Energy Reports 14 (2025) 1834–1854

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Review article

Toward a unified framework for electric vehicle infrastructure: Insights into charging management, communication and emerging technologies

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ARTICLE INFO

Keywords:
Charging infrastructure
Charging management systems (CMS)
Electric vehicle (EV)
EV communication protocols
Unification

ABSTRACT

The transportation sector remains a major contributor to greenhouse gas emissions, and the widespread adoption of electric vehicles (EVs) is a key strategy for mitigating this impact. However, scaling EV adoption requires an equally robust expansion and integration of charging infrastructure, which currently suffers from fragmented management systems and incompatible communication protocols. This paper systematically reviews the existing landscape of EV infrastructure, identifying gaps in charging efficiency, grid integration, and user accessibility. Through an analysis of EV simulation platforms, communication standards, and central management systems, we synthesize key insights into a unified framework that leverages emerging technologies such as blockchain, AI-driven optimization, and reinforcement learning. Furthermore, we propose strategies for enhancing scalability, including EV unification, gamification, and adaptive charging mechanisms. By providing a structured roadmap, this study serves as a comprehensive guide for researchers, policymakers, and industry leaders, offering actionable insights to optimize the EV ecosystem and accelerate the shift toward sustainable transportation.

1. Introduction

Air pollution poses a significant global health threat, necessitating immediate and effective measures to mitigate its impacts. In response to growing environmental concerns, the transportation industry has increasingly adopted electric vehicles (EVs) as a viable solution to reduce greenhouse gas emissions (Chaikhy et al., 2022). However, the widespread adoption of EVs is hindered by several critical challenges, particularly in the management of charging systems and infrastructure (Sanguesa et al., 2021). These challenges include limited driving range, battery reliability issues, range anxiety, inadequate charging station availability, adverse effects on existing network operations and consumer mistrust of emerging technologies.

Numerous studies have proposed various models and strategies to improve EV charging and address the barriers to adoption. Despite these efforts, significant obstacles remain, with range anxiety being one of the most pressing concerns (Pevec et al., 2020). Range anxiety, the fear of running out of battery power without access to charging stations, is further intensified by the fragmentation of available data sources (Tuffour and Ewing, 2024). This fragmentation results in inconsistent information about the location, availability and reliability of charging stations, making it difficult for consumers to plan trips confidently. Addressing this issue by unifying data across platforms and improving real-time access to reliable charging infrastructure information could play a critical role in alleviating range anxiety and encouraging greater EV adoption (Dimitriadou et al., 2023).

To address these challenges, there is an urgent need for a comprehensive, unified management framework that integrates charging strategies, real-time data access, and user-friendly applications across the EV ecosystem. This study contributes to ongoing efforts across various disciplines, including computer science, transportation and renewable energy, by addressing the pressing challenges of EV integration and infrastructure management. Through a comprehensive literature review, we explore existing EV management approaches, focusing on opportunities to reduce fragmentation and alleviate range anxiety. By analyzing relevant research, we aim to propose a framework that unifies data sources, optimizes charging management and enhances user experience, ultimately facilitating broader EV adoption. This paper seeks to answer the following research questions:

RQ1: What are the key challenges to interoperability, scalability, and data fragmentation in current EV management systems, and how can a unified framework address these issues?

RQ2: What strategies can be employed to optimize EV charging management systems to alleviate range anxiety and better manage grid loads?

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https://doi.org/10.1016/j.egyr.2025.08.011
Received 12 May 2025; Received in revised form 3 July 2025; Accepted 10 August 2025

RQ3: How can future developments such as EV-to-EV communication, gamification, and unified ecosystems drive large-scale EV adoption and improve sustainability in urban environments?

This paper contributes to the field in the following ways:

1. **A targeted review and synthesis of current EV management systems**, covering simulation tools, communication protocols, charging strategies, and CMS platforms, to identify critical gaps in interoperability, scalability, and user engagement.
2. **A unified cross-layer architecture (the All-in-One EV Companion)** that integrates EV simulation platforms, communication protocols, and charging management systems to enable real-time coordination across traditionally siloed EV subsystems.
3. **Gamification for sustainability**, introducing a behavior-driven incentive layer that encourages eco-conscious driving through features like regenerative braking rewards, efficiency tracking, and user achievement systems.
4. **AI-enhanced charging and routing optimization** using real-time analytics to balance grid load, improve battery performance, and minimize user cost and inconvenience.
5. **Blockchain-based energy transactions** leveraging smart contracts and decentralized ledgers for transparent, automated billing and secure, trustless interactions between EV users and charging infrastructure.
6. **Vehicle-to-Vehicle (V2V) communication integration**, enabling collaborative energy and traffic data sharing to enhance route planning, reduce range anxiety, and support future autonomous fleets.
7. **A modular and phased deployment strategy**, allowing flexible implementation across diverse infrastructure environments with future extensibility to smart grid, gamification, and V2G integration.
8. **Future-proof adaptability**, with support for stochastic energy sources, mobility variability, and potential integration of high-fidelity simulations and real-world datasets via APIs.

Table 1 provides a list of frequently used terminology and their definitions for convenience. This paper is structured as follows. Section 2 presents the methodology for selecting relevant research papers and analyzing data sources, outlining the criteria used for inclusion, the data extraction process and the approach for organizing and classifying the studies. In Section 3, the selected papers are categorized into multiple fields of study, including EV simulation systems, EV communication protocols, charging management systems, central management systems and mobile apps, to provide an overview of current research and technological advancements. Section 4 reviews existing strategies and challenges, focusing on critical issues like range anxiety, data fragmentation, and obstacles hindering EV adoption, while also identifying areas for improvement to enhance infrastructure and user experience. Section 5 introduces the proposed solution through the development of the “All-in-One EV Companion” framework, outlining how the integration of simulation systems, communication protocols, charging management, and user-friendly applications can address these challenges and improve operational efficiency. Finally, Section 6 summarizes the key findings of the paper, emphasizing the need for standardization and collaboration across the EV ecosystem to overcome fragmentation, while exploring future advancements to enhance user experience and drive broader EV adoption, ultimately contributing to a more sustainable transportation system.

2. Data source analysis

This research provides a comprehensive examination of various aspects of EVs by synthesizing previous studies and literature. By compiling and analyzing research results from a wide variety of academic sources, this research aims to offer a thorough summary of cutting-edge technologies and techniques used in the EV ecosystem.

Table 1
List of acronyms and abbreviations used in the paper.

Acronyms	Words
AI	Artificial Intelligence
AT	Arrival Time
ATC	Available Time for Charging
BCA	Branch and Cut Algorithm
BVCS	Blockchain-Enabled V2V Communication Systems
CAMs	Cooperative Awareness Messages
CAN	Controller Area Network
C-EMTP	Compact Electromagnetic Transient Program
C-V2X	Cellular Vehicle-to-Everything
ChaaS	Charging-as-a-service
CIMS	Charging Infrastructure Management System
CMS	Charging Management System
CS	Charging Station
CSMS	Charging Station Management System
CU	Controller Unit
DEXIP	Data Exchange Interoperability Protocol
DRL	Deep Reinforcement Learning
DSRC	Dedicated Short Range Communication
EM	Electromobility
EPMS	Electrical Power Monitoring System
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
EVSE	Electric Vehicle Supply Equipment
FPGA	Field Programmable Gate Arrays
GA	Genetic Algorithm
GCU	Gateway Controller Unit
GC	Grid Coordinator
GS	Global Search
ICT	Information and Communication Technology
ILP	Integer Linear Programming
IoE	Internet of Everything
IoT	Internet of Things
ISS	Intelligent Scatter Search
ITS	Intelligent Transportation Systems
LIN	Local Interconnect Network
LoS	line-of-sight
LSTM	Long Short-Term Memory
LTE-V	Long-Term Evolution-Vehicle
LV	Low-Voltage
MADDPG	Multiagent Deep Deterministic Policy Gradient
MAS	Multi-Agent System
NR	New Radio
NDN	Named Data Networking
NLoS	non-line-of-sight
OCPP	Open Charge Point Protocol
OSCP	Open Smart Charging Protocol
PL	Parking Lot
PnC	Plug and Charge
PoS	Proof-of-Stake
PoW	Proof-of-Work
PSA	Parking Slot Availability
PSO	Particle Swarm Optimization
PV	Photovoltaic
P/S	Power/Signal
RFID	Radio-Frequency Identification
RL	Reinforcement Learning
RNN	Recurrent Neural Network
RPG	Renewable Power Generator
RSU	Road Side Units
RT	Reservation Time
SIMA	Scalable IoT Monitoring Application
SoC	State of Charge
SPEVC	Solar Powered EV Charging
SPP	Shortest Path Problem
UX	User Experience
V2G	Vehicle-to-Grid
V2I	Vehicle-to-Infrastructure
V2N	vehicle-to-network
V2P	vehicle-to-pedestrian
V2R	vehicle-to-roadside
V2V	Vehicle-to-Vehicle
V2X	vehicle-to-everything
VANET	Vehicular Ad-Hoc Network
VLC	Visible Light Communication

Fig. 1. Keywords that are commonly used within the examined articles.

2.1. Literature search

The literature search was conducted using the following academic databases: IEEE Xplore, ScienceDirect, Google Scholar, ResearchGate, and MDPI. Specific keywords were used to refine the search, including terms such as "Electric Vehicle" and "Communication Protocols", "EV Charging Management", "EV Central Management System" or "CMS", "EV Mobile Applications" and "Simulation Systems" among others (see Fig. 1). These keywords helped define the scope of the search and ensure that relevant studies were identified.

2.2. Selection criteria

The selection criteria (see Table 2) were designed to ensure relevance and timeliness. Only studies published within the last ten years (2014–2024) were included to reflect the most current advancements in EV technologies. The selected sources were limited to publications available in English to maintain consistency, and only peer-reviewed journal articles, conference papers, and reputable industry reports were included. Studies were required to be directly related to EV communication protocols, charging management techniques, CMS, mobile/web apps, and simulation systems (see Fig. 3 for the ratio of each field).

2.3. Search results

The initial search yielded 765 papers, but many were found to be irrelevant or duplicated across databases. After removing duplicates and applying exclusion criteria, 148 papers met the criteria for this survey. Excluded studies focused primarily on topics unrelated to the core research areas, such as battery health management and market trends in EVs. The search strategy, including filtering by publication date and subject area is illustrated in Fig. 2.

2.4. Screening process

The screening process involved an initial review of titles and abstracts to identify potentially relevant studies. This step resulted in the exclusion of 664 studies due to duplication or lack of relevance. The remaining papers underwent a full-text review to ensure they met the inclusion criteria. Ultimately, 101 studies were selected for detailed analysis.

2.5. Data extraction and analysis

Key variables were extracted from each selected study, including objectives, methods, findings and limitations, to enable systematic analysis. The selected studies were categorized into distinct fields of study; EV communication protocols, charging management techniques, CMS and mobile/web apps, and simulation systems (see Fig. 3). A narrative synthesis was performed to summarize findings qualitatively, and a thematic analysis was conducted to identify common themes and trends across the studies. Comparative analysis was also employed to evaluate different methodologies and technologies. Through this rigorous data extraction and categorization process, the research provides a comprehensive overview of the EV ecosystem from a software and systems perspective.

