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A Comprehensive Study of Electric Vehicle Charging and Energy Storage System Management

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ABSTRACT

Recent EV technology research focuses on charging infrastructure and storage. In this paper, a review is conducted on off-grid (standalone), grid-connected, and hybrid charging infrastructures for electric vehicle battery charging operations. Charging techniques integrated with different grid topologies are being studied to improve EV lifetime and efficiency. EVs are multienergy systems that need optimization of power control to efficiently utilize resources. The charging methods are also reviewed to highlight a fast and efficient charging approach that prolongs cell cycle life and charges efficiently. Our methodology, results, and implications are further elucidated in the subsequent sections. Methodology that is first revealed: a variety of challenges and issues are revealed, and the various varieties of electric vehicles (EVs) are described. Secondly, the inventory encompasses the appropriate EV and ESS models. In this examination, Section 3 provides information about energy management systems and the analysis explains how EV charging loads dynamically adjust their charging expectations to align with the time-of-use power price, utilizing demand response techniques. Conclusion provides a summary of contributions and suggests a variety of potential future research areas.

Keywords: Power distribution grid; Electric vehicles; Peak shaving; V2G; Connected vehicle network.

1. INTRODUCTION

A comprehensive evaluation of various charging schemes—reveals their efficacy in specific scenarios. Hybrid charging, which integrates CC and CV methodologies, optimizes charging efficiency and minimizes charging time. Furthermore, the integration of ESS into EV infrastructure enhance grid stability, balance energy supply and load management. Novel approaches, such as dynamic energy storage management algorithms, provide adaptive solutions to fluctuating supply and demand conditions, ensuring both energy efficiency and grid reliability (Aljehane and Mansour, 2022). This manuscript explores the contribution of electric vehicles (EVs) in facilitating the integration of renewable energy sources into the power grid. Studies highlight how EVs can reduce renewable energy surpluses, particularly through interactions with wind and solar energy. Despite extensive research on wind-EV integration, studies on photovoltaic (PV)-EV synergy remain limited, presenting an opportunity for further exploration (Colmenar-Santos *et al.* 2019). Plug-in electric vehicles (PEVs) powered by renewable sources like solar and wind offer a more environmentally friendly alternative to conventional vehicles, reducing dependency on fossil fuels and enhancing sustainability.

The review further investigates emerging smart charging solutions, such as vehicle-to-grid (V2G) systems, which capitalize on EVs' ability to act as distributed energy resources (DERs). This interaction between EVs and the grid facilitates innovative solutions for renewable energy integration while addressing challenges in grid stability and energy management. The growing adoption of EVs—rising from 450,000 in 2015 to over 2.1 million by 2019 globally—highlights the urgency of addressing these challenges to sustain the momentum of EV deployment (Gaurav *et al.* 2019).

By addressing the gaps in existing research, this review seeks to provide a structured analysis of EV charging infrastructure, focusing on off-grid, grid-connected, and hybrid systems. It also emphasizes the role of ESS in balancing energy needs the role of electric vehicles (EVs) in supporting the integration of renewable energy into the electricity system.

The key questions explored in this review include:

1. How do various EV charging infrastructures compare in terms of efficiency, cost-effectiveness, and sustainability?

2. What role do ESS play in optimizing energy management and ensuring grid stability?

3. How can renewable energy sources be effectively integrated into EV charging systems?

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4. What technological advancements and barriers influence the widespread adoption of advanced EV charging systems?

This review aims to bridge the knowledge gaps and provide actionable insights for researchers, policymakers, and industry stakeholders working to develop sustainable EV charging solutions.

Forecasting suggests that plug-in electric vehicles (PEVs) have the potential to reduce oil consumption and greenhouse gas emissions. However, during peak hours, it can increase the demand for electricity and force the need for more generation. This increases consumers' overall electricity costs (Gerengi and Sahin, 2012). It is important to assess and contrast various charging methods, including constant voltage or constant current, in order to determine their effectiveness in specific situations. Hybrid charging schemes use CC and CV methodologies to optimize efficacy and minimize charging time. Energy Storage System (ESS) The integration aims to optimize energy storage system management, enabling efficient electric vehicle (EV) charging while ensuring power grid stability. This involves assessing the potential synergy between EV charging infrastructure and energy storage systems (ESS) in areas such as reserve power, energy storage, and load balancing. The creation of dynamic energy storage management algorithms that can swiftly adjust to fluctuating supply and demand conditions is a novel discovery (Gropi *at al.* 2021).

