iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: V Month of publication: May 2025

DOI: https://doi.org/10.22214/ijraset.2025.71909

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue V May 2025- Available at www.ijraset.com

Advancements in Electric Vehicle Charging Technologies and Infrastructure: A Comprehensive Review

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Abstract: Infrastructure construction and charging technology have advanced significantly as a result of the growing popularity of electric cars (EVs). This study looks at a number of EV charging methods, including as Level 1, Level 2, and DC fast charging (Level 3). It also looks at new developments like wireless charging, ultra-fast charging systems, and vehicle-to-grid (V2G) integration. The study investigates how these solutions tackle important EV adoption issues like range anxiety, charging speed, and convenience. The study also looks into how electric car charging stations are made and distributed, evaluating how they affect EV accessibility and user experience. This study attempts to shed light on how EV charging infrastructure is changing and how it contributes to sustainable transportation by looking at both present and emerging trends.
Keywords: E-Vehicle (EVs), Charge Station, Hybrid electrical vehicle, Wireless Charging, Renewable Energy.

I. INTRODUCTION

The transportation sector is undergoing a transformative shift toward sustainability, driven by the rapid adoption of electric vehicles (EVs) and advancements in charging technologies [1]. While EVs significantly reduce greenhouse gas emissions and fossil fuel dependence [2, 9], their integration with power grids introduces challenges such as grid instability, uneven charging infrastructure, and unresolved standards for interoperability [1, 3, 11]. Recent research highlights progress in charging methods—including conductive, wireless, and battery swapping systems [5, 8, 13]—and underscores the role of hybrid renewable energy systems in enhancing reliability [4, 17]. However, critical gaps persist, including the lack of global charging protocols [3, 7], insufficient focus on socioeconomic barriers to adoption [11, 16], and limited understanding of long-term battery degradation from fast charging and vehicle-to-grid (V2G) systems [18]. Additionally, while optimization models for charger placement exist [6, 14], real-world implementation strategies remain understudied, particularly in urban-rural contexts [15, 16]. This paper synthesizes insights from 18 seminal studies to identify these gaps and propose actionable solutions for scalable, user-centric EV-grid integration.

II. LITERATURE REVIEW

The following are selected researchers who carried out their work-related Electric Vehicle Charging Technologies and electric vehicle charging stations. The literature presented below is taken from various peer review indexed journals.
Fariborz Musavi et al. (2013): Studies provide a detailed review of wireless power transfer technologies used in electric vehicle (EV) battery chargers, exploring various concepts and evaluating their feasibility in terms of power electronics limitations, cost, and consumer acceptance. The analysis highlights the advantages and challenges of each technology, offering insights into their practicality and current constraints. A comprehensive comparison of these technologies is conducted, leading to the proposal of a hybrid conductive/wireless charging system as a potential solution to address existing issues. This approach aims to enhance efficiency and tackle limitations inherent in current charging methods [8].
Islam Safak Bayram et al. (2020): Studies emphasize the importance of planning charging infrastructure to accommodate the growing adoption of plug-in electric vehicles (PEVs). Research primarily focuses on developing closed-form expressions to solve capacity planning problems at commercial charging stations. Two main scenarios are addressed: determining the optimal service capacity for workplace charging lots, considering predefined parking statistics, and optimizing arrival rates for a given station capacity. Advanced models are proposed to evaluate the optimal customer load for various charger technologies based on their charging rates, with analyses encompassing both social and individual optimality. Markovian queue modeling is utilized to account for interactions among customer load, wait times, and electricity costs, with convex optimization methods providing solutions for

optimal station capacity and arrival rates. Analytical and simulation results reveal significant efficiency improvements, reducing waiting times by 60% and queue lengths by 42%, demonstrating the effectiveness of optimal capacity planning in PEV infrastructure development. [6]

Val Hyginus U. Eze et al. (2021): Investigate the challenges of modeling and enhancing Electric Vehicle (EV) designs, highlighting the potential of hybridized renewable energy sources to address issues of reliability, durability, and charging constraints. EV charging stations are classified based on their power sources—renewable, non-renewable, and hybrid—with a focus on their applicability to EV performance and modeling. The article extensively reviews various designs, battery technologies, efficiency-enhancing (EE) components, and connectors, analyzing their advantages and limitations. A review of 15 recent articles demonstrates the reliability and efficiency of hybridized EV charging stations, emphasizing their benefits in fast charging, priority scheduling, and superior battery backup. The findings provide a valuable guide for researchers and engineers in adopting optimal designs for EV charging infrastructure [4].