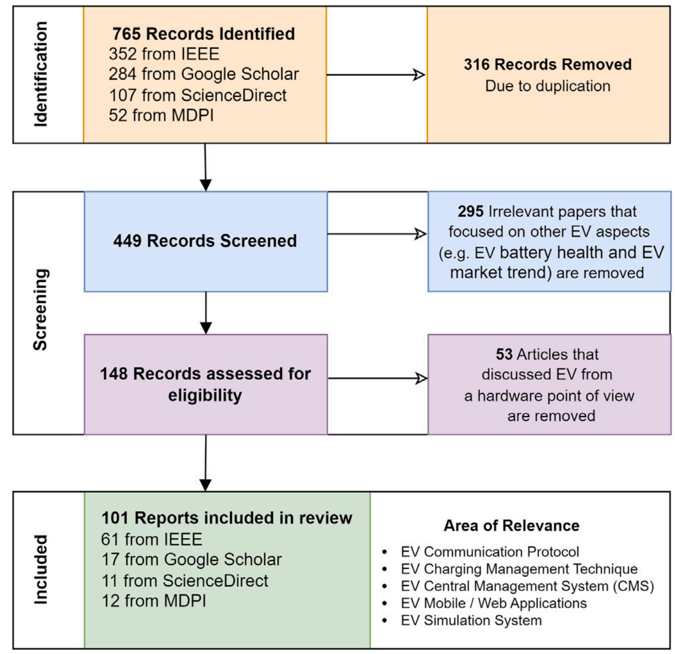

Fig. 2. Strategy for selecting the related papers.

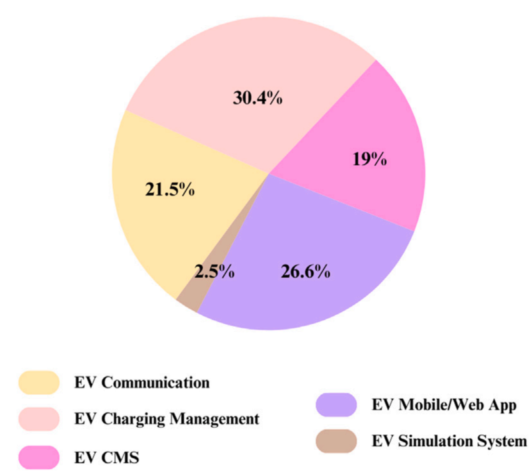

Fig. 3. Distribution of examined articles based on distinct fields of study.

3. Literature review

Several advanced EV technology components are required to guarantee a smooth transition to electrified transportation (Deb et al., 2018). Among these, EV simulation systems play a critical role in testing and simulating various scenarios related to electric vehicle charging, such as grid integration, load management, and optimization strategies. By providing a virtual environment for evaluating EV performance and infrastructure interactions, these systems allow engineers to identify potential challenges and refine solutions before

Table 2
Inclusion and exclusion criteria for literature review.

Criteria	Details
Inclusion	
Publication Date	Studies and data sources published within the last ten years (2014–2024) to ensure relevance and currency
Language	Publications available in English to ensure accessibility and consistency
Type of Publication	Peer-reviewed journal articles, conference papers, and reputable industry reports
Relevance	Articles and data directly related to EV communication protocols, charging management techniques, EV Central Management Systems, EV mobile/web apps, simulation systems, and integrated EV solutions
Exclusion	
Irrelevant Topics	Studies solely addressing battery health management and EV market trends
Duplicates	Duplicate studies identified during the search process

real-world implementation. This minimizes development time and costs while ensuring the reliability and efficiency of the overall EV ecosystem. In addition to simulation systems, other key components include EV communication protocols, charging management techniques, and Central Management Systems with mobile apps. EV communication protocols establish standardized methods of communication between electric vehicles and charging stations (Khan et al., 2018), enabling seamless and efficient charging, as well as data collection on vehicle charging patterns. Charging management techniques optimize the flow of electricity, ensuring effective use of grid resources and reducing charging expenses (Deb et al., 2018). Furthermore, EV CMS and mobile apps provide users with real-time monitoring of charging stations, information on availability and rates, and user-friendly interfaces to locate, check, and reserve charging stations. These apps also allow users to monitor charging progress remotely and receive notifications when their vehicles are fully charged. By leveraging these advanced technologies, the development of a robust and reliable charging infrastructure becomes more feasible. The following section provides valuable insights into various aspects of the advanced EV technological infrastructure.

3.1. EV simulation systems

EV simulation systems are essential tools that allow engineers and researchers to virtually test and validate a wide range of scenarios, such as vehicle dynamics, charging infrastructure performance, grid integration, energy consumption, and load management. These simulations provide critical insights into potential challenges before physical deployment, significantly reducing development time and costs. More importantly, while general simulations are commonly used across the research community, recent studies have focused on developing comprehensive simulation frameworks that push the boundaries of EV system integration and optimization. These frameworks go beyond standard simulation approaches by providing more holistic platforms that enable researchers to investigate complex interactions between EVs, infrastructure, and power grids. By replicating EV behavior and interactions with power grids, these advanced simulation systems help identify inefficiencies and bottlenecks, ultimately optimizing both EV technology and infrastructure for real-world applications. This leads to the development of more robust, efficient, and reliable EV infrastructures (Chaudhari et al., 2018; Bedogni et al., 2015). The following studies showcase how comprehensive simulation frameworks have been applied to test and validate innovative technologies, refine design decisions, and improve the overall integration of EVs into energy ecosystems.

Building on the need for comprehensive simulation environments, Bedogni et al. (2015) developed a novel simulation framework that analyzes EV operations in complex, large-scale and heterogeneous settings. This framework integrates various models, including vehicular mobility, battery charging and discharging, and electromobility (EM)-related city services. By leveraging the semantic architecture of the Internet of Everything (IoE), the framework seamlessly combines real and simulated components. The framework allows for an in-depth examination of EV interactions with smart grids and urban infrastructures, providing researchers with a more sophisticated tool for analyzing the impact of EVs on various city systems. The authors suggest that future research should extend the battery model to include the effects of regenerative braking on energy consumption, as this would provide a more accurate representation of real-world driving conditions and improve the overall efficiency and effectiveness of energy management strategies in EVs. Additionally, integrating this simulation framework with smart grid simulators and planning tools will enable the simultaneous study of EV charging and grid interactions, facilitating complex analyses of energy production, pricing dynamics, and renewable energy integration.

Ferraris et al. (2019) developed a control algorithm for an All-Wheel-Drive Full Electric Vehicle equipped with wheel-hub motors, focusing on enhancing vehicle dynamics through torque vectoring while optimizing energy efficiency. The algorithm was tested and refined using a co-simulation environment to create a dynamic vehicle model. Offline simulations were initially conducted to fine-tune the controllers and assess their impact on vehicle dynamics and energy efficiency. The model was then validated using a real static simulator, allowing a virtual driver to perform subjective evaluations of the vehicle's dynamic behavior. This approach enabled the authors to simulate and evaluate the effects of torque vectoring on handling, while ensuring that improvements in dynamic responsiveness did not compromise energy efficiency. The simulations demonstrated a significant reduction in lap time and energy consumption, underscoring the effectiveness of the control strategies developed within the simulated environment. Additionally, they highlighted the value of well-tuned EV simulation platforms for pre-production systems. Through this framework, researchers were able to refine and validate control strategies in a realistic yet virtual environment, providing insights that would be difficult to obtain with simpler simulation setups.

In a related effort, Diaz et al. (2024) employed advanced simulation techniques to optimize the design and integration of EV charging stations. The study thoroughly examined the charging process, infrastructure needs, and the impact on the electrical grid. Simulations provided valuable insights into the behavior of charging stations in terms of efficiency, reliability, and harmonic distortion. By simulating various operational conditions and charging strategies, the researchers created a comprehensive platform for testing mitigation techniques that enhance charging process stability. Li et al. (2020) introduced a novel simulation framework for real-time simulation of electric vehicle charging stations, with a focus on handling the complexities introduced by high-frequency power electronic switches on electric vehicle chargers. The authors proposed a compact electromagnetic transient program (C-EMTP) algorithm tailored for an FPGA-based (Field Programmable Gate Arrays) simulation platform. This approach significantly reduced the simulation time step and enhanced the accuracy of simulating high-frequency power electronics, improving the overall performance and reliability of EV charging stations.

Yan et al. (2020) developed an EV charging load simulation framework that addresses the complexities of modeling charging behavior

Table 3
Comparison of representative EV simulation systems.

Study	Methodology	Key features	Limitations/Future directions
Bedogni et al. (2015)	Integrated simulation for EVs in urban settings using IoE	Combines mobility, charging, city services, and real-time interactions; supports grid integration	Lacks regenerative braking modeling; suggests integration with grid planning tools
Ferraris et al. (2019)	Co-simulation of AWD EV with wheel-hub motors	Simulates torque vectoring, energy efficiency, and dynamic responsiveness; validated with static simulator	Focused on single-vehicle performance; requires extension to fleet-level dynamics
Diaz et al. (2024)	Charging infrastructure optimization via simulations	Tests reliability, efficiency, and harmonic distortion under multiple charging scenarios	Does not model grid interaction or user behavior in depth
Li et al. (2020)	FPGA-based real-time simulation with high-frequency switch modeling	Reduces simulation timestep; improves accuracy for power electronics	Hardware-specific implementation may limit portability
Yan et al. (2020)	Spatial–temporal modeling of EV charging load	Includes real-world factors like temperature and traffic; enables realistic load profiles	Dependent on synthetic travel data; suggests deeper integration with renewable forecasting
All-in-One EV Companion	Conceptual framework supporting modular simulation integration	Emphasizes extensibility to tools like MATLAB/Simulink, SUMO, and OpenDSS; targets full EV-to-grid modeling	Conceptual phase; real-world validation and physical integration needed

by incorporating critical real-world factors such as temperature and traffic conditions. Recognizing the limitations posed by the lack of historical charging data, the authors proposed a spatial–temporal simulation method that enhances accuracy by factoring in the effects of temperature on battery capacity and air conditioning power consumption, as well as the impact of varying traffic conditions on energy use during vehicle operation. This simulation methodology integrates these elements into refined probabilistic models that capture daily travel patterns, allowing for the generation of realistic charging load profiles across different regions and scenarios. The resulting profiles provide valuable insights into the optimal planning of distributed renewable energy resources like wind and solar power, demonstrating the paper's contribution to improving the integration of EVs with renewable energy systems.

In conclusion, the reviewed studies demonstrate significant advancements in the simulation and modeling of EVs across various aspects, including vehicle dynamics, charging infrastructure, and the integration of renewable energy resources. The research highlights the effectiveness of advanced simulation techniques in optimizing EV performance, enhancing energy efficiency, and improving the interaction between EVs and the power grid. These simulations offer critical insights into factors such as traffic conditions, temperature, and power electronics, contributing to more accurate modeling of EV behavior and charging loads. Table 3 provides a structured summary of representative EV simulation systems, highlighting their capabilities, target applications, and key limitations. However, several areas still require further investigation. Future work should prioritize the integration of these simulation frameworks to develop a fully interoperable platform capable of modeling the entire spectrum of EV operations. This would include simulating vehicle dynamics under varying conditions, real-time interactions with charging infrastructure, and the seamless integration of EVs with grid management systems for load balancing, energy optimization, and grid stability. Additionally, expanding the scope of these simulations to account for emerging technologies, such as Vehicle-to-Grid (V2G) systems and advanced battery management techniques, will be essential to fully understanding EVs' role in future energy ecosystems.

3.2. EV communication protocols

As advancements in EV simulation and modeling progress, the communication framework for EV technology becomes increasingly important. This framework consists of standardized rules and protocols governing how EVs, Electric Vehicle Supply Equipment (EVSE), and the power grid interact and exchange information. It acts as the communication hub for the EV ecosystem, enabling the data exchange necessary for effective charging, improved grid management and enhanced user experiences.