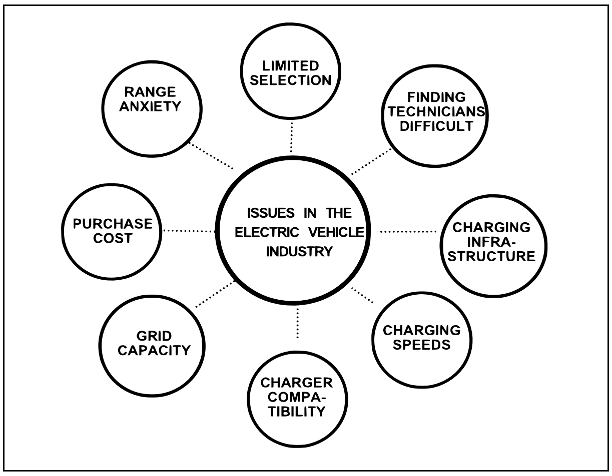
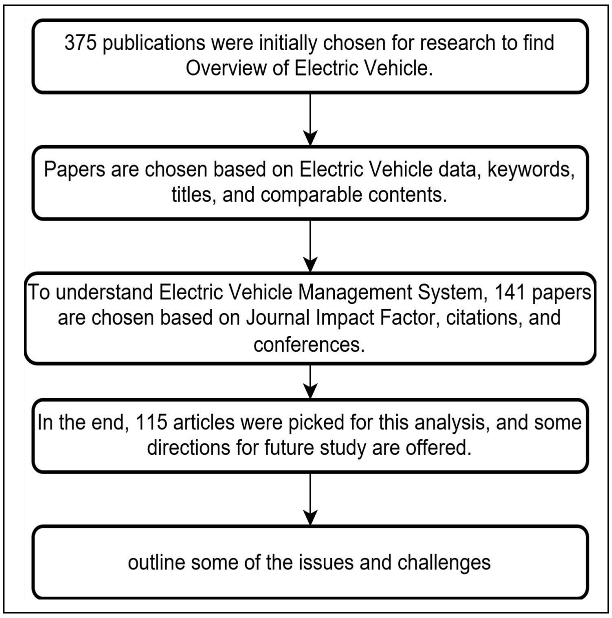


Fig. 1: Issues in the electric vehicle industry

Electric cars (EVs) will increase, creating opportunities for vehicle-to-grid services, yet they may cause distribution grid issues. Figure 1 illustrates the primary challenges that the electric vehicle (EV) industry is now facing (Harish and Surendra, 2012; Kapustin and Gureshevenko, 2020). EVs can be used as distributed energy resources (DERs) and affect micro grid DER investment and scheduling. When charging at home, at least 24% of vehicles are available at charging stations throughout the day in all nations. At least 45% of workers may charge at work and are constantly ready. About 5 million electric vehicles are registered worldwide. Sales of EVs have increased in the US (2%), Portugal (3%), China (5%), Ireland (7%), the Netherlands (8%), and Norway (50%) among other nations. EV demand has skyrocketed, and by 2019, 2.1 million people will drive them, up from 450 thousand in 2015. Electric vehicles (EVs) are realistic grid/Microgrid ESSs with synchronized charging to compensate for wind and solar power fluctuations. Energy management systems predict peak load periods to ensure EV access. Integrating renewable energy sources into the electrical grid allows innovative G2V and V2G systems (Li *et al.* 2022).

2. REVIEW METHODOLOGY

This analysis shows that we read research papers that Scopus and Google Scholar have to offer that cover the Web of Science. In the beginning, 375 articles were chosen for the downloading research by employing keywords, titles, and other containers in a similar fashion. Based on journal impact factors, conferences attended, citations, and reputable websites, the author examined 141 articles.


375 publications were initially chosen for research to find Overview of Electric Vehicle.

Papers are chosen based on Electric Vehicle data, keywords, titles, and comparable contents.

To understand Electric Vehicle Management System, 141 papers are chosen based on Journal Impact Factor, citations, and conferences.

In the end, 115 articles were picked for this analysis, and some directions for future study are offered.

outline some of the issues and challenges

Fig. 2: Methodology for conducting the review, in brief

This research analyzes 115 papers, with over 85 published in the last four years, emphasizing the latest advancements in EV charging infrastructure and ESS management. The study is structured into five key stages:

1. Comprehensive Literature Review: A thorough review of EV-relevant energy storage systems (ESS) and charging infrastructures was conducted to identify trends and gaps in the research.

2. Evaluation of Energy Storage Systems: An overview of ESS technologies relevant to EVs, including their integration with microgrids, wind, photovoltaic (PV) systems, and EV charging stations (EVCS), is presented.

3. Assessment of Energy Management Systems: The role of EMS in optimizing charging efficiency, grid stability, and renewable energy integration is analyzed.

4. Identification of Challenges: Key issues such as range prediction accuracy, charging infrastructure design, and ESS deployment challenges are discussed.

