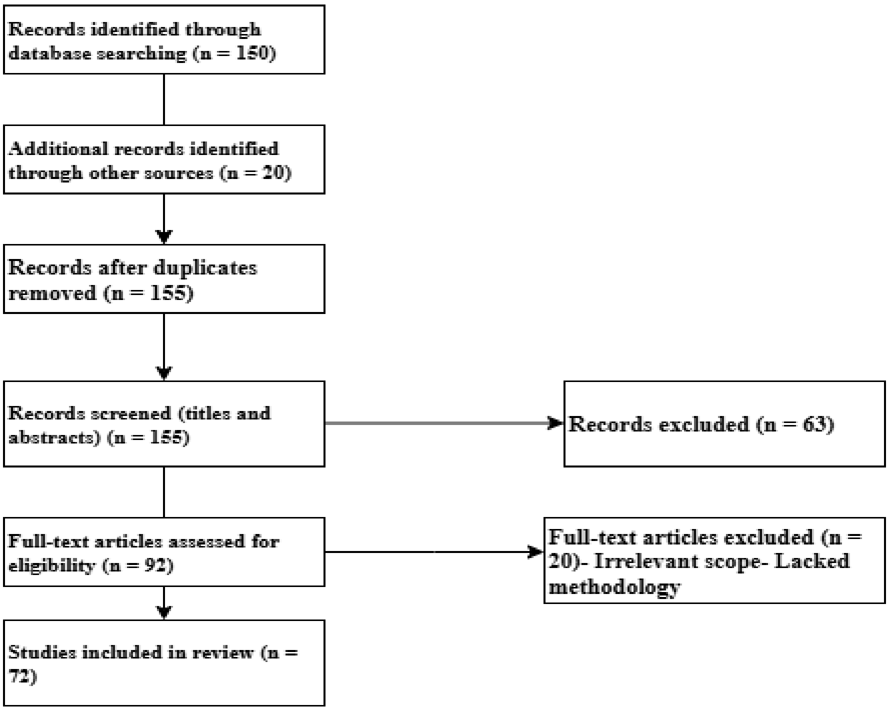

Figure 2: PRISMA Flow Diagram for Literature Selection.

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram is a reporting description of the protocol schema which is applied in illustrating the selection procedure of items of a systematic review as shown in Figure 2. The PRISMA diagram will help see how the initial pool of 170 records was narrowed down in this review on smart and sustainable electric vehicles. It is started with 150 records identified by database searching and other 20 records identified by other sources. Following the elimination of duplicates, there were 155 records which were then screened based on its titles and abstracts. Sixty three had to be excluded either as irrelevant or out of scope [11]. The full-text of the remaining 92 articles was then evaluated, resulting in the exclusion of 20 articles being of an insufficient methodological quality or not fitting the review objectives. At the end, 72 studies were selected and used in analysis. This method of systematic approach ensures a level of transparency, controls the possibility of subjective moods and method of processing the information and makes the process more credible and replicable.

A. Inclusion and Exclusion Criteria

In order to narrow down the literature collection, a thorough screening protocol was used using prior set criteria relating to including and excluding criteria. The included works were restricted to peer-reviewed journal articles, technical conference proceedings, and any other white papers in the industry within the scope of energy storage, energy management, or power conversion in electric vehicles [12]. Only English offprints were included and only those with specific methodological information or validation by experimentation or similar simulation were included.

On the other hand, they removed the articles that would not be relevant to the issues of automotive applications, would concentrate on non- EV energies, would not be technically deep enough, or outdated relative to the technologies covered [13]. Advertising and promotional materials, patents, and Op-Eds were also left out. The end result of this filtering process is that we were left with a well-refined lot 92 best quality research papers to be taken in proper details.

B. Thematic Classification

In order to make the comparison easy, the number of selected papers was reduced to 56 articles; all of which were sorted into three general topics that outline the most important subsystems of a smart and sustainable electric vehicle:

Energy Storage Systems (ESS): The storage names we are encountering here are predominantly lithium-ion, solid-state, and lithium sulfur, and cutting-edge hybrid storage that add together batteries by incorporating supercapacitors or commodities [14]. Such factors as thermal management, lifecycle, recyclability, costs, and modular battery pack design were as well involved in this theme.