Syed Muhammad Arif (2021): Examines advancements in electric vehicle (EV) technology, focusing on charging methods, standards, and optimization strategies. It delves into the features of Hybrid Electric Vehicles (HEVs) and EVs, alongside innovative charging techniques such as Battery Swap Stations (BSS), Wireless Power Transfer (WPT), and Conductive Charging (CC). Additionally, EV standards, including charging levels and configurations, are discussed to highlight system compatibility and efficiency. The review also addresses optimization methods for determining the optimal sizing and placement of EV charging stations, aiming to enhance accessibility and functionality. Based on these insights, the studies propose several recommendations for advancing future research and fostering development within the EV ecosystem. [5].

George Fernandez Savari et al. (2022): Studies comprehensively analyze the advancements in electric vehicle (EV) charging infrastructure, associated technologies, and the challenges linked to identifying appropriate charging stations. The reviewed literature highlights a significant rise in attention toward EVs over the last decade, stemming from concerns about global warming and the predicted scarcity of fossil fuels such as petrol and diesel. EVs are increasingly recognized for their ability to mitigate fuel dependency and reduce emissions, thereby addressing urgent sustainability needs within the transport sector. Researchers have directed considerable focus toward Plug-in Hybrid Electric Vehicles (PHEVs) and EVs, critically examining charging technologies and the infrastructures that support them. The studies further investigate charging power, methods of power transfer between EVs and the grid, and consumer-related concerns in selecting charging stations. Additionally, efforts have been made to propose solutions that simplify and enhance user-friendly charging station selection processes, addressing practical challenges for customers. This comprehensive body of research provides valuable insights into the evolution of EV systems and informs strategies for developing the infrastructure essential for their widespread adoption [2].

SITHARA S. G. ACHARIGE et al. (2023): Highlights the pivotal role of electric vehicles (EVs) in driving the global transition to sustainable energy. The integration of EVs into the power grid presents challenges related to grid planning, operation, stability, and safety standards. To support widespread adoption, advancements in EV charging systems and EV supply equipment (EVSE) are critical for enhancing battery charging solutions and ancillary services. Comprehensive analysis focuses on EV charging technologies, international standards, charging station architecture, and power converter configurations. Dedicated converter topologies, control strategies, and compliance with standards and grid codes are essential for optimizing charging and discharging processes while improving grid support. Key topics include onboard and offboard chargers, AC-DC and DC-DC converter configurations, and the architecture of AC- and DC-based charging stations. Furthermore, integrating renewable energy sources into charging systems is explored, showcasing the evolving powertrain of modern charging infrastructure. The review outlines future trends and challenges, including energy optimization, grid integration, and technological advancements. It serves as a guide for researchers to address these issues and contribute to the development of efficient and sustainable EV ecosystems [7].

Babji Bommana et al. (2023): Investigated the numerous advantages electric vehicles (EVs) offer over internal combustion engines (ICEs), such as reduced carbon emissions, improved energy efficiency, and decreased dependence on petroleum resources. Studies have focused on how EV charging infrastructure and power levels impact battery performance, comparing onboard and offboard charging methods. Findings suggest that unidirectional chargers simplify hardware requirements and connectivity issues, while bidirectional chargers facilitate energy transfer between the vehicle and the power grid. Research also highlights the limitations of onboard chargers due to size, weight, and cost, although both conductive and inductive technologies are deemed viable. Offboard chargers have been explored as feasible solutions for high current rates that EVs cannot accommodate. In addition, the studies have reviewed various charger categories, including level-1 (slow), level-2 (semi-fast), and level-3 (fast), comparing their charging times, power output, costs, and infrastructure configurations. These analyses collectively provide valuable insights into the practical applications and challenges of EV charging technologies [9].

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Ahmed Zentani et al. (2024): Studies highlight the rapid evolution charging systems, covering techniques like inductive and DC fast charging, Tesla Superchargers, and battery swapping. Challenges include infrastructure limitations, standardization efforts, and energy optimization. Advancements in battery technology, wireless charging, and user experience are emphasized as critical for future development. The research advocates for global collaboration to establish universal standards and enhance interoperability in EV fast charging systems [3].