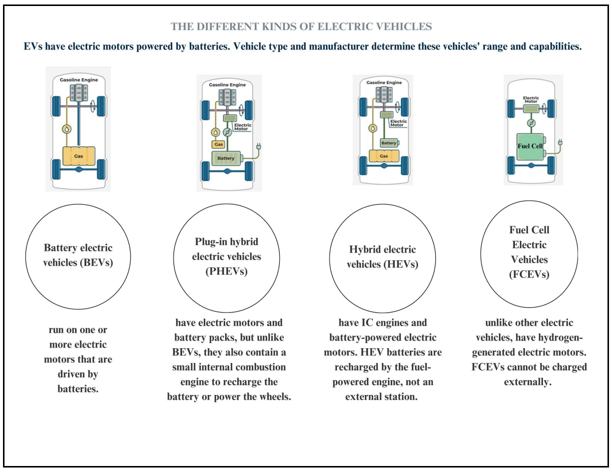
5. Recommendations: Practical solutions for overcoming identified obstacles are proposed, aiming to enhance EV adoption, improve user experience, and support infrastructure development.

A visual summary of these research stages is illustrated in Figure 2. A brief summary of key authors and important literature: • Major Contributor 1: (Li *et al.* 2021) found that a microgrid with an ESS, wind, PV, and EVCS helps electric car adoption. The main discovery is EV parameter estimation and robust optimisation.• Major Contributor 2: (Marulasiddappa and Pushparajesh, 2023) uses machine learning to predict EV range. These contributions have established a robust foundation; however, they also underscore numerous deficiencies, including the necessity for precise range prediction in order to enhance the user experience, EV adoption, and charging infrastructure design. Based on this investigation, several concerns and obstacles are highlighted. Finally, some recommendations for solving the problem with EV systems are provided.

3. ELECTRIFIED VEHICLE TECHNOLOGY

As plug-in electric vehicles (PEVs) become more widespread, electricity demand and mobility needs rise (Patel *et al.* 2021). Mobility is not considered in electricity planning or management. Transmission capacity is running out as renewable energy sources (RES) grow in the global energy market (Pang *et al.* 2018).

By connecting electric vehicles to the power grid, Customers' behaviors dictate the effect's extent, but VGI benefit value evaluations rarely consider this. The economic benefits of implementing the ideas using the power pricing model (Raja *et al.* 2021). Figure 3 illustrates the various types of electric vehicles (Schermeyer *et al.* 2021). As plug-in electric vehicles (PEVs) become more popular, electricity demand and mobility need rise. Mobility is not considered in electricity planning or administration. BEVs rely completely on battery-stored electricity. To regain SE, a vehicle must recharge its battery pack at a charging station using regenerative braking. Battery upgrades boost a battery-electric vehicle (BEV)'s range from 100 to 400 km per charge (Schenke and Wallscheid, 2021).

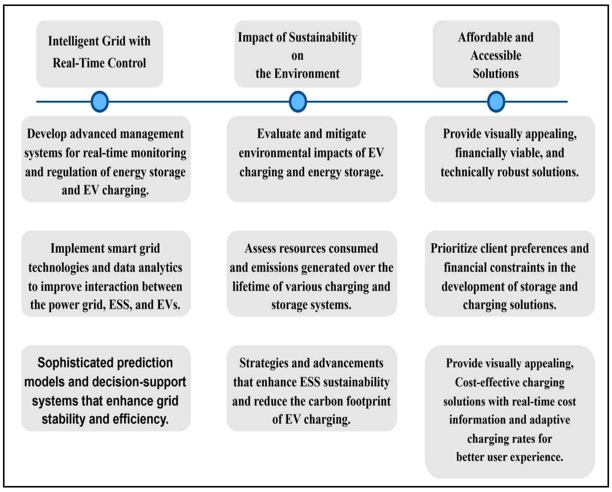


THE DIFFERENT KINDS OF ELECTRIC VEHICLES

EVs have electric motors powered by batteries. Vehicle type and manufacturer determine these vehicles' range and capabilities.

Battery electric vehicles (BEVs)	Plug-in hybrid electric vehicles (PHEVs)	Hybrid electric vehicles (HEVs)	Fuel Cell Electric Vehicles (FCEVs)
run on one or more electric motors that are driven by batteries.	have electric motors and battery packs, but unlike BEVs, they also contain a small internal combustion engine to recharge the battery or power the wheels.	have IC engines and battery-powered electric motors. HEV batteries are recharged by the fuel-powered engine, not an external station.	unlike other electric vehicles, have hydrogen-generated electric motors. FCEVs cannot be charged externally.

Fig. 3: Different kinds of electric vehicles



Intelligent Grid with Real-Time Control	Impact of Sustainability on the Environment	Affordable and Accessible Solutions
Develop advanced management systems for real-time monitoring and regulation of energy storage and EV charging.	Evaluate and mitigate environmental impacts of EV charging and energy storage.	Provide visually appealing, financially viable, and technically robust solutions.
Implement smart grid technologies and data analytics to improve interaction between the power grid, ESS, and EVs.	Assess resources consumed and emissions generated over the lifetime of various charging and storage systems.	Prioritize client preferences and financial constraints in the development of storage and charging solutions.
Sophisticated prediction models and decision-support systems that enhance grid stability and efficiency.	Strategies and advancements that enhance ESS sustainability and reduce the carbon footprint of EV charging.	Provide visually appealing, Cost-effective charging solutions with real-time cost information and adaptive charging rates for better user experience.