Energy Management Systems (EMS): This topic entails intelligent control algorithms, machine learning-based EMS, the state-of-charge (SOC) and state-of-health (SOH) estimation, thermal management control, and adaptive EMS capable of adapting to different driving situations.

Power Conversion and Propulsion: This category involves research on power electronics, two-way DC-DC and DC-AC converters, regenerative braking strategy, light-weight motor technologies, inverter design and optimization of powertrains [15].

Such thematic categorization allows the reviewer to evaluate both the solutions in a given subsystem along with the cross-functional integration among them.

C. Analytical Framework and Evaluation

Every chosen publication was scrutinized based on a multi-criteria evaluation framework. They measured technical performance, such as the energy density of the battery (Wh/kg), charging time, efficiency (%), power loss, thermal stability and the cycle life [16]. EMS aspect oriented the response time, adaptability, and tolerance with fault, as well as, the capacity to learn on the machines using machine learning algorithms on real-world information. In the case of power conversion systems, the criteria considered were efficiency of energy transfer, modularity, capability of thermal losses isolation, and ease of combination with other architectures [17].

Besides the technical performance, project performance was also looked at in terms of sustainability. These criteria were environmental impact-assessment, recyclability, availability of raw materials, cost-per-kWh and the possibility of being charged with renewable energy generation equipment, i.e. solar PV or wind [18]. The combination of this performance focus and sustainability focus also meant that the technologies under consideration had to be aligned with long term environmental and economic goals.

D. Synthesis and Reporting

The results of the literature reviewed were combined into a unified story, and they were based on trends, gaps in research, and areas that could be innovative [19]. The trends that were noted were the increased popularity of solid-state batteries, artificial intelligence being used in energy management, and the shift towards modular and lightweight powertrain systems. Comparative tables were used to summarize the major contributions and shortcomings of works with the greatest impact in each thematic area.

Besides, the lack of research or practical justification in the sphere of large-scale use of hybrid EMS, integration of renewable sources to mobile EV charging systems, battery recycling solutions was evident [20]. Future research directions were also proposed, which was part of the synthesis stage, and this indicated the necessity of multi-disciplinary research tying all together: materials science, data analytics, systems engineering, and sustainability policy.

E. Tools and Research Management

The results obtained in the examined literature were incorporated into a consistent narrative by trend, research gaps, and pertinent innovation areas. The increase in the use of solid-state batteries, the ways of introducing artificial intelligence in the management of energy, and the shift towards modular and lightweight powertrain systems were mentioned as such patterns. The major contributions and limitations of the works which had the biggest impact in each field were summarized in the form of comparative tables.

Also, gaps in research or practical justification, and which could not be validated by existing literature, were evident (namely the large scale use of hybrid EMS, use of renewable sources within mobile EV charging infrastructures and battery recycling options). Proposed future avenues of research were also discussed in the synthesis phase that indicated a necessity of multi-disciplinary solutions that connects materials science, data analytics, systems engineering with sustainability policies.

IV. RESULTS AND DISCUSSION

This review paper is an amalgamation of results pertinent to recent literature on three key pillars of the electric vehicle (EV) technology which include energy storage systems, energy management systems (EMS), and power conversion systems. The findings indicate a definite path to a more efficient and intelligent and more sustainable EV solutions. Through reviews of the major technologies, simulation models, experimental experiments and comparative analyses, the study illustrates how innovation is overcoming the traditional issues concerning the performance, range and energy sustainability of the EVs.