Various studies have focused on optimizing EV communication protocols to improve data flow across the EV ecosystem. Dhianeshwar et al. (2016) introduced a Charging Infrastructure Management System (CIMS) that streamlines communication between EVs and EVSE. The system integrates with Central Management Systems and mobile applications, enabling users to seamlessly reserve charging points, monitor sessions in real-time, and update session details. Similarly, Gowri and Sivraj (2021) developed a dual-protocol communication system that integrates Controller Area Network (CAN) and Wi-Fi to facilitate communication between EVSE and EVs. CAN, known for its reliability and low latency, is ideal for in-vehicle communication, while Wi-Fi supports high-volume data exchange. However, the study identified a potential bottleneck; as the network scales up, CAN's transmission speed may become limiting, while Wi-Fi though, offering greater bandwidth, is prone to interference and security vulnerabilities. The authors suggest hybrid models that dynamically switch between CAN and Wi-Fi based on operational demands, thus optimizing performance by balancing reliability and data throughput. While CAN and Wi-Fi handle direct communication between EVs and EVSE, higher-level protocols are necessary to ensure broader system compatibility.

One such standardized protocol, the Open Charge Point Protocol (OCPP), has been widely emphasized by researchers (COURT, 2015; Hsaini et al., 2022; George et al., 2019) for ensuring compatibility across different charging stations and management systems, regardless of the hardware or software provider. Pruthvi et al. (2019) highlighted the flexibility OCPP offers, allowing users and operators to switch mobile carriers without being restricted to a single ecosystem. In addition, the Open Smart Charging Protocol (OSCP) facilitates sustainable power distribution by communicating available capacity to the charge point operator, optimizing energy management. Cao et al. (2014, 2017) proposed a Power/Signal (P/S) communication framework, where charging stations (CSs) are connected to Road Side Units (RSUs) via reliable communication channels to publish their Available Time for Charging (ATC) information. Through this system, EVs can make remote reservations with the Grid Coordinator (GC) before arriving at the selected CS. In this framework, CSs regularly publish ATC data to RSUs, which compile and store this information. When an EV approaches an RSU, it fetches the cached ATC information. This communication system operates in two modes; Push Mode, where EVs passively receive information from nearby RSUs, and Pull Mode, where RSUs respond to explicit queries from EVs using cached historical data about CS availability. Ensuring the accuracy and security of data in both modes is critical. Blockchain technology is proposed as a solution to enhance the transparency and trustworthiness of the P/S system, as noted in Martins et al. (2019), Dorokhova et al. (2021). Cao et al. (2017) also highlighted a challenge in congestion areas, where EVs must decelerate, potentially affecting data accuracy. To mitigate this, the authors suggest integrating dynamic routing algorithms and predictive models that account for real-time traffic conditions into the P/S system.

Other research has explored the potential of Vehicular Ad-Hoc Networks (VANETs) in the EV ecosystem (Gharbaoui et al., 2012; Vendan and Chaudhary, 2023). Vendan and Chaudhary (2023) proposed a solution that builds a Peer-to-Peer (P2P) infrastructure on top of a VANET to enable secure and reliable power trading between users. This approach guarantees reliable charging points by considering factors such as waiting time, reliability and cost. However, the ad-hoc nature of VANETs can lead to higher latency and potential data loss, which could negatively impact real-time performance. The study also suggests using blockchain-based smart contracts to facilitate energy trading agreements between EVs and charging stations, while Named Data Networking (NDN) routing helps identify the most cost-effective and reliable electricity provider. Mukherjee et al. (2023) introduced a Bluetooth-enabled Controller Unit (CU) or Gateway Controller Unit (GCU) paired with an Android app, which gathers vehicle parameters over CAN and LIN (Local Interconnect Network) protocols, transmitting data to the user's mobile phone via Bluetooth. However, the limited range of Bluetooth poses a challenge in terms of continuous monitoring when the user is not in close proximity to the vehicle. To improve reliability and extend range, the study recommends implementing a hybrid communication system that combines Bluetooth with other wireless technologies like Wi-Fi or cellular networks, providing backup options in case of Bluetooth failure.

The reviewed literature presents a diverse range of communication protocols and architectures tailored to meet the evolving needs of the EV ecosystem. Systems like CIMS, dual-protocol solutions integrating CAN and Wi-Fi, and standardized protocols such as OCPP and OSCP have improved the seamless communication and energy management within EV infrastructures. However, despite significant progress, achieving an optimal communication framework for EVs requires hybrid models capable of adapting to dynamic operational demands. By adopting such models, data transmission can remain secure and reliable, while maintaining interoperability across different systems and technologies. Further investigation into these hybrid strategies, utilizing advanced technologies like blockchain and smart contracts, is crucial for addressing the evolving needs of EV communication networks and enhancing overall ecosystem performance and user experience. Table 4 offers a comparative overview of these approaches, along with their limitations and contributions to EV ecosystem evolution.

3.3. Charging management techniques

Advancements in communication protocols are paralleled by developments in charging management techniques, which play a crucial role in optimizing the charging process for both EVs and the power grid. These techniques aim to maximize charging efficiency, minimize strain on the grid, and reduce overall charging costs.

To address the need for more efficient and accessible EV charging, Kandasamy et al. (2023) developed a prototype system that uses a multi-tap transformer. This system provides adaptable charging voltages of 52 V, 60 V, and 72 V, which are tailored to popular EV models. Additionally, the system includes a mobile app that allows users to monitor battery status, adjust voltage input, and implement an auto cut-off feature to prevent overcharging, improving both safety and energy efficiency. Although the prototype offers versatility and user-friendliness, it is limited by its ability to charge only one vehicle at a time. Wang et al. (2005) presented a system that optimizes charging patterns based on factors such as ambient temperature, voltage, current, and time of day. Meanwhile, Güldorum et al. (2019) proposed a platform that allows EV owners to convey their charging demands while enabling system operators to manage power demand and charging station occupancy based on grid conditions. The platform provides real-time data on the number of EVs, charge levels, and power usage, allowing operators to dynamically monitor grid status and other relevant factors. Future enhancements include implementing power flow-based optimization to balance grid load efficiently and minimize the risk of overloading any specific node. Cao et al. (2016) proposed a scheme that manages EV charging plans by considering reservations, parking durations, and mobility uncertainties like traffic jams. The system uses a global management entity to oversee charging plans for all EVs within the network. A three-step process estimates trip duration, including intermediate charging, considering factors like available charging slots, future station status, and trip destinations. The authors suggest that integrating advanced charging technologies like battery switching could reduce charging times and improve service speed. However, the system's reliance on a central entity raises concerns about security and scalability, prompting the need for a robust communication framework to ensure safe operation.

Mittal et al. (2023) focused on optimizing EV charging by developing a software application that helps users identify the most efficient charging stations. Using an integer linear programming (ILP) model combined with the Branch and Cut Algorithm (BCA), the software minimizes the time spent traveling to and charging at stations by considering the vehicle's current charge, nearby station locations, and queue lengths. Designed for use on dashboards or mobile devices, the application aims to reduce wait times and enhance convenience, suggesting future integration of this technology as a standard feature in EVs. Cui et al. (2023) addressed the challenges of large-scale EV deployment by developing a prediction system for fast-charging behavior at public stations. Using a stacking regression framework, the system predicts EV user behavior such as charging energy, duration, and post-charging dwelling time with high accuracy. This predictive model aims to optimize power management and ensure grid stability. Future research directions include deploying the system via cloud-based platforms for real-time grid management and further investigating multi-vehicle fast-charging behavior. Several studies have also focused on advanced algorithms for optimizing charging and discharging behavior (Mao et al., 2019; Zhang et al., 2016).

Mao et al. (2019) introduced the Intelligent Scatter Search (ISS) algorithm, designed to handle both unidirectional and bidirectional EV charging, considering flexible and constant power rates. The ISS algorithm outperforms traditional methods like global search (GS), genetic algorithms (GA), and particle swarm optimization (PSO) by smoothing daily load profiles and minimizing charging costs. For large-scale EV scenarios, the study proposes a hybrid GA-ISS method, which combines GA theory with ISS for efficient, accurate results with reduced computational time. The authors suggest future enhancements, such as accounting for battery degradation and integrating other power system components. Blockchain-based frameworks for charging management have also gained attention (Dorokhova et al., 2021; Martins et al., 2019). Dorokhova et al. (2021) proposed a practical blockchain framework using Ethereum to manage EV charging, integrating physical and software infrastructure to ensure accurate energy flow accounting and streamline charging processes. A real-world case study demonstrated the system's feasibility, showing potential to reduce costs, speed up billing, and simplify market access for charging station owners. However, the study acknowledges challenges such as transaction

Table 4
Comparison of representative EV communication protocols.

Study	Protocol(s) Used	Key features	Limitations
Dhianeshwar et al. (2016)	Custom CIMS with CMS/mobile app integration	Real-time session monitoring, reservation, centralized control	Does not address protocol standardization or multi-vendor interoperability
Gowri and Sivraj (2021)	CAN + Wi-Fi hybrid system	Dual-protocol architecture for balancing latency and bandwidth	CAN limited by speed; Wi-Fi suffers from interference and security concerns
Pruthvi et al. (2019)	OCPP	Vendor-agnostic communication between EVSE and CMS	No direct support for energy forecasting or grid coordination
Cao et al. (2014, 2017)	Power/Signal (P/S) + RSU infrastructure	Remote reservation, Push/Pull data exchange, ATC publishing	Congestion impacts accuracy; relies on cached data
Vendan and Chaudhary (2023)	VANET + P2P + Blockchain	Peer-to-peer charging, energy trading via smart contracts, NDN routing	High latency in VANET; limited real-time reliability
Mukherjee et al. (2023)	Bluetooth + CAN/LIN + Android app	In-vehicle diagnostics, mobile integration	Bluetooth range limitations; no fallback protocol
All-in-One EV Companion	OCPP/OSCP + Middleware Layer + Blockchain + AI integration	Hybrid interoperability layer for legacy and emerging standards; secure, real-time coordination; scalable integration	Conceptual; requires future pilot validation and empirical latency testing

costs and energy consumption, suggesting further research to improve blockchain's applicability in energy management.

Managing energy prices is another area of research. Abdullah et al. (2021) applied Reinforcement Learning (RL) to optimize EV charging management, shifting from traditional heuristic approaches to data-driven strategies. RL algorithms, designed to maximize cumulative rewards, are particularly effective in uncertain environments with fluctuating energy prices and grid loads. In the charging context, the RL-based charging management controller determines optimal actions by trial and error to maximize long-term rewards. Despite computational complexity and large dataset requirements, RL frameworks offer significant potential for real-time decision-making and adaptive learning in response to grid dynamics. The study suggests integrating RL with predictive analytics to improve both decision-making accuracy and operational efficiency. Lee et al. (2014) used game theory to explore how EVCSs set electricity prices to attract EVs. The study demonstrated that integrating renewable power generators (RPGs) into EV CSs could lower electricity prices and increase station revenues, benefiting both station operators and EV users, as long as RPG costs remain manageable.

Several reviews have examined the development of EV technologies, with a particular emphasis on advancements in charging management (Das et al., 2020; Calearo et al., 2021; Afshar et al., 2021). These studies highlight key trends, including the shift toward advanced charging management techniques that are replacing traditional methods. Innovations such as smart charging strategies, wireless charging, and grid-responsive systems aim to optimize charging efficiency, reduce operational costs, and balance grid loads more effectively. However, significant challenges persist, particularly in managing the computational complexity of these systems and the requirement for large datasets to accurately predict demand. Moving forward, leveraging technologies such as predictive analytics, modular design, and real-time data monitoring will be crucial in improving the adaptability, efficiency, and scalability of EV charging infrastructure. Table 5 summarizes representative approaches, highlighting their core methodologies, contributions, and limitations to contextualize the strengths of the proposed All-in-One EV Companion framework.

3.4. EV CMS and mobile apps

Central Management Systems and mobile applications are integral to the evolution of charging management techniques, increasingly being developed and proposed across various platforms. Numerous studies have explored CMS solutions and mobile applications with comparable features.