Fig. 4: A concise overview of the significant and academic contributions

The most effective methods for charging hybrid vehicles are as follows: The work introduces and verifies hybrid charging strategies that incorporate CC and CV methodologies, thereby contributing to the field. Energy storage systems that dynamically adjust to real-time data improve grid stability, electric vehicle charging, and energy storage efficiency. Figure 4 presents a brief summary of the significant academic contributions. Smart grid technologies and powerful predictive models simplify network, energy storage, and electric vehicle (EV) management. By making electric vehicle (EV) charging and storage systems more sustainable, current energy management can be improved. This extensive study offers innovative energy storage and EV charging system management strategies (Cardoso *et al.* 2014).

To enhance the manuscript, a discussion on future technological advancements in EV charging infrastructure should be included, focusing on emerging technologies that could significantly transform the industry.

Ultra-fast charging is one such advancement, aiming to drastically reduce charging times to just a few minutes, similar to refueling a traditional vehicle. These chargers could use higher voltage and current levels, as well as advanced cooling systems, to handle the intense power requirements while minimizing energy loss and heat generation (Fendany *et al*. 2023).

Wireless charging is another promising technology that eliminates the need for physical connectors. Through inductive charging, vehicles can charge without being physically plugged into a charging station. This technology could be integrated into roads, allowing for dynamic charging while driving, or used in stationary charging pads at parking spots, providing a seamless and convenient user experience.

AI-driven charging optimization systems offer significant potential in enhancing charging efficiency and grid management. Artificial intelligence can control energy flow between EVs, charging stations, and the grid, forecast energy consumption, and optimise charging plans depending on current grid circumstances.AI can also improve battery life by adjusting charging rates according to factors like battery health, environmental conditions, and user preferences. These innovations combined with the incorporation of renewable energy and advancements in energy storage, could greatly improve the sustainability, efficiency, and convenience of EV charging, playing a crucial role in the transition to electric mobility (Wang *et al*. 2023).

3.1 E-Vehicle Charging Stations

Electric vehicle growth depends on cost; it provides innovative, beneficial ways to overcome present restrictions and add value to the area (Dominguez *et al.* 2019). Freedom, recharge time, and infrastructure. This study discusses a fast-charging station for electric cars (EVs) to boost profits and reduce grid energy demand (Sedding *et al.* 2019). Demand-side resources and storage technologies can shift flexibility requirements from generating to loading, easing the power grid's future issues from intermittent and non-dispatchable wind and solar energy production.

Various forms of Energy Storage Systems are illustrated in Figure 5 (Shi *et al.* 2020). The four types of energy storage systems (ESS) suitable with electric vehicles (EVs) are electrochemical storage, electromagnetic storage, chemical storage, and hybrid storage systems. Every ESS is unique in some manner. Energy Storage Systems (ESS) are essential components of contemporary EV charging infrastructure because they solve issues with energy supply and demand, especially during peak hours and in situations where renewable energy sources like wind and solar are erratic. ESS aids balance varying energy needs.

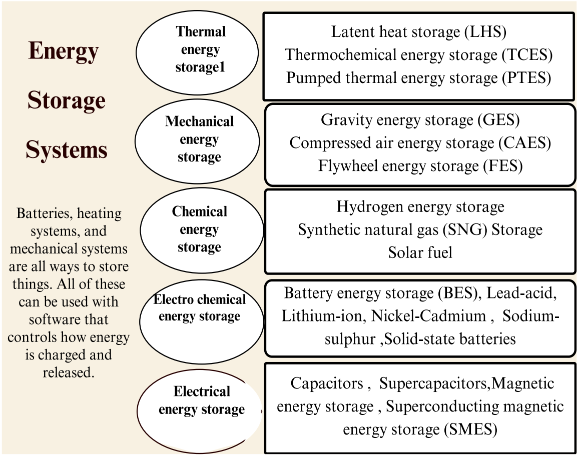


Fig. 5: Energy storage systems

Additionally, by accumulating surplus energy generated during periods of elevated renewable production and discharging it during intervals of diminished generation, ESS help to integrate renewable energy. This ensures a steady power supply for EV charging by mitigating the intermittent nature of renewable energy sources. By accumulating lower-cost electricity during off-peak periods and discharging it during peak periods, ESS also facilitate time-of-use shifting, which lowers system congestion and saves money (Kondoh *et al.* 2020). ESS act as a buffer to guarantee steady charging at times of high EV demand or low renewable generation, averting grid interruptions. Technological advancements in Energy Storage Systems, such as enhanced lithium-ion batteries and novel flow battery technologies, are augmenting their efficiency and scalability for electric vehicle charging infrastructure. Lithium-ion batteries offer high energy density and fast charging capabilities, making them ideal for use in EV charging stations. Meanwhile, flow batteries, with their ability to store energy for longer durations, are being explored for large-scale applications. Additionally, AI-driven energy management systems optimize the charging and discharging cycles of ESS based on real-time data, such as weather forecasts and grid conditions (Deane *et al.* 2014). These systems can predict energy demand and adjust the energy flow accordingly, ensuring optimal performance and reducing costs. In summary, ESS are crucial for optimizing the performance and sustainability of EV charging infrastructure, enabling efficient renewable energy integration, grid stabilization, and long-term environmental benefits, with technological advances further improving their capability and efficiency. Appropriate ESS not only permits the client to reserve electricity for an extended duration but also reduces electricity costs. Researchers and manufacturers are working diligently to enhance ESS performance and develop a cost-efficient battery (Singh *et al.* 2018). The manufacturing award policy could be suspended or combined with other electric car quality standards (Sterchele *et al.* 2020; Subramanian and Das, 2019).

