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Review

A Comprehensive Review on Smart Electromobility Charging Infrastructure

Idowu Adetona Ayoade * and Omowunmi Mary Longe

Department of Electrical and Electronic Engineering Science, University of Johannesburg, Johannesburg 2006, South Africa; omowunmil@uj.ac.za
* Correspondence: 224089150@student.uj.ac.za

Abstract: This study thoroughly analyses Smart Electromobility Charging Infrastructure (SECI), exploring its multifaceted dimensions and advancements. Delving into the intricate landscape of SECI, the study critically evaluates existing technologies, integration methodologies, and emerging trends. Through a systematic examination of literature and empirical studies, the article elucidates the evolving ecosystem of smart charging solutions, considering aspects including advancements in charging protocols. Additionally, the review highlights challenges and prospects in the SECI domain, providing insightful information for scholars, practitioners, and policymakers involved in the dynamic field of electromobility. Technical potentials, including functionalities and integration with the smart grid, have been thoroughly reviewed. An analysis is conducted on the effects of intelligent charging on power distribution systems and strategies to lessen these effects. This study also examines the development of intelligent charging algorithms, optimisation methods, and security analysis. This paper, therefore, contributes to fostering a more thorough comprehension of the current state and future trajectories of Smart Electromobility Charging Infrastructure.

Keywords: electromobility; electric vehicle; smart charging; charging infrastructure

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1. Introduction to Electromobility Charging Systems

Electromobility, the use of EVs as a means of transportation, is gaining momentum as a greener substitute for conventional internal combustion engine (ICE) vehicles. However, the successful implementation of electromobility relies heavily on the availability and accessibility of a dependable infrastructure for charging networks [1]. Installing charging stations is essential to advancing electromobility, especially in nations with well-established land and marine transportation [2]. One of the main challenges in developing electromobility is the lack of available charging infrastructure. The number of charging outlets and high-speed charging infrastructures is insufficient to meet the demand for charging EVs [3]. The lack of infrastructure hinders the expansion and adoption of EVs, as potential users are deterred by the limited availability of charging stations [4]. Therefore, an expanded charging infrastructure network supporting electromobility's widespread adoption must be incorporated into national developments.

Adopting transformative, innovative technologies in the electromobility industry significantly enhances EVs' acceptability and widespread adoption. Research by [5] highlights a critical distinction between static wireless charging (SWC) and dynamic wireless charging (DWC) systems. SWC systems involve the charging of EVs while they are stationary, with a charging pad mounted on the ground transmitting power to a corresponding pad on the vehicle [6]. Conversely, DWC systems facilitate the recharging of EV batteries while the vehicle is in motion, utilising charging pads embedded in the roads [6]. Recent efforts to improve SWC systems have focused on power stabilisation through the switching control of segmented transmitting coils, particularly in scenarios such as traffic lights where multiple loads must be managed simultaneously [7]. Figure 1 illustrates an overview of a static wireless charging system for electromobility. Furthermore, studies have investigated the effects of various operating parameters on the efficiency of wireless charging systems. These parameters include operating frequency, coil configuration, and the physical spacing between transmitting and receiving coils, which are crucial in optimising the performance of wireless charging technologies [8].