Gowri and Sivraj (2021) developed a CMS featuring a dual-interface architecture. The system comprises a web application built with PHP and HTML, along with a mobile app designed for the Android platform. This dual-interface setup allows users to monitor EV charging in real-time, make remote reservations, and interact with the system through either a web browser or mobile device. Similarly, other authors, such as Komasilovs et al. (2018), Anderson et al. (2023), have contributed to the growing number of web-based EV management applications. Additionally, Nasr et al. (2023) introduced ChargePrint, a multi-layer framework designed to discover and fingerprint EVCS to identify potential security vulnerabilities for EVCS operators, users, and the power grid. ChargePrint enabled large-scale security analyses of EVCMS using a hybrid approach that examined both firmware and online instances. However, the study noted limitations in obtaining comprehensive information on all EVCMS, particularly those protected by robust security mechanisms. The authors suggest that developing an online platform for real-time discovery and vulnerability assessment of EVCMS could allow developers to submit their products for continuous security evaluations. Anderson et al. (2023) developed a CMS focused on optimizing operating costs and improving the reservation process for EV operators. This system also enhances grid reliability by adjusting power supply to EVSE facilities based on real-time demand. Currently, the system includes a basic token-based payment mechanism, and the authors suggest future improvements, such as integrating a comprehensive payment system for purchasing tokens and enabling dynamic pricing based on charging speeds at the time of reservation. Furthermore, other researchers including (Qureshi et al., 2023; Zhang et al., 2018; Nethravathi et al., 2023) have explored dynamic and tailored pricing models for EV charging infrastructure, aiming to optimize cost-efficiency for both operators and users by adjusting prices based on factors such as demand, charging speed, and grid load.

Mobile applications for EV charging management have also been developed to enhance user convenience. Güldorum et al. (2019), Krishna et al. (2022) presented mobile applications that allow EV owners to submit charging requests, monitor available stations, and view transaction histories. Krishna et al. (2022) developed an app that enables users to join waiting lists and sends regular notifications about charging station availability. Currently available for Android, the app's future plans include cross-platform support via Flutter to accommodate iOS users.

Table 5
Comparison of representative EV charging management techniques.

Study	Methodology	Key features	Limitations/Notes
Kandasamy et al. (2023)	Multi-tap transformer + mobile app	Adjustable voltage levels; real-time monitoring; auto cut-off for safety	Single-user design; limited scalability
Güldorum et al. (2019)	Interoperability platform with grid feedback	Real-time monitoring of charge levels and grid load; adaptive power allocation	Power flow optimization not yet implemented
Cao et al. (2016)	Centralized global entity for EV plan management	Trip-aware scheduling with reservations and traffic conditions	Central control raises security and scalability concerns
Mittal et al. (2023)	ILP model + Branch and Cut Algorithm	Minimizes wait and travel time; mobile-compatible routing tool	Assumes static traffic and station data
Cui et al. (2023)	Stacking regression for fast-charging behavior	Accurate prediction of energy, duration, and dwell time	Focused on public fast-charging only
Mao et al. (2019)	ISS and GA-ISS hybrid algorithm	Handles uni/bidirectional charging; balances loads efficiently	Further work needed on degradation-aware optimization
Dorokhova et al. (2021)	Ethereum-based blockchain for charging	Transparent billing; energy accounting; smart contracts	High transaction cost; PoW is energy-intensive
Abdullah et al. (2021)	Reinforcement Learning for load balancing	Dynamic pricing and charging strategy under uncertainty	High data and computational demands
Lee et al. (2014)	Game theory + RPG integration	Price optimization; higher profits for EVCSs; user cost reduction	Depends on RPG cost and market conditions
All-in-One EV Companion	Modular AI- and blockchain-enhanced CMS framework	Real-time grid-responsive scheduling; scalable; fair pricing; layered integration	Conceptual framework; future validation required

The authors suggest additional features, such as managing multiple vehicles through a single account, introducing reward systems for frequent users, and leveraging Artificial Intelligence (AI) to suggest nearby stations with minimal queues. The app could also send alerts reminding users to charge their vehicles based on travel history. Sadreddini et al. (2021) proposed a reservation system for EV parking lots (PLs) that takes into account user behavior, parking slot availability (PSA), state-of-charge (SoC) of EVs, and users' historical parking lot usage. Similar to the reward system suggested by Krishna et al. (2022), this system awards users based on reservation time (RT) and arrival time (AT), balancing user satisfaction with parking lot revenue, particularly for early reservations. Trinko et al. (2023) introduced Charging-as-a-Service (ChaaS), an intermediary model between electricity providers and EV customers that facilitates the flow of information, electric power, and capital. ChaaS aims to address unpredictable electricity costs for EV customers and low equipment utilization for utilities or charging site owners.

Collectively, these studies emphasize the rapidly evolving nature of CMS and mobile applications within the EV ecosystem. As the demand for secure, user-friendly charging solutions grows, developers are focusing on creating systems with advanced features, such as real-time monitoring, remote reservation capabilities, and robust security measures. The integration of dynamic pricing (including models that vary based on charging speeds), cross-platform compatibility, AI-driven recommendations, reward systems for frequent users, and ChaaS will likely further enhance user experience, operational efficiency, and grid reliability in the near future. Table 6 presents a structured comparison of representative systems, summarizing their methodologies, key features, and limitations to highlight gaps that the proposed unified framework seeks to address.

Table 7 summarizes the various areas of study in EV charging infrastructure, categorizing them into EV simulation systems, communication protocols, charging management techniques, CMS and mobile applications, with examples of specific study details under each category.

4. Identified gaps and opportunities for enhancing EV operational effectiveness

As the EV industry rapidly advances, overcoming critical barriers is key to seamless integration and mass adoption. Core challenges such as fragmented communication protocols, charging inefficiencies, and suboptimal user experience, demand immediate attention. These issues not only slow the growth of the EV ecosystem but also hinder its potential to transform transportation into a more sustainable and efficient model. Yet, tackling these gaps opens significant opportunities. By leveraging cutting-edge solutions including enhanced interoperability among charging stations, novel EV communication methods, and smart charging management, we can greatly improve EV performance and user satisfaction. This section explores both the key obstacles and the groundbreaking solutions shaping the future of electric mobility. By resolving these challenges, the EV industry can establish a truly interconnected, efficient, and scalable transportation network.

4.1. Existing challenges

Understanding the key challenges in the EV ecosystem is essential before proposing solutions. A review of existing studies highlights several obstacles that hinder seamless EV adoption, including fragmented communication protocols, inefficient charging management, and inconsistent user experiences. Addressing these issues is crucial for developing a unified and accessible EV infrastructure. By overcoming these barriers, the industry can drive innovation and accelerate global adoption.

One of the most significant hurdles is achieving interoperability and standardization across the communication protocols used in the EV ecosystem. Effective communication protocols connect EVs, charging stations, and the power grid. However, the lack of global standards results in inefficiencies, inconsistent user experiences, and reduced operational reliability. Effective coordination requires uniform communication protocols (Das et al., 2020). Currently, protocols such as Controller Area Network, Wi-Fi, Bluetooth, and proprietary systems

Table 6
Comparison of representative EV CMS and mobile apps.

Study	Methodology	Key features	Limitations/Future Directions
Gowri and Sivraj (2021)	Dual-interface CMS (web + Android)	Real-time monitoring, remote reservation, cross-platform control	No discussion of pricing or grid integration
Nasr et al. (2023)	ChargePrint framework for security analysis	Vulnerability fingerprinting of EVCS firmware and APIs; hybrid scanning approach	Limited coverage of highly secure or private systems; suggests live vulnerability tracking
Anderson et al. (2023)	CMS for cost optimization and demand-based power control	Token-based payments; grid-aware load balancing; improved reservation system	Lacks full payment system; future focus on dynamic pricing integration
Krishna et al. (2022)	Mobile app (Android) for EVCS reservations	Queue tracking, alerts, historical travel reminders, reward mechanisms	Android-only; proposes cross-platform expansion and AI recommendations
Sadreddini et al. (2021)	PL reservation algorithm with SoC + behavior	Points-based incentives tied to RT and AT; balances user fairness and revenue	Focuses on PLs only; could integrate into broader CMS for network effects
Trinko et al. (2023)	Charging-as-a-Service (ChaaS) intermediary model	Balances cost uncertainty and low utilization; intermediates flow of energy, data, and money	Conceptual; lacks implementation/testing data
All-in-One EV Companion	Conceptual unified CMS with integrated AI, blockchain, and gamification	Modular architecture; scalable deployment; supports smart charging, dynamic pricing, V2V	Implementation roadmap and real-world testing required

serve distinct purposes, each with limitations. CAN, for instance, excels in low-latency, in-vehicle communication but struggles with scalability due to bandwidth constraints, as noted by Gowri and Sivraj (2021). Meanwhile, Wi-Fi offers higher bandwidth for large data transfers but faces interference and security risks in crowded environments. Similarly, Bluetooth provides an affordable short-range solution, yet its limited range makes it impractical for continuous monitoring when users are away from their vehicles (Mukherjee et al., 2023). Fragmented communication protocols hinder interoperability, causing inconsistent charging experiences, particularly for users traveling between regions with differing EVSE standards. Globally, this lack of compatibility slows innovation, prevents cross-platform integration, and undermines the scalability of EV infrastructure.

The ramifications of this fragmentation extend beyond the user experience to operational efficiency and grid management. For example (Cao et al., 2014, 2016) demonstrated how non-standardized protocols hinder the ability of charging stations to coordinate effectively with the power grid. In high-demand areas, such inefficiencies exacerbate bottlenecks, compromise data accuracy, and reduce service reliability. While standardized frameworks such as the OCPP and OSCP have made progress in improving compatibility and energy management, they still fall short of addressing the full spectrum of challenges, particularly with emerging technologies like blockchain and advanced predictive algorithms (Pruthvi et al., 2019).

Beyond communication challenges, optimizing the EV charging process is equally critical. This includes reducing grid strain, lowering costs, and maximizing energy efficiency. Although advanced algorithms and real-time data analysis hold promise for energy distribution, their implementation faces obstacles such as computational complexity and integration challenges with existing grid systems (Parastvand et al., 2020). RL techniques provide adaptable solutions for efficient charging management (Abdullah et al., 2021). However, they require large datasets and often struggle with scalability, limiting their widespread adoption. Current ICT infrastructures are insufficient to support the rapidly growing EV population, and the lack of modular designs restricts the ability to manage large-scale charging networks. Additionally, global coordination is essential to address security risks and ensure seamless charging plan execution, yet such systems remain underdeveloped (Cao et al., 2016). Integrating renewable energy sources and smart grid simulators offers potential solutions, but balancing energy production and consumption is complex. Yan et al. (2020) emphasized the challenges of creating realistic charging load profiles that account for variables like temperature and traffic, highlighting the need for sophisticated models to optimize renewable energy utilization.

User Experience (UX) plays an essential role in encouraging the transition to EVs. Despite advancements in Central Management Systems and mobile applications, fragmentation across charging networks persists. Gowri and Sivraj (2021) observed that many CMS and mobile apps are region-specific, limiting their global applicability. Dual-interface systems, while innovative in enabling real-time monitoring and reservations, often lack interoperability with other platforms, forcing users to rely on multiple apps. Unified platforms capable of cross-network compatibility are essential to eliminate inefficiencies and enhance user convenience.

Moreover, real-time monitoring and predictive tools require further refinement. Current apps, such as those described by Krishna et al. (2022), provide notifications and waiting lists but fail to adapt dynamically to station conditions, such as queue lengths or charging speeds. AI-driven features could revolutionize this space by analyzing travel history and offering tailored recommendations for nearby stations with minimal waiting times. Similarly, predictive tools could proactively suggest charging based on travel needs, optimizing both resource utilization and user satisfaction.