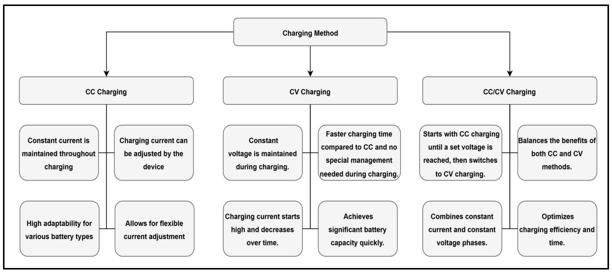


Fig. 6: Battery charging methods

The future of electric vehicles depends on price, range, charging speed, and station availability as shown in figure 6. The station uses wind and photovoltaic energy and storage technology (Subramaniya *et al.* 2023) to make fast-charging stations more profitable and lessen power grid pressure. Electric vehicle-to-grid (V2G) interface technology increases renewable energy utilization and system reliability. Renewable energy can power a microgrid and a bigger grid to tackle intermittent power generation. Electric vehicles are becoming more popular and renewable energy output is unpredictable (Sun, 2021).

Centralized and decentralized control for microgrids are shown in Figure 7. Centralised control (CC) is used in microgrids (MGs) to manage and supervise the system. Decentralized control in microgrids refers to the autonomous operation of each individual entity using a local controller (LC) (Suroso *et al.* 2024; Syranidis *et al.* 2018).

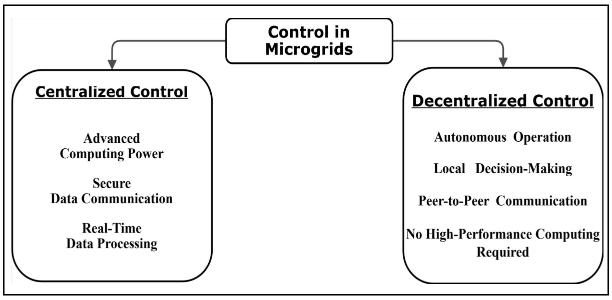


Fig. 7: Centralized Control and Decentralized Control in Microgrids

Regional profile simulations optimize dispersed wind and solar capacity planning for EV charging (Wan der Walt *et al.* 2018). Comprehensive academic research has examined the global expansion of battery electric vehicles (BEVs), a sustainable technological achievement. Rapid charging facilities are needed to grow the electric vehicle (EV) market. The electrification of the transport sector is being studied as one of the technologically feasible solutions to the deteriorating climate change problems.

Because of this dependence, effective energy management is required, which is predicated on optimising the vehicle's energy system's design and functionality (production, storage, and consumption) (Wang *et al.* 2021). Traditional optimization, artificial intelligence, hybrid, and cutting-edge planning optimization strategies are the five primary categories. The number of electric vehicles (EVs) has significantly increased over the past decade, This may put stress on the electrical grid when demand for power is high (Wies *et al.* 2014).

Widespread, uncoordinated EV charging has an adverse effect on the operation of the electrical grid. Table 1 shows that EVs under various transport electrification scenarios need more power, energy density, and ESS lifespan (Wolinetz *et al.* 2018).

Table 1. Electric vehicle (EV) market share under various transport electrification scenarios

Description	EV30@30 campaign	EV @2047 campaign	Progressive
Two-wheelers(2W)	30% by 2030	100% by 2047	100% by 2040
Three-wheelers(3W)	30% by 2030	100% by 2047	100% by 2040
Passenger cars (PC)	30% by 2030	100% by 2047	100% by 2047
Utility and multi-purpose vehicles	30% by 2030	100% by 2047	100% by 2047
Light-duty bus	30% by 2030	100% by 2047	100% by 2044
Light-duty truck	28.1% by 2030	100% by 2044	100% by 2044
Heavy-duty bus	30% by 2030	100% by 2047	100% by 2047
Heavy-duty single unit and combination trucks	10% by 2030	100% by 2060	100% by 2060
Medium-duty truck	10% by 2030	100% by 2060	100% by 2060

3.2 Batteries

Primary batteries are responsible for storing energy through a chemical process, while secondary batteries convert that energy into electricity. Electric vehicles use secondary batteries that are electricity-powered and have a higher specific energy. As the sole source of power for advancements in battery technology have significantly influenced the development and growth of electric vehicle (EV) transportation (Xu *et al.* 2018). First-generation electric vehicles were powered by lead-acid batteries. Since then, scientists have been working hard on the EV system, developing concepts for stronger and more efficient storage batteries. Electric vehicles require battery efficiency, high temperature tolerance, extended cyclic life, and high cyclic power. Electric vehicles use rechargeable batteries such as lead-acid, sodium sulphur, zinc air, nickel-based, and lithium-ion (Yan *et al.* 2020).