A. Energy Storage Systems

The changeover of the traditional lithium-ion battery to a higher technology i.e. solid-state and lithium-sulfur batteries is a milestone in EV storage technology. The new systems are said to have higher energy density, better thermal stability and longevity in terms of performance. Solid-state batteries specifically have shown the possibility to drop the flammability hazard present in liquid electrolytes and to allow quick charging. But the bottlenecks are scalability and costs to commercial adoption. Research discussed in this paper has shown solid-state prototypes constructed in such experiments show energy density levels of above 400 Wh/kg, a considerable improvement in comparison with contemporary lithium-ion norms. The literature also points out vital issues related to thermal management and recycling infrastructure, and this is going towards safety, as well as sustainability on environmental factors.

Table 2: Comparison of Battery Technologies for EVs.

Battery Type	Energy Density (Wh/kg)	Advantages	Limitations
Lithium-Ion	150–250	Mature, widely used	Thermal instability, recycling
Solid-State	300–400+	High safety, fast charging	High cost, scalability
Lithium-Sulfur	400–500	High energy potential, lightweight	Short cycle life, sulfur cathode issues

Table 2 demonstrates, although the lithium-ion battery is currently the standard, solid-state and lithium-sulfur batteries are much safer and higher energy densities, but so far have issues such as high cost and restricted cycle life.

B. Energy Management Systems (EMS)

Recent developments in EMS, especially artificial intelligence and machine learning in practice, brought about dynamic and real time optimizations. The advanced EMS systems now rely on previous driving habits, battery health data, and environmental conditions to make intelligent predictions aimed at minimizing energy use and extend battery life. A few model-based works demonstrate that AI-based EMS can help increase energy efficiency by up to 8-15 percent in comparison with the regular rule-based system. In addition, adaptive EMS solutions can integrate more effectively with regenerative braking and V2G functionality, and thereby EVs can deliver electric power to the grid, not only consume electric power. Though these systems can be speculated to promise a lot of benefits, there are still some issues regarding the practicality of implementing such as systems due to it being computationally difficult, too computationally demanding to process in real time, or generalise on various vehicle models and driving situations.

Table 3: AI-based Energy Management System Benefits.

Metric	Traditional EMS	AI-based EMS
Energy Efficiency Improvement	Baseline (0–5%)	8–15%
Battery Lifespan Extension	Minimal	Enhanced via predictive control
Adaptability	Limited	High (real-time driving adaptation)

Table 3 illustrates why the use of artificial intelligence (AI) based energy management systems (EMS) can be better than the conventional rule-based applications, since it results in better energy consumption, longer battery life and better responsive to real-time driving parameters.

C. Power Conversion and Drivetrain Efficiency

The drivetrain efficiency and power conversion efficiency are also part of the power efficiency. Some of the factors that contribute to efficiency include: The key technologies in power conversion are in the bidirectional DC-DC power converters, in advanced inverters, and in highly efficiency electric motors. The use of lightweight drive train materials and the ability to make designs smaller has helped to achieve greater range of vehicles at costs to manufacture that do not rise significantly. Regenerative braking systems are now fitted on most EVs and can help recover up to 30 per cent of the energy dissipated during braking under an ideal situation, as demonstrated in simulation studies and using modelling and simulation tools, such as MATLAB/Simulink. Nevertheless, real energy recovery is a variable influenced by the road gradient, the driving style and the battery charge level. Combination of such systems with EMS increases the value even more but is more sensitive and has to be perfectly coordinated to prevent energy overload or uneven load sharing.

Table 4: Regenerative Braking & Power Conversion Summary.

System Component	Efficiency / Recovery Rate	Notes
Regenerative Braking	10–30% energy recovery	Depends on terrain, driving style
DC–DC Bidirectional Converter	92–96%	Supports energy flow in both directions
Inverter and Motor Drive	85–95%	Higher with optimized control algorithms

Table 4 also specifies the performance of regenerative braking and power conversion elements and shows that the regenerative efficiency can go up to 30 percent and that bidirectional converter and inverter-motor drive designs have efficiencies of above 90 percent.