Payment systems and pricing models also need enhancement. Anderson et al. (2023) proposed token-based payment mechanisms, but these systems require further evolution to incorporate dynamic pricing that adjusts for variables like demand and grid load. Advanced solutions, such as those explored by Qureshi et al. (2023), Zhang et al. (2018), could improve cost efficiency for users and operators. Integrating flexible payment options such as mobile wallets, subscriptions, or credit cards into CMS and mobile apps would further streamline the process and ensure transparent pricing. Globally scalable UX solutions must address regional variations in infrastructure, user behavior, and economic conditions. An emerging solution to enhance the accessibility and efficiency of EV charging is Charging as a Service (ChaaS), introduced by Trinko et al. (2023). ChaaS enables users to access flexible, on-demand charging solutions through subscription-based or pay-per-use models, improving user convenience and grid load management. By standardizing charging services and reducing dependency on fragmented networks, ChaaS has the potential to address interoperability and scalability issues within the EV ecosystem

Table 7
Summary of various areas of study in EV charging infrastructure.

Field of study	Applied technology	Datasets	Description	Access link
EV Communication Protocols	CAN module and Wi-Fi and Ethernet-based networks	Gowri and Sivraj (2021)	Providing comprehensive communication between EVs and EVSE over the mentioned communication technologies	Link
	Bi-directional communication	Wang et al. (2015)	A smart EV charging algorithm employing bi-directional communication and smart meters for remote monitoring	Link
	Power/Signal Technology	Cao et al. (2014)	Disseminate dynamic charging station information to EVs on the move using RSUs to relay information from CSs to EVs	Link
	On Board Diagnostics (OBD)	Khorsravinia et al. (2017)	Develops a system which communicates with OBD of Electric Vehicle by using CAN communication protocol	Link
	Publish/Subscribe Framework	Cao et al. (2017)	Propose a publish/subscribe communication framework where charging availability of CSs and charging reservations of EV drivers are shared among network entities	Link
	Practical Byzantine Fault Tolerance (PBFT)	Abishu et al. (2021)	Propose a consensus energy trading mechanism that leverages the benefits of PBFT and Proof of Reputation (PoR)	Link
	Wireless Charging Technology	Yan et al. (2022)	Utilizing Mobile Energy Disseminator (MED) for Dynamic Wireless Charging,	Link
		Porselvi et al. (2022)	Integrating Wireless Power Transfer (WPT) for a contactless power transfer, minimal power loss, reduced transmission and distribution costs	Link
		Panchal et al. (2012)	Designing Wireless Planar Transformers (HFWPTs) with bifilar windings on PCB and incorporating a LLC resonant converter to address flux leakages and EMC problems	Link
	VANETs and Wireless Mesh Networks	Gharbaoui et al. (2012)	Leveraging VANETs and Wireless Mesh Networks technology for bidirectional energy dispatching	Link
	Vehicle-to-Vehicle (V2V)	Bulut and Kisacikoglu (2017)	Develop a mobility model for EVs during their trips and provide communication with other EVs in proximity through a location based social networking system	Link
	vehicle to infrastructure (V2I)	Vishnu and Sivraj (2018)	Develop a user space modules for battery management and infrastructure modules like V2I communication based entry management, navigation management to allotted parking slot, and a centralized server for monitoring, analytics and control	Link
	open-APIs	Dhianeshwar et al. (2016)	Explains the criteria for ranking of different standards for EV-EVSE communication for low voltage DC chargers	Link
	OCPP	COURT (2015)	Implementing the compatibility between a supervision system and several charging stations from different constructors using OCPP	Link
		Pruthvi et al. (2019)	Review of the functionalities OCPP offers in the EV charging infrastructure	Link
	V2G Communication	Boglou and Karlis (2023)	Develop an optimal charging and V2G management system for the integration of EVs into low voltage distribution networks	Link
		Tan et al. (2016)	Review on V2G technologies and optimization techniques	Link
		Helmy et al. (2023)	Designing a system using AUTOSAR architecture which provide real-time traffic and weather updates and serve as a mobile energy storage system as well as supplying power to the grid during peak demand	Link
EV Charging Management Techniques	Blockchain Framework	Dorokhova et al. (2021)	Utilize emerging blockchain technology, specifically Ethereum, for decentralized, efficient, fast, and secure EV charging management	Link
	Internet of Things (IoT) and Blockchain Paradigm	Martins et al. (2019)	Integrating the IoT with a decentralized blockchain approach to streamline the EV charging process in shared spaces like condominiums	Link
	Branch and Cut Algorithm (BCA)	Mittal et al. (2023)	Using BCA for optimizing the selection of EV charging stations to minimize travel and charging times	Link
	Stacking regression technology	Cui et al. (2023)	A charging behavior prediction framework that leverages stacking regression technology, improving prediction accuracy and effectively evaluating charging priorities	Link

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Table 7 (*continued*).

Field of study	Applied technology	Datasets	Description	Access link
	Dynamic pricing strategy	Qureshi et al. (2023)	The dynamic pricing mechanism proposed a menu of prices based on demand and deadlines for each EV request	Link
	Pricing scheme	Zhang et al. (2018)	Design an optimal pricing scheme to minimize the service dropping rate of the charging station	Link
	PSO algorithm	Liu et al. (2022)	Introduce a real-time pricing strategy for charging station alliances (CSAs) and utilizes a modified PSO algorithm to solve the model	Link
	Tailor-made Billing Model	Nethravathi et al. (2023)	Using the dynamic pricing model to maximize user satisfaction and renewable energy utilization while minimizing grid dependency and charging costs	Link
	OCPP	Hsaini et al. (2022)	An algorithm to optimize charging schedules through binary integer programming, and a remote module to manage charging operations	Link
	Voltage Changing	Kandasamy et al. (2023)	Utilizing the multi-tap changing transformer to control output charging voltage to the vehicle	Link
	RL	Abdullah et al. (2021)	A review on the existing RL-based framework for the charging coordination strategies of EVs in the power systems	Link
	Intelligent Scatter Search (ISS) algorithm	Mao et al. (2019)	Integrating unidirectional and bidirectional charging through the ISS framework to smooth the daily load profile and minimize charging costs, showing superior performance and reduced computational time	Link
	Big data analysis	Oad et al. (2023)	Leveraging big data analytics to enhance decision-making and prevent grid instabilities	Link
	Scheduling Algorithm	Mukherjee and Gupta (2014)	A Review of Charge Scheduling of Electric Vehicles in Smart Grid	Link
	Game Theory	Lee et al. (2014)	Analyze the competitive interactions between EVCSs using game theory, where transmission line capacity, the distance between EV and EVCS, and the number of charging outlets at the EVCSs is considered	Link
	max-weight matching algorithm	Zhang et al. (2016)	Utilizing a bipartite graph model and a max-weight matching algorithm to optimize charging and discharging behaviors	Link
	Review	Sun et al. (2019)	A review on Technology Development of Electric Vehicles	Link
		Das et al. (2020)	A Technological review on EV standards, charging infrastructure, and impact on grid integration	Link
		Calearo et al. (2021)	A review of data sources for EV integration studies	Link
		Sanguesa et al. (2021)	A Review on EV Technologies and Challenges	Link
		Afshar et al. (2021)	A review on mobile charging stations for EVs	Link
EV CMS	CMS	Cao et al. (2016)	Propose a CMS that considers EVs' anticipated charging reservations and parking duration at CSs	Link
	Multi-stage CMS	Nasr et al. (2023)	multi-stage framework, ChargePrint, to discover Internet-connected EVCMS and investigate their security posture	Link
	Stochastic Optimization	Honarmand et al. (2015)	Proposed a stochastic charging and discharging scheduling method for a large number of parked EVs in an intelligent parking lot where intelligent parking lots are potentially introduced as aggregators allowing EV interact with the utilities	Link
	Adaptive Utility-oriented Scheduling (AUS)	Wei et al. (2017)	Develop a multi charging system and design an intelligent charging management mechanism to maximize the interests of both the customers and the charging operator	Link
	Random Forest and Linear Search Algorithm	Sarika and Sivraj (2022)	A cloud-based recommender system integrating the Random Forest Algorithm to identify nearby stations, the Linear Search Algorithm to filter stations based on user needs, and the Haversine formula to calculate distances	Link
	Ridesourcing system	Wang and Yang (2019)	Propose a general framework to describe ridesourcing systems	Link
	Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) method	Wu et al. (2016)	a PROMETHEE method-based decision system combined with the cloud model is proposed in this paper for EVCS site selection	Link
	IoT	Kharade et al. (2020)	IoT Based Charging Slot Locator at Charging Station	Link
	Solar PV	Speidel and Bräunl (2014)	Review on driving and charging patterns of EVs and solution of using Solar PV for energy usage	Link

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Table 7 (*continued*).

Field of study	Applied technology	Datasets	Description	Access link
	Multiple-criteria decision-making (MCDM) techniques	Sadreddini et al. (2021)	Proposing a smart reservation system considering the behavior of EV users, parking slot availability (PSA), state-of-charge (SoC) value of EVs, and PL usage history of EV users using MCDM techniques	Link
	Roaming	Ratej et al. (2013)	An integrated roaming solution which mediates between the electromobility entities to enable roaming	Link
	AI and IoT	Bharathi et al. (2022)	EV monitoring system leveraging AI and IoT to track critical battery parameters and determine the SOC	Link
	An Interoperability Platform	Güldorum et al. (2019)	Propose an interoperability software for EVSE Considering Dual System Operator and EV Owner Sides	Link
	Simulation Platform	Bedogni et al. (2015)	Proposing a novel EV simulation platform that can assist in the pre-deployment of charging infrastructures and services on realistic large-scale EM scenarios	Link
	Microcontroller	Tannahill et al. (2015)	Proposes an improved SoC estimation algorithm for implementation which provides an enhanced range estimation method that can consider various environmental and behavioral factors	Link
EV Mobile/Web Application	Google maps SDK and API	Krishna et al. (2022)	Mobile App display charging station locations and directions as well as providing an option to add EV owner to the waiting list at a charging station	Link
	Web Application	Komasilovs et al. (2018)	Developed Web platform for sharing information about privately owned charging stations, to link station hardware with software for real-time charging data and station availability updates	Link
		Anderson et al. (2023)	Propose a charger reservation web application to monitor, control and mitigate operating costs	Link
	ICT platform, recommender and data integration systems	Ferreira et al. (2013)	Mobile App providing information on Full Electric Vehicle range, charging station locations, electricity market updates, and route planning that includes public transport and sharing systems	Link
	Navigation APIs	Andreasson and Axelsson (2020)	Comparing technologies and algorithms behind mapping and routing APIs for EVs	Link
	Bluetooth	Mukherjee et al. (2023)	A Mobile App capable of gathering the vehicle parameters such as speed, odometer reading, SoC and battery temperature from the IVN over a secured Bluetooth connection	Link
	on-board diagnostic (OBD) tool	Giron et al. (2023)	Developed an OBD system based on CAN protocol, an ESP32-based interface tool, and an Android-based mobile application and discussed data capturing, logging, and processing techniques of the proposed system	Link
	An open-source solution and Human Machine Interface (HMI)	Sumith et al. (2022)	Designed a Digital Dashboard which provides vehicle dynamics information to the user that can be used during travel, use and maintenance of the EV	Link
	Waterfall Method	Priatna et al. (2023)	A Mobile App integrating authentication, maps, and location APIs	Link
	Dart Programming Language	Dhanesha et al. (2023)	Planning and implementation of an EV charging station finder application developed in Android Studio using Dart Programming Language	Link
	Java and Kotlin language	Muddalkar et al. (2022)	Develop an EV charging station finder application developed in android studio using Java and Kotlin language	Link
	Flutter based mobile application	SM et al. (2023)	A mobile application provides the user with details of charging station locations, number and type of present chargers and availability of slots during a specific period	Link
	An open-source solution and Human Machine Interface (HMI)	Sumith et al. (2022)	Designed a Digital Dashboard which provides vehicle dynamics information to the user that can be used during travel, use and maintenance of the EV	Link
	Mobile App	Qian et al. (2022)	A mobile platform for chargEV with the purpose of filling in the possible gaps in the EV charging experience in Malaysia	Link

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Table 7 (*continued*).