Table 2. Electric battery parameters

Name	Li-Ion	Na-NiCl$_2$	Ni-MH	Li-S	Unit
Maximum Charge	75	84	85	80	Ah
Nominal Voltage	323	289	288	305	V
Stored Energy	24.2	24.2	24.2	24.2	kWh
Maximum / Minimum Voltage	339 / 308	275 / 304	274 / 302	290 / 320	V
Initial Charge	100	100	100	100	%
Number of Cells per Cell-Row	12	12	20	26	-
Internal Resistance charge/discharge	1 / 1	1 / 1	1 / 1	1 / 1	Ω
Specific Heat Transition	0.4	6	0.4	0.08	W/K
Mass of Battery	318	457	534	173	kg

3.3 Supercapacitor

The capacity of a supercapacitor to store energy depends on electrodes, electrolytes, ionic size, and the voltage required to break down the electrolyte. Supercapacitor is equivalent to UC or Supercapacitors, or ultra-capacitors, are increasingly recognised as viable substitutes for batteries owing to their superior specific power, rapid initial charging, extended cyclic lifespan (up to one million cycles), and reduced weight. Researchers are concentrating on improving performance for applications that necessitate rapid energy storage and release, rendering them suitable for sectors such as electric vehicles and renewable energy systems. These advantages render supercapacitors a potential technology for energy storage applications (Zhou *et al.* 2020).

3.4 Technological Barriers to Advanced EV Charging Adoption

The widespread adoption of advanced electric vehicle (EV) charging systems is hindered by several technological barriers in the areas of hardware, software, and communication technologies. These challenges must be addressed to ensure the efficient, scalable, and reliable deployment of EV charging infrastructure (Lin *et al.* 2022).

Hardware Challenges involve the need for standardized charging connectors, voltages, and protocols across various EV models and regions. The lack of universal standards leads to compatibility issues, making it difficult for users to find compatible charging stations. Additionally, advanced charging systems, particularly ultra-fast chargers, require substantial investments in hardware that can handle high power levels (e.g., 350 kW or more), which is not always feasible due to grid capacity limitations. Moreover, ensuring the durability and longevity of charging stations, especially high-power ones, is crucial. These stations are exposed to frequent use and environmental conditions, leading to wear and tear and, consequently, high maintenance costs (Wu *et al.* 2019). ESS must efficiently store and discharge energy, and current battery technologies face issues such as limited capacity, high costs, and shorter lifespans, making their widespread adoption more complex.

Software Challenges primarily revolve around the need for sophisticated charging management systems that can handle large volumes of data from multiple charging stations and EVs. These systems must optimize energy distribution, particularly during peak demand periods, to avoid grid overloads and maintain charging efficiency. Additionally, user experience plays a critical role in the success of EV charging networks. Software platforms must offer seamless experiences for users, such as real-time availability of charging stations, easy payment systems, and interoperability between different networks. Furthermore, smart charging algorithms are required to optimize when and how EVs are charged based on factors like grid conditions, energy demand, and the health of the vehicle's battery. Efficient charging optimization helps prevent battery degradation while ensuring that energy is used effectively (Mosetlhe *et al.* 2021).

Communication Technologies also pose significant challenges. For advanced charging systems to function effectively, there needs to be standardized, secure, and simultaneous communication among electric vehicles, charging stations, and the power grid. Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) technologies, which allow energy to flow both ways between the EV and the grid, require a robust communication protocol to manage this bi-directional energy exchange. However, the lack of universal standards for V2G and G2V communication and the absence of secure data protocols create barriers to their effective implementation. Additionally, the interoperability of charging networks is essential for users to seamlessly access charging stations across different providers. This requires standardized communication to enable roaming between networks. In addition, interaction with the grid is crucial for load balancing and the incorporation of intermittent renewable energy sources such as solar and wind. Charging stations must engage in real-time communication with grid operators to modulate energy consumption according to supply and demand dynamics (Li *et al*. 2021).

Overcoming these hardware, software, and communication barriers will be critical for ensuring the reliable, cost-effective, and user-friendly adoption of advanced EV charging systems. Standardization, improved charging infrastructure, advanced software for smart charging, and robust communication technologies will collectively enhance the efficiency of EV charging networks, promote for the incorporation of renewable energy sources and facilitate the worldwide shift towards electric mobility (Bilal *et al.* 2023).