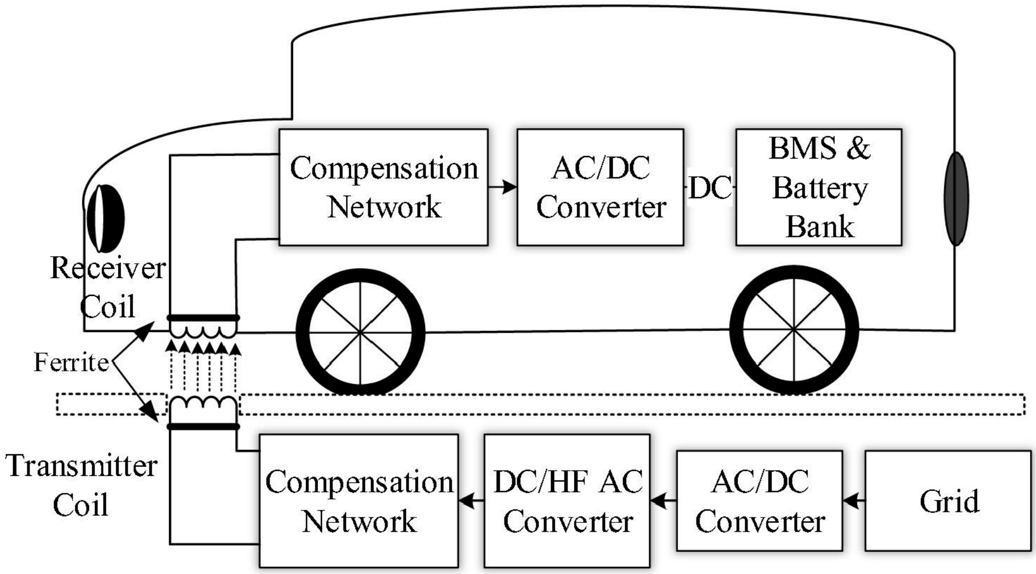

Figure 1. Overview of a static wireless charging system for EVs [9].

Sharing infrastructure for charging has been recognised as a beneficial approach to accelerate the expansion of the market for electromobility charging infrastructure [4,10]. By sharing charging infrastructure, the environmental benefits of electromobility can be maximised, and the costs linked with establishing and maintaining charging stations can be shared among multiple users [11]. This approach promotes the sustainable development of electromobility and facilitates the market's growth for infrastructure used for charging. The location of charging stations is another critical factor in the development of electromobility. Local authorities play a crucial role in deciding the siting of new charging stations [11,12]. Decision-making support tools can assist local authorities in choosing the ideal sites for charging stations depending on variables, including population density, traffic patterns, and closeness to important transportation hubs [11].

From the energy policy standpoint, electromobility provides the means to decarbonise and decentralise electricity sources [13]. EVs can be used as mobile electricity storage facilities, allowing for renewable energy sources' incorporation into the electrical grid [11,14]. This integration can help address the intermittency and fluctuation in renewable energy production, resulting in a more robust and sustainable energy system. The deployment and optimisation of charging stations are essential to effectively executing electromobility [14,15]. Various optimisation strategies and algorithms have been demonstrated to ascertain the ideal quantity and placement of charging stations [12,14–16]. These strategies consider charging demand, traffic flow, spatial–temporal distribution, and network planning to ensure the charging infrastructure is deployed effectively and efficiently [10,12]. By optimising the locations of the charging stations, the coverage and capacity of the infrastructure for charging can be maximised, meeting the increased need for EV charging [17]. Smart electromobility charging with augmented reality-aided energy trading is an emerging concept that combines innovative charging technology with energy trading systems. Smart charging optimises the charging process of EVs to ensure economical usage of electricity and minimise the impact within the electrical grid [18]. In contrast, augmented reality superimposes digital data over the physical world, improving users' awareness and engagement with their surroundings [19]. Energy trading systems enable the buying and selling of electricity between different stakeholders, allowing for more efficient usage of grid resources and renewable energy sources [18].

The integration of AR into smart electromobility charging can offer several benefits. One potential application is visualising charging infrastructure and available charging stations in real time through AR (augmented reality) interfaces/displays, which indicates digital devices used to display AR, including wearable devices, human–machine interfaces, and mobile/screen [17]. This can help EV owners quickly locate and navigate to nearby charging stations, reducing range anxiety and improving the overall user experience [20]. Additionally, AR may give consumers up-to-date information about charging station availability, costs, and rates, thus enhancing the EV user charging time [21]. Furthermore, augmented reality can enhance the energy trading aspect of smart electromobility charging. By overlaying real-time energy prices and demanding information onto the user's field of view, AR interfaces can enable EV owners to decide when to charge their vehicles based on the current energy market conditions [20,22]. This can incentivise consumers to recharge their automobiles during periods of low demand and low energy prices, contributing to the overall stability of the power grid [22].

Along with the advantages for EV owners, augmented reality can also support energy trading between different stakeholders. AR interfaces can provide information in real-time about the availability and demand for energy in a specific area, allowing energy traders to identify potential trading opportunities and optimise their energy transactions [20]. This may make incorporating renewable energy sources into the system easier and support the transition to a more sustainable energy system [17].