Field of study	Applied technology	Datasets	Description	Access link
	IoT	Al Kahfi et al. (2023)	Propose a system that gives information on battery conditions supported by accurate sensor devices, such as voltage, current, and temperature sensors	Link
		Sivaramkrishnan et al. (2023)	Develop system integrates IoT to provide real-time updates and critical information about the EV's parameters	Link
		Meisenbacher et al. (2021)	Presents the User Interface (UI) of the Smart Charging Wizard web app to start, adjust and monitor the charging process and using IoT technology to connect with the charging station	Link
		Bedogni et al. (2014)	The application provides functionalities of battery monitoring, dynamic range prediction, and EV supply stations (EVSS) discovery along the way and allows EV drivers to reserve a charging slot	Link
	OCPP	George et al. (2019)	Design a system that displays the SoC of the EVs battery constantly as well as the nearest charging stations. With the ability to direct the driver to the slot booking website	Link
	Review	Csiszár and Pauer (2019)	Review on the existing Mobile Applications Aiding the Electromobility	Link
	Cybersecurity	Muhammad et al. (2023)	A cybersecurity risk assessment of EV mobile applications	Link
EV Simulation System	Simulation model	Chaudhari et al. (2018)	Agent-based aggregated behavior modelling for EV simulation system	Link
		Li et al. (2020)	Propose a compact electromagnetic transient program (C-EMTP) algorithm for the real-time simulation of an EV station with multiple high-frequency chargers	Link
		Diaz et al. (2024)	Optimization of EV charging stations through a comprehensive simulation approach	Link
		Yan et al. (2020)	Present a spatial–temporal EV charging load profile simulation method considering weather and traffics	Link
		Ferraris et al. (2019)	Develop a control algorithm capable of independently managing wheel torques to enhance vehicle dynamics, which is implemented within a vehicle dynamic model in a co-simulation environment	Link
		Bedogni et al. (2015)	Integrated simulation framework to model EV operations and services	Link

In addition, simulation systems are invaluable for predicting real-world outcomes, but existing platforms have limitations. For example, Bedogni et al. (2015) developed a comprehensive simulation framework, but it does not fully capture the impact of regenerative braking on energy consumption. Similarly, Ferraris et al. (2019) highlighted the importance of cosimulation environments for optimizing control algorithms, yet these tools often require significant computational resources and struggle to replicate diverse real-world scenarios. Integration with renewable energy and grid systems remains another challenge. Although such integration could improve grid stability, current models often lack interoperability and fail to incorporate emerging technologies (Yan et al., 2020).

Finally, collaboration among stakeholders is vital for establishing common standards and protocols that can unify the EV ecosystem. Such collective efforts are essential to addressing interoperability challenges, which currently hinder seamless integration, and fostering innovation to accelerate the shift toward sustainable EV infrastructure (Sun et al., 2019; Das et al., 2020). Achieving a globally standardized communication framework demands international cooperation to harmonize existing protocols, the development of hybrid systems that balance reliability with throughput, and the deployment of predictive algorithms to enhance grid interaction. By tackling these challenges, the EV industry can unlock its full potential, paving the way for an efficient, scalable, and sustainable transportation system. To achieve this vision, future research should prioritize refining hybrid communication models, exploring the integration of advanced technologies like blockchain and artificial intelligence, and promoting global standardization efforts. By advancing these solutions, the EV industry can drive a global shift toward more efficient, scalable, and sustainable transportation, ensuring a cleaner future for generations to come.

4.2. *Key functionalities for enhancing EV performance and efficiency*

The rapid expansion of the EV market has intensified the need for advanced technologies that enhance performance, efficiency, and seamless integration with the energy grid. As EV adoption accelerates, addressing challenges related to scalability, grid connectivity, and user convenience becomes crucial. Key functionalities such as smart energy management, advanced communication protocols, charging interoperability, and data-driven optimization play a central role in this transition. Smart energy management leverages predictive algorithms to optimize energy demand and supply, ensuring efficient use of resources. Advanced communication protocols facilitate real-time data exchange between vehicles, charging infrastructure, and grid operators, enabling dynamic load balancing and improved grid stability. Additionally, interoperable charging solutions reduce downtime, enhance accessibility, and lower costs by standardizing connections across diverse charging networks. Finally, data-driven optimization enhances decision-making by leveraging real-time insights to improve charging efficiency and network reliability. The following subsections explore these functionalities in greater detail, building upon the foundational principles outlined in the previous section.

4.2.1. *Interoperability across charging management*

The growing adoption of Electric Vehicles has underscored the pressing need for interoperability and standardization in communication protocols within the EV ecosystem. Seamless interaction between EVs, EVSE, and the power grid is crucial for an efficient and scalable charging network. However, the absence of globally recognized standards has resulted in fragmentation and inefficiencies, which impede the development of a cohesive EV ecosystem. To address these challenges, researchers have explored innovative solutions to enhance compatibility, improve accessibility, and standardize communication protocols across various components of the EV infrastructure. This paper highlights some of these key advancements and their contributions to tackling the interoperability challenge.

Gupta et al. (2024) leverages the integration of streetlight networks with Wi-SUN communication technology and oneM2M middleware to create an interoperable EV charging infrastructure. Using Level 2 charging standards and OCPP, this approach improves compatibility across different charging networks. This combination of OCPP, Wi-SUN, and oneM2M establishes a scalable solution that seamlessly integrates with broader smart city infrastructures. Building on the need for interoperability, Güldorum et al. (2019) introduces a platform for EV charging services that incorporates the perspectives of both system operators and EV owners. This platform uniquely integrates power system operators into the ecosystem while addressing the critical role of EV charging service aggregators. Similarly, Haneem et al. (2023) advances the effort by proposing the Data Exchange Interoperability Protocol (DEXIP), designed to enhance the accessibility of EV charging stations. Using a RESTful Web API, DEXIP enables seamless cross-network access among service providers, thus improving user convenience. Shirsat et al. (2022) introduces a DC fast-charging system that enables multiple EVs to charge simultaneously, improving efficiency. Lastly, Ahmet (2024) focuses on Plug and Charge (PnC) technology, emphasizing the importance of Public Key Infrastructure (PKI) for secure and intelligent charging.

These efforts mark significant progress in overcoming EV interoperability challenges. The provided solutions are vital steps toward creating a more connected and efficient EV ecosystem. However, despite these advancements, the need for a unified, globally recognized platform that ensures seamless interoperability across diverse systems remains critical. To fully realize the potential of electromobility, future efforts should focus on developing a unified, globally recognized framework. Collaboration among industry leaders, researchers, and policymakers will be key to integrating these fragmented solutions into a truly scalable and interoperable EV ecosystem.

4.2.2. Novel approaches in EV communication

The advancement of Intelligent Transportation Systems (ITS) depends on robust communication technologies that enable seamless interaction between vehicles and infrastructure. V2V and Vehicle-to-Infrastructure (V2I) communication are pivotal in facilitating safer, more efficient transportation systems (Nguyen et al., 2021). Vehicle-to-everything (V2X) communication extends beyond V2V and V2I, incorporating vehicle-to-network (V2N), vehicle-to-roadside unit (V2R), and vehicle-to-pedestrian (V2P) interactions for a fully connected ecosystem (Wang et al., 2020). V2X began with Dedicated Short-Range Communication (DSRC) (IEEE 802.11p) but has evolved to advanced Cellular Vehicle-to-Everything (C-V2X) systems. These technologies exchange critical information, such as vehicle speed, location, and traffic conditions, reducing accidents and congestion. While early communication standards like IEEE 802.11p laid the groundwork, the evolution toward Long-Term Evolution-Vehicle (LTE-V) (Park et al., 2018; Sangsuwan and Poochaya, 2021), 5G New Radio (NR) (Li et al., 2017; Thiruvasagam et al., 2019), and C-V2X (Sabeeh and Wesołowski, 2020; Sabeeh et al., 2022) has moved the field forward, addressing challenges such as latency, reliability, and scalability. C-V2X introduces Cooperative Awareness Messages (CAMs) that ensure efficient data broadcasting, enabling critical applications like collision warnings, speed guidance, and autonomous driving (TR, 2015). These new technologies provide highly reliable and low-latency communication, significantly improving road safety and enabling the development of intelligent transportation networks (Li et al., 2023). However, achieving interoperability and standardization across diverse communication protocols remains a significant obstacle. The transition from fragmented solutions to integrated systems requires innovative approaches to ensure compatibility and enhance the operational efficiency of the EV ecosystem.

Researchers have tackled the challenges of interoperability and standardization within the EV ecosystem by proposing innovative solutions. For instance, Wi-Fi-based communication systems utilizing ESP-MESH and ESP-NOW protocols have demonstrated real-time operation capabilities for low-speed vehicles, enabling large-scale deployment (Nguyen et al., 2021). Similarly, relay routing methods for 5G C-V2X that optimize relay selection have expanded communication areas while minimizing interference and infrastructure needs (Kawamatsu et al., 2022). Other advances include wireless communication networks for EVSE based on IEEE 802.15.4 and OCPP protocols, which ensure seamless interaction between charging points, Local Charging Managers, and Central Systems (Rodríguez-Serrano et al., 2013).

Studies comparing IEEE 802.11p and LTE-V2V under different conditions (line-of-sight (LoS) vs. non-line-of-sight (NLoS)) highlight alternative protocols for improving communication reliability (Singh and Singh, 2020). Protocol integration efforts, such as systems combining IEC 61851-1 and OCPP 2.0.1 standards, enable real-time communication between EVSE, EVs, and management systems, emphasizing scalability for urban deployment (Yamamoto et al., 2023).

Emerging technologies, such as Li-Fi and blockchain, have introduced novel approaches to EV communication. Visible Light Communication (VLC) systems have demonstrated eco-friendly and energy-efficient V2V communication, reducing reliance on traditional wireless channels (Soundari et al., 2022). Meanwhile, Blockchain-Enabled V2V Communication Systems (BVCS) leverage smart contracts and decentralized algorithms to ensure secure and trusted data sharing, addressing challenges related to data security and privacy in future autonomous vehicle systems (Das et al., 2020).

The field of EV communication has witnessed significant progress, with researchers proposing novel solutions to overcome challenges related to interoperability, reliability, and scalability. From cost-effective Wi-Fi-based systems to advanced 5G relay routing methods, each contribution addresses unique facets of communication within the EV ecosystem. These advancements not only enhance operational efficiency but also pave the way for safer and more sustainable transportation systems. To achieve a fully connected transportation network, prioritizing global standards and seamless interoperability is essential. Future research should focus on harmonizing communication protocols to unlock the full potential of intelligent mobility.

4.2.3. Smart charging management

Efficient management of EV charging is essential to meet the rapidly increasing demand for charging infrastructure while ensuring grid stability and user satisfaction. Smart charging systems optimize energy distribution, ease grid strain, and enhance user experience. Using advanced algorithms, real-time data, IoT, and machine learning, these systems tackle scalability, energy efficiency, and cost challenges. This section highlights several innovative approaches proposed in recent studies to enhance smart charging management. Das et al. (2020) introduces a dual-method approach to EV charging station load management, focusing on constant and variable current strategies. The constant current method deactivates charging slots to manage load, while the variable current method adjusts charging rates based on energy deficits and user availability. Simulations show reduced energy trade, improved charging efficiency, and minimal impact on user wait times.