Arvind R. Singh et al. (2024): The transportation sector is undergoing a significant shift toward sustainability, driven by advancements in technology, innovative materials, and a focus on environmental conservation. This research delves into the integration of electric vehicles (EVs) with power grids, particularly focusing on passenger cars. It highlights the critical role of modernized transport infrastructure in reducing greenhouse gas emissions and advancing carbon reduction goals in electricity systems. While EV adoption brings notable benefits such as improved grid efficiency and reduced emissions, it also introduces challenges in the design and operation of power systems at both transmission and distribution levels. The study underscores the importance of collaboration among key stakeholders to address these challenges and enhance EV-grid integration. Furthermore, it explores optimal strategies for deploying and managing EV charging infrastructure and examines efforts to establish unified standards to resolve existing issues. Through a detailed analysis of EV impacts on power systems, this research contributes to advancing sustainable mobility and energy systems by proposing effective integration solutions.[1]

Vikram Goud Madaram et al. (2024): Provided a comprehensive analysis of electric vehicle (EV) technologies, charging methods, and optimization strategies, comparing electric and hybrid vehicles to highlight their operational impact on energy efficiency and the environment. The studies have evaluated the effectiveness of conductive charging (CC), wireless power transfer (WPT), and battery swap stations (BSS), examining their feasibility, integration into urban infrastructure, and adoption challenges. EV standards related to charging rates and system configurations have also been reviewed for their role in ensuring compatibility across regions and manufacturers. Furthermore, algorithms and mathematical models have been analyzed for their ability to enhance charging efficiency, reduce costs, and improve resource accessibility. The findings underscore the importance of optimization strategies for urban planners and policymakers in enhancing EV infrastructure. Concluding with suggestions for future research, the studies identify knowledge gaps and propose solutions to improve EV technologies and charging systems, addressing technical and socioeconomic barriers. These insights serve as a valuable resource for researchers, engineers, and decision-makers working toward advancing EV adoption and infrastructure development [10].

Jigar Sarda et al. (2024): Highlighted the recognized advantages of electric vehicles (EVs) in reducing petrol emissions and dependence on oil-based transportation. The increasing adoption of EVs has led to a corresponding rise in charging stations, significantly impacting energy grid operations. Studies emphasize the importance of developing robust charging infrastructure to support both rural and urban areas, particularly in regions with limited or unreliable electrical grids. However, the integration of EVs into the power grid introduces challenges related to grid management, network planning, and safety due to increased electricity demand, power quality issues, and greater power losses. The analysis explores the infrastructure of EV charging stations, shedding light on their benefits and potential drawbacks. Additionally, it reviews the impact of EVs on grid integration while providing an in-depth examination of the standards and regulations that govern charging station operations. This comprehensive study offers valuable insights into addressing these challenges and advancing EV charging infrastructure to support global adoption [11].

Mohammed Amer et al. (2024): Researchers have examined advancements in EV battery technology, charging standards, and AI integration. Lithium-ion batteries dominate for their efficiency, while solid-state batteries and wireless charging hold promise despite challenges. AI improves battery management, autonomous driving, and grid communication. Key issues like recycling, resource scarcity, and infrastructure need innovation, with government policies playing a crucial role in advancing EV adoption [12].

Youness Hakam et al. (2024): Reviewed electric vehicles (EVs) and charging systems, highlighting advancements like wireless power transfer, V2G/V4G communication, and DC fast charging. They focus on charger configurations, standards, and AI-powered control strategies like MPC algorithms to optimize fast chargers. Challenges and future prospects, including smart grid integration and reactive power management, are also addressed [13].

Sigma Ray et al. (2024): Investigated the growing challenges faced by power grids due to the rising demand for electric vehicles (EVs) and the need for expanded charging infrastructure. Efforts to align photovoltaic (PV) and battery energy storage system (BESS) designs with distribution system requirements aim to enhance supply reliability and economics. A criteria weight ranking mechanism has been introduced to prioritize EV charging requests based on owner-specified weights. The study employs a multi-objective remora optimization algorithm (MOROA) to determine the optimal placement of two EV charging stations (EVCS), including PV and BESS capacities, by minimizing power loss, substation power costs, and emissions. The effectiveness of these methods has been demonstrated using IEEE 33 bus radial distribution system (RDS), showing that smart EV charge scheduling reduces grid load and benefits both EVCS operators and EV owners [15].