However, implementing smart electromobility charging with augmented reality-aided energy trading faces several challenges. One challenge is the development of reliable and accurate AR interfaces that can seamlessly integrate with the infrastructure for charging and energy trading systems [23]. The accuracy of the information displayed through AR interfaces is crucial to ensure that users make informed decisions about their charging and energy trading activities [24]. Another challenge is the interoperability and standardisation of the technologies involved, including the charging infrastructure, AR devices, and energy trading platforms [25]. Interoperability standards are necessary to ensure seamless data transmission and communication between several stakeholders in the intelligent electromobility charging ecosystem [26]. Smart electromobility charging with augmented reality-aided energy trading is an innovative concept that combines intelligent charging technology, augmented reality, and energy trading systems. The integration of augmented reality can enhance the user experience by providing real-time information on charging infrastructure and energy market conditions. It can also support energy trading between stakeholders, facilitating the more effective use of renewable energy sources and grid resources. However, implementing this concept requires addressing challenges related to AR interface development, interoperability, and standardisation.

Significance of Smart Charging in Facilitating the Transition towards Electromobility Proliferation

Smart charging is a crucial aspect of the transition to electromobility as it allows EVs to be seamlessly integrated into the electrical grid and guarantees the long-term viability of public EV charging stations [27]. Smart charging strategies allow for the organised control of the charging process, which is essential for grid integration and the profitability of charging infrastructure [28]. EVs can function as adaptable grid resources by using smart charging and provide electromobility ancillary services (EMAS) to the grid during emergencies [29]. EMAS refers to the secondary functions and support mechanisms provided by electric vehicles and charging infrastructure beyond primary mobility services. These may include grid stabilisation, demand response, and energy trading facilitated by augmented reality technologies within the framework of intelligent electromobility systems [29]. The potential application of EVs as a component of an intelligent grid system in sustainable urban development is demonstrated by the development of EVs and their success, as well as the expansion of charging infrastructure [30]. Smart charging also significantly enhances safety against risks associated with automated driving, communication among vehicles, and smart charging of EVs [31]. Additionally, integrating PV solar panels and electric vehicles (EVs) into smart cities can be enhanced by incorporating smart charging and battery storage, leading to more efficient energy consumption and less dependency on the grid [32].

From a consumer perspective, smart charging offers various benefits. It allows EV users to make charging choices based on peak-valley pricing, optimising their economic benefits and promoting peak load shifting [33]. Furthermore, smart charging can provide consumers with affordable mobility options while ensuring that the charging process is aligned with the power system's needs [34]. In terms of grid management, smart charging enables EVs to contribute effectively to the grid by rapidly responding to the energy system's needs. With the expected growth in the number of EVs, smart charging can aid in balancing the revenue between EV users and intelligent energy systems, ensuring the efficient scheduling of the energy system [35]. Moreover, smart charging can help manage the stress on distribution transformers caused by the charging requirements of EVs, ensuring the reliable operation of the power system [36].

However, the implementation of smart charging also raises cybersecurity concerns. It is imperative to ensure the security of EV intelligent charging management systems to protect against potential cyber-attacks [37]. Smart charging is of utmost importance in the transition to electric vehicles. It makes it possible for EVs to be effectively integrated into the power system, provides flexibility to the grid, and benefits consumers and the overall energy system. However, it is crucial to address cybersecurity concerns to ensure the secure operation of EV intelligent charging systems [37].

2. Overview of Smart Electromobility Charging Systems

Due to the growing popularity of EVs and the requirement for an effective and sustainable infrastructure, smart electromobility charging systems have recently gained much attention. The authors in [38,39] highlighted the optimisation requirement for an electromobility charging infrastructure, the management of the demand side on the grid [40], and the integration of a plethora of renewable energy sources as key features to indicate an intelligent electromobility charging system. The effects of uncoordinated charging of EVs can lead to increased peak demand, grid instability, and higher electricity costs [28]. Smart electromobility charging systems address challenges connected to the execution strategies optimising the charging process [28]. To reduce the effects of disorganised charging on the grid, several variables, including grid conditions, electricity costs, and user preferences, have been considered in scheduling electromobility charging [39]. Several studies have demonstrated the benefits of smart charging, including reduced grid stress [28], lower electricity costs [41], and increased integration of renewable energy [42].