Building on load management, Guo et al. (2023) proposes a Kalman filter-based model to enhance load prediction and minimize grid impact. This approach includes day-ahead predictions for 24 time scales and rolling optimization in the intra-day stage, addressing uncertainties during charging. The model, tested on real-world charging station data, achieves superior prediction accuracy compared to traditional

BP neural network and ARIMA models, showcasing its effectiveness in optimizing daily charging costs and improving grid integration.

Machine learning algorithms are also being utilized to prioritize grid stability and driver satisfaction. Researchers (Sabzi and Vajta, 2024) developed a driver satisfaction classification model which was integrated into an optimization framework to manage charging behaviors. It also highlights the role of State of Charge (SoC) and charging fees in influencing user decisions while maintaining scalable solutions for grid stability.

The development of smart metering infrastructure offers another avenue for improving EV charging efficiency. A study by Hewalekar and Gadgune (2020) presents a smart metering system featuring real-time energy monitoring, secure payment via smart cards, and accurate KWh metering. The system emphasizes reducing charging times, enhancing battery performance, and supporting fast-charging applications while aiming for cost-effective and secure solutions for widespread deployment.

Additionally, Margowadi et al. (2023) has proposed a smart charging architecture integrating a Charging Station Management System (CSMS) with an Electrical Power Monitoring System (EPMS). Leveraging IoT devices, this system utilizes the OCPP and MQTT for seamless communication between charging stations and the electrical grid. By analyzing datasets from EVs, electrical power systems, and EV owners, the architecture effectively optimizes charging profiles, enhancing grid reliability and energy management.

Finally, an IoT-based smart EV charging system, IoTSEVC, has been introduced to improve user convenience and energy distribution efficiency (Vijayashanthi et al., 2024). This system incorporates cloud-based transaction storage, QR code payments, and Android-based station management, enabling real-time energy trading and metering. Compared to traditional Solar Powered EV Charging (SPEVC) systems, the platform offers enhanced energy demand management and actionable insights for grid operators. Future developments envision faster payment methods and dynamic EV allocation, paving the way for scalable and efficient EV charging solutions.

In conclusion, smart charging management systems play a pivotal role in addressing the challenges associated with EV adoption. Integrating these innovations optimizes energy distribution, enhances user satisfaction, and ensures grid stability. As illustrated in Fig. 4, current EV ecosystems remain fragmented across multiple communication protocols and stakeholders, highlighting the urgent need for a more unified approach. As the EV ecosystem continues to evolve, further research and development in smart charging systems will be critical to supporting the transition to sustainable transportation.

Section 4 Highlights

- Lack of global EV standards limits charging scalability and integration.
- Charging protocols hinder real-time grid coordination and efficiency.
- Optimization methods face scalability and grid integration issues.
- UX suffers from region-specific apps and poor dynamic pricing support.
- Simulations lack support for renewables and realistic EV behaviors.

5. All-in-One EV companion

Building on the gaps identified in EV infrastructure in Sections 3 and 4, this section introduces the All-in-One EV Companion, a unified framework designed to eliminate fragmentation within the EV ecosystem. As noted in Section 3, EV simulation systems, communication protocols, and charging management lack cross-platform compatibility, causing inefficiencies. Additionally, Section 4 underscores critical challenges related to interoperability, scalability, and user experience. Addressing these challenges requires a comprehensive solution that seamlessly integrates EV simulation, standardized communication protocols, and advanced charging management technologies. The "All-in-One EV Companion" is designed to streamline the development and deployment of EV technologies, focusing on improving charging efficiency, reducing infrastructure fragmentation, and alleviating range anxiety. This framework integrates blockchain, AI, and gamification to standardize and unify the EV ecosystem. By fostering interoperability and enhancing user experience, this unified approach has the potential to optimize operational efficiency and accelerate large-scale EV adoption, as illustrated in Fig. 5. To provide a more detailed view of its operational structure, Fig. 6 presents the layered system architecture of the proposed framework. This includes the infrastructure, middleware, and application layers that support real-time coordination, stakeholder communication, and service delivery across the EV ecosystem.

5.1. V2V communication

One of the key pillars in enhancing safety and efficiency in the EV ecosystem is V2V communication. V2V communication enables vehicles to share real-time traffic, battery status, and charging station data, helping drivers make informed route decisions and reducing range anxiety. While our proposed framework outlines V2V as a conceptual pillar, we acknowledge that implementing this capability in real-world scenarios requires strict latency constraints, particularly under NLoS and high-traffic conditions. Future work should focus on validating sub-100 ms latency performance through simulation-based studies and exploring integration with C-V2X technologies to mitigate data packet loss and ensure robust connectivity in urban environments.

5.2. Standardization and infrastructure unification

The standardization and unification of EV systems and infrastructure are integral to this framework. Collaboration among industry leaders, policymakers, and standards organizations is crucial to establishing universal charging, payment, and communication standards. This unification would streamline the user experience by eliminating concerns over compatibility and simplifying the charging process. A phased approach, starting with charging infrastructure standardization and expanding to incorporate advanced smart grid technologies, will accelerate EV unification and drive broader adoption.

To support secure and equitable cross-network data sharing, the framework incorporates a federated governance model. Data ownership is preserved through role-based access control and standardized APIs embedded within the DEXIP protocol, allowing stakeholders to share only necessary metadata while retaining proprietary control. In compliance with the General Data Protection Regulation (GDPR) and the California Consumer Privacy Act (CCPA) regulations, the system supports consent management, data minimization, and anonymization or pseudonymization of personally identifiable information. Smart contracts may also be used to enforce data access rights and maintain transparent audit trails, ensuring that the framework supports legal compliance alongside operational interoperability.

5.3. Gamification for user engagement and sustainable driving

Gamification offers an innovative strategy to engage users and promote responsible driving behavior. By incorporating game-like features into the EV ecosystem such as rewarding drivers for energy-efficient behavior or optimal use of regenerative braking, this framework encourages users to adopt environmentally friendly habits. Through competition, achievement-sharing, and reward systems, users will be motivated to embrace electric vehicles and sustainable driving practices.

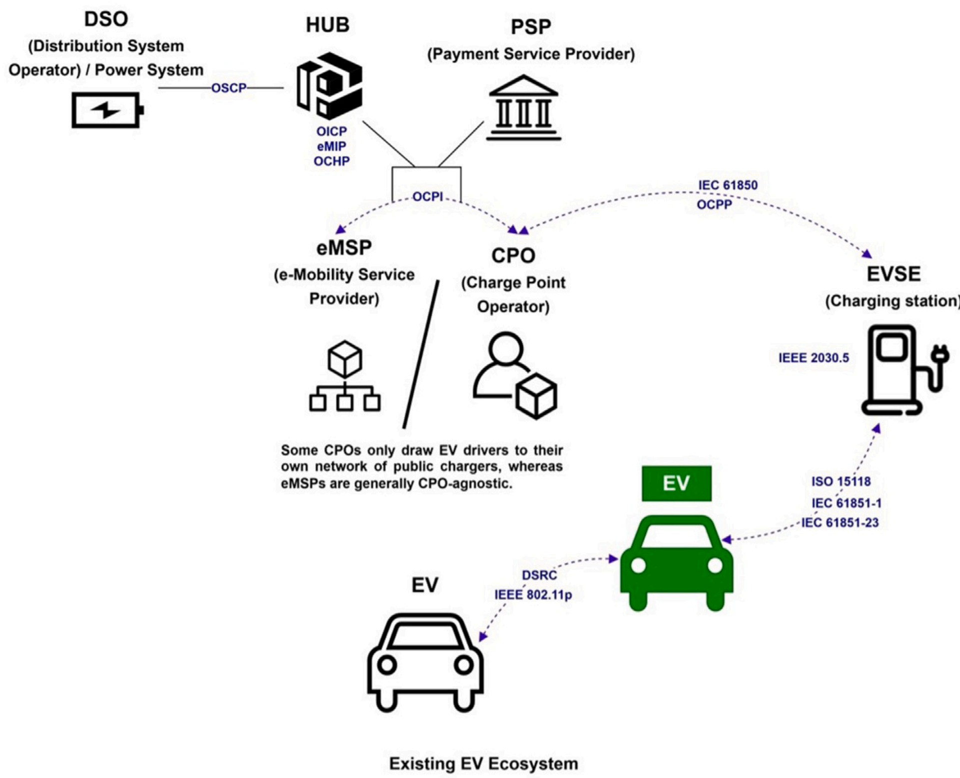

Fig. 4. Fragmented structure of the current EV ecosystem, illustrating the lack of interoperability across communication protocols, platforms, and stakeholders.

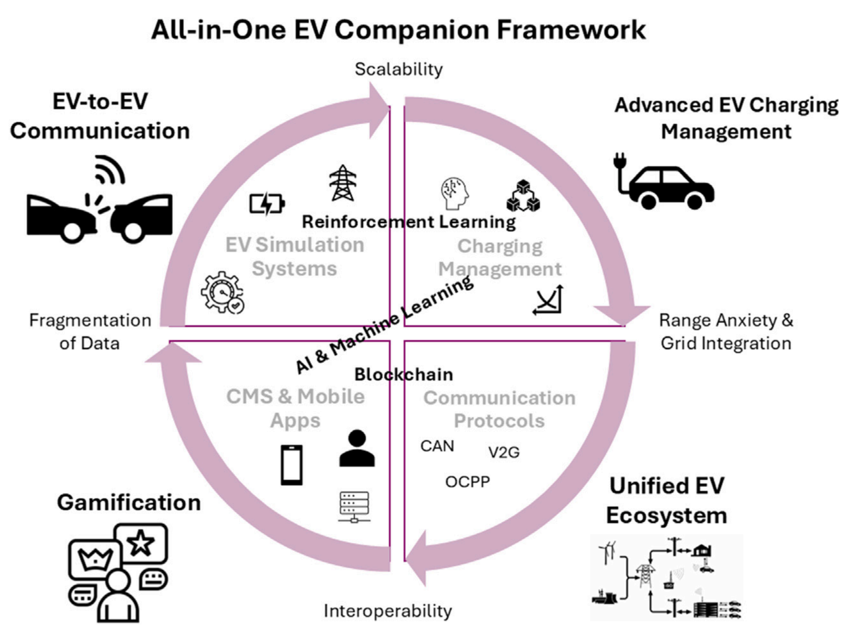

Fig. 5. A Unified Framework for Future EV Adoption.

While this component of the framework is conceptual, it is informed by findings in the reviewed literature that highlight the positive behavioral impact of gamified interventions. Empirical validation remains essential to substantiate its comparative effectiveness against traditional incentive structures. As part of future work, pilot studies are planned using quantifiable behavioral metrics such as improved charging compliance, increased regenerative braking usage, and eco-routing adoption to evaluate the effectiveness of gamification in promoting sustainable driving behaviors.

5.4. Key considerations in the design of advanced EV management systems

Another key component of this framework is the integration of advanced CMS capable of real-time monitoring of battery health, route planning, and charging station availability. Leveraging AI and IoT, these CMS platforms can predict optimal charging times, reduce grid strain, and lower operational costs, enhancing both system efficiency and user satisfaction.