V.N. Saraswathi et al. (2024): Emphasized the growing importance of charging station (CS) design alongside the rising popularity of electric vehicles (EVs) due to their zero carbon emissions. Charging stations typically deliver either direct current (DC) or alternating current (AC) power, depending on EV requirements and grid capabilities. On-board chargers (on-BCs) and off-board chargers (off-BCs) are commonly used, with power flow options categorized as unidirectional, which simplifies hardware, or bidirectional, which allows energy to flow back to the grid. The key challenges include charging time and the need for robust infrastructure. Fast charging systems reduce dependency on on-board energy storage while improving charging efficiency. Various charging technologies, including wired and wireless methods, and multiple on- and off-board charging topologies are reviewed, alongside EV battery charging standards and levels. Alternative CS designs incorporating architecture, energy storage, and renewable energy sources are also discussed. The findings highlight the necessity of developing an advanced EV charging network to support renewable energy integration and reduce grid strain effectively [17].

Amit Kumar et al. (2025): Analyzed strategies for optimal placement and distribution of EV charging stations within power distribution networks, considering parameters like proximity to load centers, system capacity, traffic volume, and land costs. Findings show that locating stations away from load centers can improve power quality and reduce distribution losses by 5–10%. Battery depth of discharge (DOD) influences service radius, with distances of 50–70 km between stations recommended for a driving range of 150–200 km. Cost estimates range from 50,000to50,000to200,000 per station, with urban land costs estimated at 500–500–2,000 per square meter. Integration of such networks enhances system power balance, reduces losses, and supports increased EV penetration by accounting for technical, economic, and environmental considerations [14].

Potsawat Oranpairoj et al. (2025): Analyzed the distribution and accessibility of public EV charging stations in Bangkok, Thailand, assessing their effectiveness in meeting user demands. Using location-allocation analysis in ArcGIS Pro, the study evaluates station coverage against estimated charging needs while factoring in limitations like operating hours and state-of-charge (SoC) regain levels. Questionnaire data provided insights into capacity constraints at stations. Findings highlight that while existing stations generally meet demand, their capacity and distribution require improvement. Additional stations are needed in specific sub-districts, particularly during peak hours. The research underscores the importance of flexible service strategies and demand-responsive planning to optimize charging infrastructure and ensure accessibility for a growing EV user base [16].

Jennifer Leijon (2025): Reviewed the integration of electric vehicles (EVs) into society, emphasizing the importance of robust charging infrastructure and power grid planning. Their studies highlight uncertainties in how various charging strategies—such as conductive charging, inductive charging, and battery swapping—affect battery ageing. Findings show that conditions like fast charging at low temperatures can accelerate battery degradation, which depends on factors like temperature, charging current, and state-of-charge. A trade-off is noted between faster charging and longer battery lifespan. While vehicle-to-grid (V2G) systems offer grid flexibility and revenue opportunities, their impact on battery ageing requires further investigation. Policymakers face the challenge of designing infrastructure that balances EV accessibility with battery longevity and cost-effectiveness. Interdisciplinary research is recommended to overcome these challenges and support the transition to clean energy [18].

III. LITERATURE GAP

1) No Global Standards: Conflicting charging protocols (Tesla vs. CCS), wireless power transfer, and battery swapping lack universal rules.
2) User Behavior Ignored: Few studies on cost barriers, rural access, or incentives for off-peak charging.
3) Renewable Integration Weak: Optimal solar/wind-grid hybrid models and energy storage solutions are understudied.
4) Battery Ageing Uncertainty: Fast/V2G charging's long-term impact on battery life needs more real-world data.
5) Grid Overload Risks: Limited real-case studies on high EV adoption's strain on power networks.
6) Charging Station Imbalance: Urban-rural distribution gaps and cost-benefit trade-offs (fast vs. slow chargers) are overlooked.
7) Biggest Gap: No research combines technical, economic, and user-friendly solutions for mass EV adoption.

IV. CONCLUSIONS

This review comprehensively examines the advancements, challenges, and future directions in EV charging technologies and infrastructure. Key findings highlight the evolution of charging methods (Level 1–3, wireless, V2G) and the critical role of renewable energy integration in enhancing sustainability. However, significant gaps persist, including the lack of global standards, uneven urban-rural infrastructure distribution, and unresolved concerns about battery degradation and grid stability. To accelerate mass EV adoption, future efforts must prioritize:

1) Standardization of charging protocols and interoperability.
2) User-centric solutions addressing cost, accessibility, and behavioral barriers.
3) Renewable-energy hybrids to optimize grid resilience.
4) Long-term studies on battery health under fast/V2G charging.