Vehicle-to-grid (V2G) technologies are critical enablers of smart electromobility charging, which supports bidirectional power exchange between EVs and the grid [28,43]. With V2G technology, EVs can supply electricity to the grid during periods of high demand or when the production of renewable energy is at its lowest [12]. This capacity can boost the use of renewable energy sources, stabilise the system, and provide additional revenue streams for EV owners [41]. Research studies and real-world field trials have shown the potential benefits of V2G technologies in terms of grid stability, energy management, and cost savings [41]. Smart charging techniques and optimisation are implemented to optimise the electromobility, maximising the use of renewable energy sources throughout the charging process. These strategies consider factors such as electricity prices, grid conditions, user preferences, and the availability of renewable energy generation [44–46]. Stochastic dynamic optimisation algorithms have been used to develop optimisation algorithms that minimise imported power from the electrical grid and maximise using sustainable energy sources [47–49]. Furthermore, incorporating energy storage technologies, specifically batteries, within EV charging systems presents an avenue for augmenting the optimisation of charging procedures [50].

Incorporating renewable energy sources in electromobility charging systems is a deep dive into integrating renewable energy sources with EV charging infrastructure, notably photovoltaic (PV) systems [50]. Smart charging systems, leveraging real-time PV generation data and electricity price information, can strategically schedule when renewable energy generation is at its highest, EV charging, and low-cost electricity periods [50,51]. This integration not only diminishes dependency on fossil fuel-derived electricity but also optimises utilising eco-friendly and sustainable energy resources [52]. The impact of grid and distribution networks has influenced the growing prevalence of EVs, and the extensive implementation of intelligent charging systems has significant ramifications for electrical grids and distribution networks. Research investigations have assessed the grid and distribution network effects of EV charging, encompassing the prospect of heightened peak demand and the necessity for infrastructure enhancements [18,53]. Nevertheless, intelligent charging systems offer potential solutions for alleviating these consequences through optimising charging procedures and adept grid demand management [28].

2.1. Smart Electromobility Charging Standards

According to [50], intelligent electromobility charging can be completed at home or public charging stations in eateries, shopping malls, office buildings, and other places. The study classifies three different EV charging system modes. Direct current (DC) charging is carried out in Mode 3, while alternating current (AC) charging is carried out in Modes 1 and 2. The United States, Japan, and many European nations are implementing these charging modes [54].

The charging characteristics modes, as displayed in Table 1, are stated by [52]. Mode 1, also known as AC Charging Level 1, is utilised for in-home charging. It is created by making a tiny alteration to domestic wiring and operates at 120 VAC electricity [54]. It compares the cost of EV charging system categories and concludes that the Level 1 EV charging system is an inexpensive charging arrangement that takes a long time to charge, i.e., 12–16 h to reach 100% State of Charge (SOC); the same was reported in [55,56]. Mode 2 charging stations use a relatively faster charging rate than Mode 1 [57]. Similarly, [58,59] for Mode 2 charging infrastructure installation is rather costly due to its significant influence on the utility. Mode 2 EV charging facility also allows for commercial DC charging arrangements [60]. Refs. [61–63] support that an EV can be charged in about 30 min using the Mode 3 DC fast-charging system, which uses an off-board supply unit with a power rating of 80–200 kW. The installation cost is also the highest and substantially impacts the utility's maximum demand rates. Table 1 displays the charging modes' attributes [64].

Table 1. Characteristics of charging modes [64].

Charging Characteristics								
Charging Modes	**Outlets for Charging**	**Voltage Range (V)**	**Current Range (A)**	**Power Range (kW)**	**Number of Phase(s)**	**Duration of Charging (h)**	**Advantages**	**Disadvantages**
Mode 1	Domestic	120 V_{AC}	12–16	1.4–1.9	Single phase	6–10	• Low installation cost • Less impact on utility	• Slow charging rate • Long charging period
Mode 2	Domestic Public	240 V_{AC}	80	19.2	Single/ Three phase	1–3	• Fast charging time • Energy-efficient	• High installation cost • Impact on the utility
Mode 3	Public	480 V_{DC}	80–200	20–120	Three phases	0.5	• Very fast charging time • High energy efficiency	• High installation cost • High impact on the utility

2.2. Technical Potentials of Intelligent Charging Apparatuses

Intelligent charging apparatuses for EVs have several technical possibilities for optimising charging schedules based on individual mobility patterns [65] and grid conditions [66]. Intelligent charging systems enable benefits like financial savings [65] for electromobility users and improved grid stability [66] for grid operators. The study by [67] demonstrates the substantial improvement while incorporating renewable energy sources into the transportation industry through smart electromobility charging. This enhancement is attributed to renewable energy sources' flexibility, enabling regulators to maintain a stable and balanced grid. Notwithstanding the potential benefits of intelligent electromobility charging, specific technical challenges are addressed by implementing V2G technologies. The EV charging mode has associated challenges and advantages, which include the requisite technical capabilities for smart charging in electric vehicles [66], concerns regarding battery degradation [68], and the necessity for potential upgrades to distribution grids to accommodate the increasing need for EV charging [66]. Table 2 highlights EV charging methods and the corresponding advantages and disadvantages.