4. INTEGRATION OF RENEWABLE ENERGY IN OFF-GRID AND HYBRID EV CHARGING SYSTEMS.

The incorporation of renewable energy sources, including solar and wind power, into off-grid and hybrid electric vehicle charging systems signifies a substantial progress towards establishing sustainable and robust charging infrastructure. This section explores how renewable energy impacts the efficiency, cost-effectiveness, and sustainability of these systems compared to traditional grid-connected charging systems.

4.1. Energy Efficiency

Off-Grid Systems: Renewable energy integration in off-grid systems ensures that EV charging is independent of the main power grid, reducing energy losses associated with long-distance power transmission. These systems leverage localized renewable energy generation which minimizes inefficiencies and improves overall energy utilization. Example: Solar-powered EV charging stations in remote locations achieve near-zero reliance on fossil fuels, improving energy efficiency substantially (Fang *et al.* 2021).

Hybrid Systems: By combining grid electricity and renewable sources, hybrid systems optimize energy use based on availability and demand. For instance, during sunny or windy periods, the system prioritizes renewable energy, reducing dependence on the grid.

4.2. Cost-Effectiveness

Renewable Energy Benefits: Utilizing free energy from the sun or wind reduces operational costs over time. Although the initial capital investment for renewable infrastructure is high, the long-term savings in energy costs make these systems economically viable. Studies show that hybrid systems with renewable integration have lower lifecycle costs compared to solely grid-connected systems, especially in areas with high electricity tariffs or unstable grids.

Challenges: High upfront costs for installation and storage solutions (e.g., ESS) remain a barrier. However, government subsidies and advancements in renewable technologies are steadily mitigating these challenges (Al-Shetwi *et al.* 2020).

4.3. Sustainability

Environmental Impact: The integration of renewable energy significantly reduces carbon emissions associated with electric vehicle charging, enhancing the sustainability of off-grid and hybrid systems. By eliminating or minimizing reliance on fossil fuels, these systems support global climate goals. Example: Wind-powered EV charging systems in coastal areas achieve near-zero carbon emissions.

Grid Decarbonization: Hybrid systems play a pivotal role in supporting the transition to decarbonized grids. These devices improve grid stability and facilitate the wider use of clean energy by reintegrating surplus renewable energy into the grid.

4.4. Comparison with Grid-Connected Systems

- **Energy Efficiency**: Grid-connected systems rely on centralized power plants, often leading to energy losses during transmission and distribution. In contrast, off-grid and hybrid systems localize energy generation, significantly reducing these losses.

- **Cost-Effectiveness**: While grid-connected systems have lower initial costs due to existing infrastructure, the rising cost of grid electricity diminishes their economic advantage over time, especially in regions with abundant renewable resources.

- **Sustainability**: Traditional grid-connected systems are often powered by a mix of renewable and non-renewable sources, leading to a higher carbon footprint compared to fully renewable off-grid or hybrid systems (Barakat *et al.* 2024).

5. BATTERY MANAGEMENT SYSTEM

Electric vehicles (EVs) powered by lithium-ion batteries are becoming more popular and valuable as greener transportation. BEV and HEV systems benefit the world economy and environment. The battery management system and Electric Vehicle system management infrastructure coordinate the battery's cells, energy transmission, and control infrastructure. Based on battery current and charging conditions, the Battery monitoring optimizes daily operations, security, and power distribution. Cell monitoring, overcharging and undercharging protection, heat and temperature monitoring, staying connected, data accumulation, and fault evaluation are essential (Meng *et al.* 2024). This work presents control structures and strategies from the literature, emphasizing their advantages and disadvantages in the context of Energy Storage System Management and Electric Vehicle Charging. Electric vehicles reduce oil and greenhouse gas emissions. However, peak hours may increase electricity demand, necessitating more generation. Demand shifting saves billions, but it only slightly lowers electricity bills. In all cases, time-of-use pricing is favorable, but optimal electric vehicle charging does not appear to justify the cost of smart grid infrastructure for real-time pricing.

Although numerous governments and countries have set goals to reduce greenhouse gas emissions by 2030, this review covers EV, renewable energy, and power generation studies. Power capacity from wind and photovoltaic solar is growing rapidly. Power generation uncertainty complicates the planning, management, and control of power system networks. EVs will encourage vehicle-to-grid services, but they may strain distribution systems (Hajiaghaei-Keshteli *et al.* 2023).

Proper energy management (EM) in microgrid (MG) systems is essential for enhancing overall system performance, reducing electrical costs, and extending the lifespan of key components such as converters, batteries, and fuel cells. Effective EM involves optimizing various factors to achieve several objectives, including:

- Maximizing Efficiency: Enhancing the efficiency and minimizing energy consumption.
- Improving Service Quality: Ensuring a high quality of service for consumers.
- Reducing Costs: Lowering electricity bills and overall system costs.
- Extending Component Life: Prolonging the lifespan of system components.