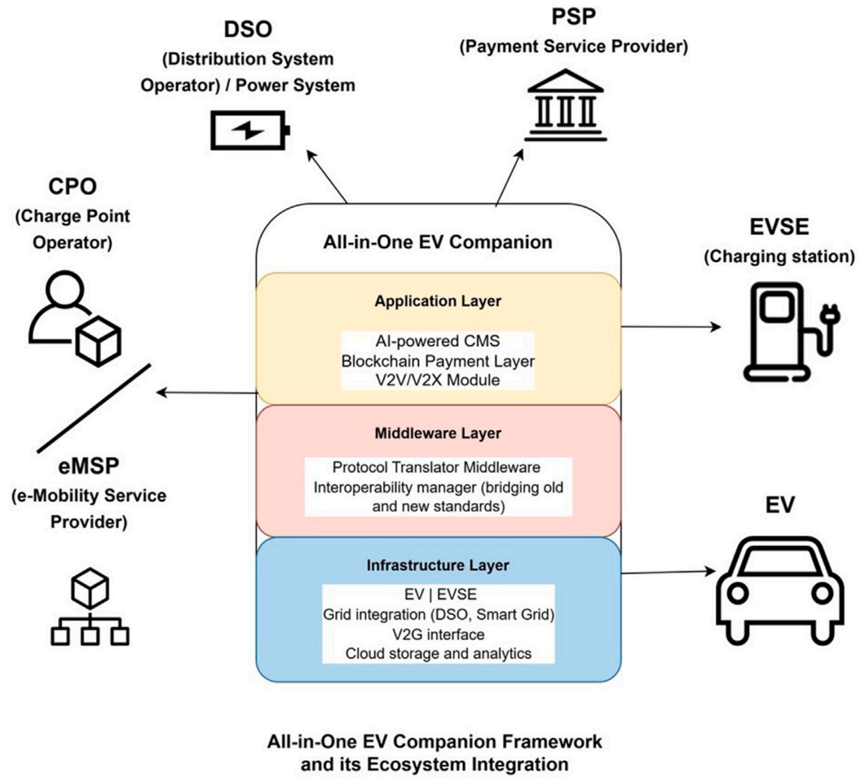

Fig. 6. Layered architecture of the proposed All-in-One EV Companion, highlighting the integration of application, middleware, and infrastructure layers across stakeholders.

5.4.1. *Dynamic pricing and game-theoretic models*

To align utility revenue models with user affordability, the framework incorporates a game-theoretic perspective in which charging stations act as price-setting agents and EV users as cost-sensitive responders. This interaction is modeled as a repeated game, allowing dynamic pricing strategies to evolve based on usage behavior and demand patterns. To avoid price surges, especially during peak periods, constraint-based optimization techniques and user elasticity data can be applied to keep pricing within equitable bounds. Future iterations may incorporate socio-economic data and incentive-compatible pricing models to support fair access, particularly for low-income users.

5.4.2. *Secure and scalable blockchain-based transactions*

To ensure secure and transparent financial transactions, blockchain technology is introduced into the payment architecture. Smart contracts automate the charging process and ensure that users are fairly billed based on actual energy consumption. However, we acknowledge that traditional Ethereum implementations, particularly those based on Proof-of-Work (PoW), are energy-intensive and may not be viable for high-volume, real-time EV charging scenarios. To address this limitation, the framework considers more energy-efficient blockchain alternatives. For instance, Dorokhova et al. (2021) propose transitioning to Ethereum 2.0's Proof-of-Stake (PoS) consensus, which substantially reduces computational load. Additionally, Layer-2 solutions such as Optimistic Rollups and zk-Rollups, can aggregate transactions off-chain and batch, submit them to the mainnet, improving throughput and minimizing gas fees. For microtransactions, state channels such as the Raiden Network provide near-instantaneous, low-cost settlement. These techniques collectively support scalable and energy-efficient charging transactions. Future work will explore hybrid Layer-1/Layer-2 architectures to ensure secure, high-performance integration across heterogeneous infrastructures.

5.4.3. *High-fidelity energy and mobility modeling*

In parallel, the framework acknowledges the importance of accurately modeling energy dynamics. Many existing EV simulation tools omit key physical behaviors such as regenerative braking, which affects V2G energy flows and system performance. To enhance fidelity, future implementations may incorporate high-resolution vehicle dynamics using platforms like MATLAB/Simulink (Simscape), SUMO, or OpenDSS. These tools can embed braking logic and simulate stochastic urban mobility patterns, strengthening the framework's robustness under real-world conditions. To optimize system behavior in the face of variable energy supply and charging demand, the framework also considers stochastic optimization techniques. Probabilistic forecasting and adaptive scheduling are proposed to dynamically balance intermittent renewable generation (e.g., solar volatility) with spatially heterogeneous EV load. These methods enable the system to align fluctuating supply with real-time demand while reducing grid dependency and avoiding transformer overloads.

5.4.4. *Intelligent forecasting and anomaly detection*

While Kalman filters offer effective short-term prediction under stable conditions, their limitations in detecting sudden anomalies are recognized. In response, the framework allows for hybrid forecasting models that incorporate real-time anomaly detection using machine learning approaches such as long short-term memory (LSTM) and recurrent neural networks (RNNs). These models can identify irregular demand patterns such as fast-charging spikes during emergencies, and activate contingency protocols like prioritized charging or load shedding to maintain grid stability. To further support intelligent, scalable coordination across EV fleets, RL is considered for route and charging optimization. Given the real-time constraints of large-scale applications, the framework proposes a hierarchical RL structure to decompose complex planning tasks into smaller subtasks, improving convergence and responsiveness. Policies can be pre-trained offline using historical data and deployed via lightweight models at the edge or in the cloud. Real-time updates and policy approximation techniques ensure adaptability without requiring full retraining, making RL practical for high-density urban settings.

5.4.5. Scalable deployment and system resilience

To ensure feasibility in real-world, dynamic urban environments, the framework adopts a modular, software-driven architecture that supports phased deployment. This allows core components such as standardized communication protocols and AI-powered charging systems to be implemented first, minimizing system complexity in early stages. Cloud orchestration and edge computing are used to distribute computational load and maintain real-time responsiveness across large EV fleets.

Additionally, resource allocation and dynamic load balancing strategies are integrated to adaptively manage congestion and system stress. Blockchain modules employ lightweight consensus mechanisms to reduce overhead, while AI and CMS components utilize scalable models that can be tuned to network size and user behavior. Future work will focus on benchmarking the framework's computational performance using synthetic urban mobility and energy datasets to validate its scalability under various deployment scenarios.

5.5. Interoperability across protocols and standards

Given the fragmented nature of EV-EVSE communication systems, interoperability is a cornerstone of our proposed All-in-One EV Companion framework. Diverse protocols, ranging from legacy systems such as CAN and Bluetooth to emerging standards like ISO 15118, currently coexist in the EV ecosystem. This coexistence presents both challenges and opportunities for integration. To ensure interoperability across heterogeneous EV-EVSE networks, we advocate for a hybrid and layered communication architecture. In this design, intermediary controller units or middleware modules serve as protocol translators between lower-layer, hardware-dependent standards and higher-layer communication protocols. For instance, middleware can bridge CAN or Bluetooth interfaces with ISO 15118-compliant message formats, facilitating consistent interaction without replacing existing infrastructure.

Importantly, standardized protocols such as the OCPP and OSCP operate at higher layers of the communication stack and can be decoupled from the underlying physical communication method. This decoupling allows CMS developers and infrastructure providers to maintain a uniform control and energy management layer, even as hardware and local communication technologies vary.

This layered approach provides:

- **Compatibility** between old and new technologies,
- **Scalability** across regional or vendor-specific deployments,
- **Smooth migration** paths for infrastructure modernization.

By highlighting this interoperability pathway, the proposed framework lays a foundation for scalable, future-ready charging infrastructure. Further research and prototyping will explore secure middleware implementations and real-world ISO 15118–OCPP integration strategies, forming part of our planned future work.

5.6. Phased implementation and industry collaboration

To realize the full potential of the All-in-One EV Companion framework, collaboration among EV manufacturers, software developers, policymakers, and standardization bodies is essential. A phased approach is recommended starting with the unification of charging infrastructure and progressively expanding to incorporate smart grid technologies, V2V communication, and gamification elements. This integrated framework will not only address the challenges identified in this study but also create an EV ecosystem that is efficient, scalable, and sustainable. By implementing these technological advancements and fostering industry-wide collaboration, stakeholders can facilitate the widespread adoption of EVs. This transformation will accelerate EV adoption, reduce environmental impact, and lay the foundation for a smarter, more sustainable transportation ecosystem.

Section 5 Key Points

All-in-One EV Companion:

- Unified EV framework integrates V2V, CMS, AI, and blockchain systems.
- Standardized protocols and layered design ensure full interoperability.
- Gamification promotes eco-driving and boosts user engagement.
- AI-enabled CMS supports dynamic pricing and load optimization.
- Modular architecture enables scalable, phased real-world deployment.

6. Conclusion

The EV ecosystem represents a highly efficient means of reducing greenhouse gas emissions and addressing the growing problem of air pollution. However, the current landscape, characterized by diverse data sources, EV systems and applications, often leads to fragmentation and confusion among users. This fragmentation poses significant barriers to the widespread adoption of EVs, as it exacerbates issues such as range anxiety and uncertainty about charging infrastructure. By investigating numerous studies and existing approaches, this paper identified gaps in current technologies and categorized data from various sources into four key areas; EV simulation systems, EV communication protocols, charging management techniques, CMS and mobile applications.

To overcome these challenges, it is essential that stakeholders in the EV industry including manufacturers, standards organizations, utility companies, and policymakers, work collaboratively to establish common standards and protocols for the EV ecosystem. These standards should encompass data formats, communication interfaces, security protocols, and compatibility testing methods to ensure interoperability across different platforms and devices. Standardization will not only streamline interactions within the EV ecosystem but also foster greater innovation, enhance customer experience, and accelerate the transition to electric vehicles.

In addition to standardization, addressing technical gaps in existing systems is crucial. For instance, limitations in EV communication technologies, fragmented EV charging stations and data all pose significant barriers to the seamless operation of EVs. Future innovations such as V2V communication, unified EV systems, and gamification to encourage sustainable driving, will further enhance the EV ecosystem and accelerate adoption.

Another critical priority is ensuring communication-layer interoperability across EV systems. As proposed in our framework, a layered architecture that bridges legacy protocols (such as CAN and Bluetooth) with emerging standards like ISO 15118, while maintaining compatibility with protocols like OCPP and OSCP, can significantly reduce fragmentation. Such middleware-based strategies will enable smoother coordination among diverse EV and EVSE platforms and support scalable, standardized deployment. Additionally, the modular design of the proposed framework enables its adaptation across a wide range of urban settings. By tailoring algorithmic components and prioritizing different technologies such as scheduling in infrastructure-rich areas or protocol unification in fragmented environments, the model can be deployed in both highly developed cities and emerging regions. Future work will explore these adaptations to support geographic and infrastructural diversity in EV ecosystems.

While the proposed framework is modular and software-centric, its real-world deployment in dense, dynamic urban environments remains a challenge. Large-scale performance under heterogeneous traffic patterns, unpredictable user behaviors, and variable renewable energy input requires further validation. To address this, future work will include simulations using synthetic city-scale datasets, followed by pilot implementations to evaluate real-time latency, fault tolerance, and grid impact. Additionally, the framework's reliance on stable connectivity and data availability may limit performance in underserved regions. Enhancements such as offline fallback logic, adaptive data caching, and protocol redundancy will be investigated to increase resilience.

Moving forward, further research is needed to develop interoperable platforms that integrate simulation models for vehicle dynamics, grid interaction, and real-time charging infrastructure. In parallel, the environmental footprint of supporting digital infrastructure such as blockchain, AI, and IoT components should be evaluated. Although the proposed framework prioritizes energy-efficient architectures, future work will include quantitative assessments of emissions trade-offs and potential e-waste impacts to ensure that technological optimizations align with broader sustainability goals. These advancements, coupled with collaborative stakeholder efforts, will pave the way for a more efficient, user-friendly, and sustainable transportation system. By overcoming these challenges and embracing technological progress, the EV industry can drive a global shift toward sustainable mobility, delivering cleaner air, reduced emissions, and a smarter transportation future.

CRediT authorship contribution statement

S. Zahedieh: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **A. Oulis Rousis:** Writing – original draft, Validation, Supervision, Conceptualization. **A. Bourazeri:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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