D. Performance and Sustainability Impact of Integrated System

A combination of these three systems, storage-management and conversion benefits multiplies. An example is hybrid energy packs (solid-state) and AI-optimized EMS and regenerative braking systems, which increase the actual driving range by up to 25%. What is more, the lifecycle assessments, provided by the recent research, verify that smart EV architectures can consume 40 per cent less greenhouse gases throughout the life cycle of the car use with renewable sources of power. Still, the majority of reviewed articles indicate that such outcomes are conditional on the thoughtful incorporation of components and an adequate test within a real use situation.

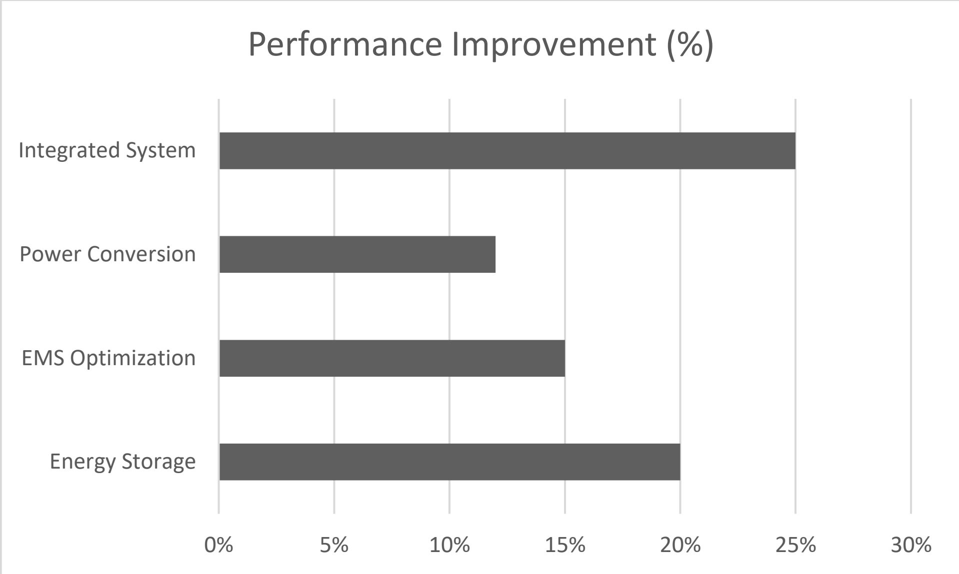

Figure 3: Estimated performance improvements across EV subsystems.

Figure 3 demonstrates the estimated improvement in the efficiency of the important subsystem in an electric vehicle (EV) indicating the contribution of performance by each subsystem. Integrated System can deliver a 25 percent improvement, with Energy Storage ranking second at 20 percent, EMS (Energy Management System) Optimization third at 15 percent and Power Conversion in fourth place at 12 percent. These numbers imply that integrating systems in the batteries of EVs results in the most marked efficiency advantages and that the changes in energy storage and optimization are also vital roles in perfecting the overall performance of the vehicle.

Overall, the individual parts have already shown remarkable improvement, but the overall results indicate that the smartest way of improvement is to combine the sub-systems. That is why future studies have to place a greater priority on the holistic approach to designing systems, standardization processes, and affordable production channels to achieve both technological superiority and commercial feasibility in smart and sustainable EVs.

V. CONCLUSION

Two main areas of concern when it comes to smart and sustainable electric vehicle (EV) development that are essential regarding energy storage, management, and conversion systems are outlined in this review. Although lithium-ion batteries are still in use, new technologies, including solid-state and lithium-sulfur batteries, will be able to provide higher energy density and safety. At the same time, real-time optimizations, battery life, vehicle efficiencies are being achieved through artificial intelligence-based energy management systems. Other advances in power conversion such as bidirectional converters and regenerative braking also improve energy use and grid communication. There are remaining issues of scaling issues, integrating issues and standardizing issues. The greatest advancements can be appreciated when such subsystems are created to work together to create a smart, adaptive living environment. In order to achieve the potential of EVs to achieve climate objectives and sustainable mobility, future interdisciplinary effort should be established on affordable manufacturing, smart system integration, and affordable production. A combination of these developments has the potential to lead to the realization of electric vehicles that will not only be highly capable but also sustainable and cost effective.

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