Energy management in microgrid systems involves balancing technical, economic, and environmental objectives through various approaches, including exact, stochastic, and predictive methods. Recent research highlights different control strategies for managing microgrid systems, such as centralized, decentralized, and hierarchical approaches. Predictive control stands out due to its ability to handle multiple objectives and constraints, integrating optimal control with flexible and robust processes. Typically, energy management strategies aim to maximize efficiency and minimize energy use while improving service quality. Some strategies focus solely on electricity availability, switching between renewable energy sources (RES), storage devices, and the utility grid without considering electricity prices or system profitability. Others might limit power generation to ensure service quality, potentially compromising battery life, installation costs, and overall profitability. Table 3 compares the control approaches based on various criteria (Shezan *et al.* 2022).

Table 3. Comparison of EV charging techniques

Charging Method	Fast Charging	Slow Charging	Optimized Charging
Charging Speed	High (30 minutes to 1 hour)	Low (8-12 hours)	Varies (smart charging)
Battery Life Impact	Reduces lifespan by 20-30% due to higher stress	Minimal impact on lifespan, extends battery life	Maximizes lifespan, optimal balance
Degradation Impact	Accelerates chemical degradation (higher heat and current)	Minimal degradation, least damaging to battery chemistry	Minimizes degradation through adaptive charging based on battery state
EV Performance Impact	Reduces range over time as capacity diminishes	No noticeable decrease in range if used infrequently	Maintains consistent range, better long-term performance
Pros	Quick charging time, convenient for urgent needs	Gentle on battery, extends battery lifespan	Efficient energy usage, prolongs battery health, good for long-term use
Cons	Increased battery wear, higher cost, heat generation	Time-consuming, may not be convenient for everyday use	Slightly slower than fast charging, may require smart systems or algorithms

The ongoing advancements in the functionality of commercial inverters, which currently manage power flows among various sources and loads with high efficiency, typically focus solely on meeting load demands. These inverters often overlook other factors, such as electricity prices and battery health. Recent improvements include integrating IoT and big data technologies, which have boosted system performance by enabling better control and prediction (Al Wahedi and Bicer, 2022). The integration of machine-learning algorithms is crucial for analysing data and forecasting actions in energy management (EM) for microgrid systems. We are developing new smart inverters to manage multiple objectives and constraints. These inverters will support predictive control strategies, allowing for real-world testing with specific constraints. The goal is to create MG networks that use IoT and Big Data for energy and data exchange, facilitated by a platform based on predictive control of these advanced smart inverters. The control approach for MG systems includes model predictive control, adaptive droop, artificial neural networks, distributed cooperation control, conventional droop, fuzzy logic-based control, and multi-agent-based control. Each approach has its advantages and disadvantages, such as reliability, flexibility, redundancy, and complexity. However, each approach requires advanced ICTs, pre-definition of control parameters, and complex coordination (Polisetty *et al.* 2024).

Table 4. Comparison control methods on several criteria

Control Approach	Advantages	Disadvantages	ICT Requirement	Pre-definition Required	Coordination Complexity
Model Predictive Control	Robust against uncertainty; Optimal control; Handles multiple objectives	Requires advanced ICTs; Control parameters need pre-definition	High	Yes	High
Adaptive Droop	Eliminates overload conditions; Minimizes circulating current	Difficult voltage level selection; Requires prior information	Medium	Yes	Medium
Artificial Neural Networks	Handles nonlinear data; Self-learning; Stability and fault tolerance	Complex model structure; Experimental interpretation challenging	High	No	High
Distributed Cooperation Control	Optimal coordination; Flexible and robust	Less security in communication; Frequency response visualization issues	Medium	No	Medium
Conventional Droop	Easy primary control implementation	Voltage regulation issues; Degradation in current sharing	Low	No	Low
Fuzzy Logic-Based Control	Improved voltage and frequency regulation; Effective power sharing	High processing requirements; Time-consuming participation methods	Medium	No	Medium
Multi-Agent-Based Control	Addresses large problems; Flexibility; Redundancy; Meets global constraints	Potential conflicts; High connectivity needs; Complex agent coordination	High	No	High

6. CONCLUSION

The electric vehicle (EV) industry has expanded to include charging methods and its infrastructures, renewable energy systems, EVs, grid- connected systems, and EV structures. Multi-source EV charging requires control and power management. This assessment covers EV categories, charging infrastructure, technology, power management, and controls. First, we analyzed EV structural topologies and their pros/cons. The main differences and uses of charging stations and methods are compared in this article. Systematic EV technology study may help researchers and engineers build future innovations. Research must improve to handle grid-connected charging stations and renewable energy sources AI-based control algorithms that estimate charging related data, different ranges, and costs may make better decisions. Theft of charging infrastructure, vehicle locations, owners, and payment information is dangerous. Hackers can also disable electric vehicle remote controls. Additionally, cyber security, resilience, and reliability must be examined to safeguard user and grid data from hostile attacks. To meet the demand for electric vehicles and consumer goods and services, business and public policy must change. Innovative business and regulatory solutions for motorists will increase EV adoption. Soon, more research subjects may be sought. This extensive survey should inspire additional investigation.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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