By bridging these gaps through interdisciplinary collaboration, EV charging systems can achieve scalability, efficiency, and equitable adoption, paving the way for a sustainable transportation future.

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ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue V May 2025- Available at www.ijraset.com

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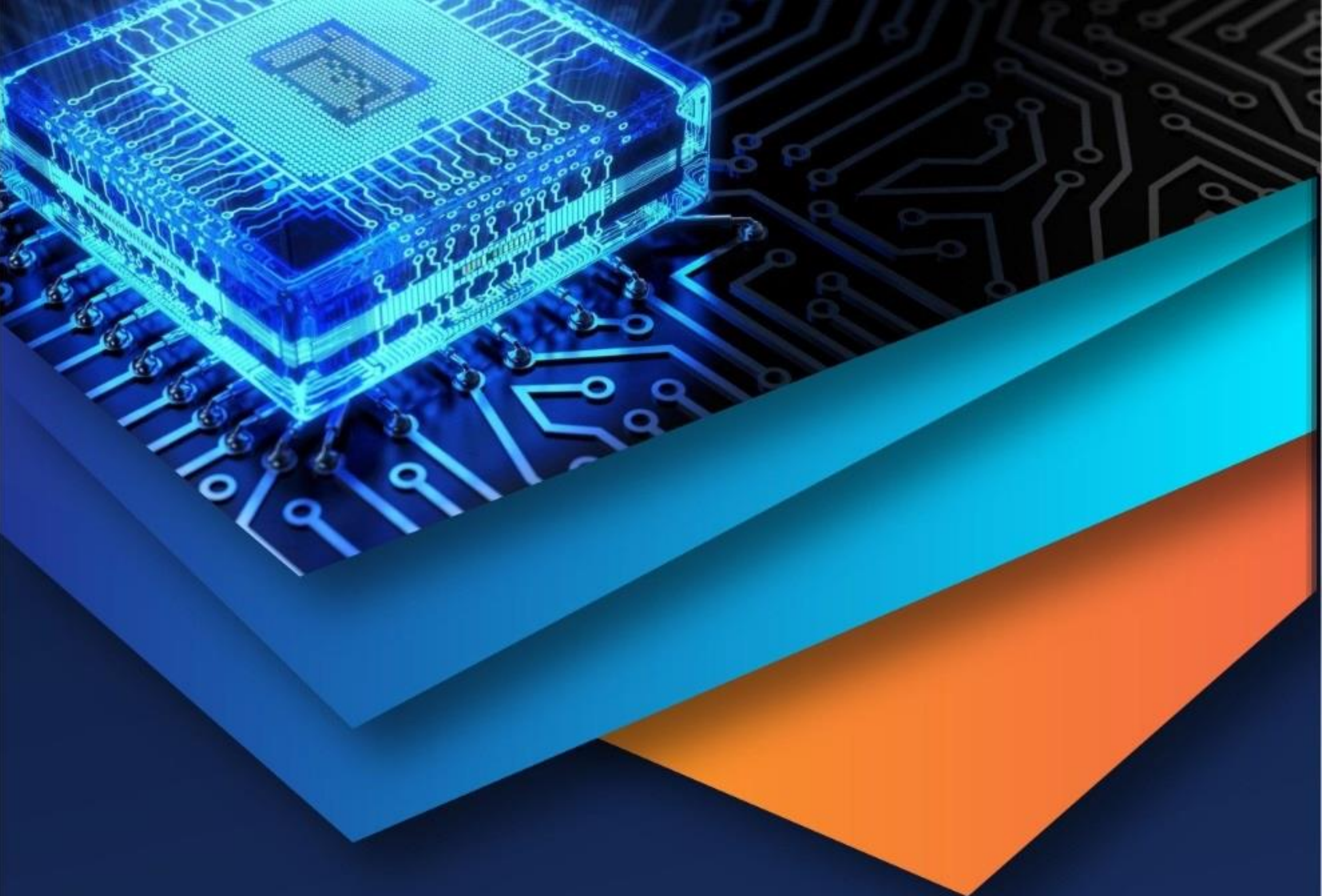

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