Table 2. Methods for charging EVs and their importance.

EV Charging Methods	Advantages	Disadvantages	Citation
Constant Current Charging	• Easy to understand • Increased effectiveness of charging • Long-lasting battery	• Low utilisation of capacity • The charge time is lengthy • Safety is required • Expensive	[69]
Constant Voltage Charging	• Low charging time; high-capacity utilisation • Simplicity and ease of implementation	• Decreased capacity to charge • Impact on battery life • Need for protection	[70]
Trickle-CC-CV Charging	• No need for protection • More effective charging • Maximum utilisation of capacity • Minimal expense	• Difficulty in balancing temperature fluctuations, energy loss, and charging speed • High cost	[70]
Five-step Charging	• Quick charging • Long battery life	• Difficulty in balancing temperature variation, energy loss, and charging speed • Complex charging pattern algorithm	[71]
Pulse Charging	• Reduced charging time, extended battery life, and increased charging efficiency	• Finding an appropriate duty cycle for the battery to receive a quick charge is rather complex.	[64,72]
VDC Charging	• Quick charging • Long battery life	• Safety is required • Inadequate charging effectiveness • Intricate algorithm for optimisation	[73]
SRC Charging	• Reduced charging time, increased charging efficiency, and the ability to solve power quality issues	• Low-capacity utilisation • SEI layer affects battery life • High level of complexity	[74]
CT-CV Charging	• Good battery life • Low charging time • Ease of use and implementation • Low cost	• A high degree of intricacy • The difficulty of balancing temperature fluctuations, energy loss, and charging speed	[75]
Boost charging	• Long-lasting battery • Low charging time • Ease of use and implementation; low costs on the speed of charge	• Protection is required • Medium intricacy • Affects battery life	[70]

Ongoing research endeavours aim to optimise smart charging systems by addressing various facets, such as balancing power demand among charging stations [76], maximising the utilisation of grid resources [6], and incorporating vehicle-to-grid technologies [77]. The optimisation of techniques for energy management stands out as a pathway to enhance the efficiency of Plug-In Hybrid Electric Vehicles (PHEVs) [78], while concurrently, electric vehicles contribute flexibility to power systems [79]. Smart electromobility charging systems exhibit technical potential for optimising charging processes, integrating renewable energy, offering grid services, and balancing electricity demand. Nevertheless, persistent technical challenges related to vehicle capabilities, battery degradation, and grid infrastructure must be addressed. Current research endeavours are focused on mitigating these challenges to fully realise the potential benefits of intelligent charging apparatuses.

2.3. Impact of Smart Charging on Power Distribution Grids

EVs' incorporation into the power distribution system has prompted increased scrutiny of the impacts of electromobility smart charging. The author in [80] proposed coordinated charging strategies to increase the primary grid load factor and reduce power losses. Another study by [36] highlights how distribution transformer load and performance in smart grids are affected by coordinated charging. Energy storage and intelligent charging are two possible ways to mitigate the effects of electromobility demands on the distribution system [81]. Studies by [76,82,83] investigate the impact of rapid and intelligent charging on the distribution infrastructures, power systems, and battery health.

Furthermore, the fluctuation effect of EV users' charging and discharging behaviour on power grid load was studied by [33] and the use of the Time-of-Use (TOU) strategy in smoothing peak and valley differences in the power grid. Clever charging techniques have been implemented to cut down on energy imports, such as charging during periods of excess output [84]. However, uncontrolled charging of EVs has been demonstrated to elevate the peak load of the power grid [85]. Evaluation of EV-related communication protocols and control algorithms for charging in local distribution grids is the primary goal of the research carried out by [86]. According to a study of related papers, coordinated and intelligent charging techniques emphasising reducing power losses are essential for reducing the adverse effects of electromobility on power distribution networks, optimising transformer loading, and balancing grid loads. These findings are essential for informing the development of effective strategies for integrating electromobility into smart grids.

2.4. Analysis of the Relationship between Smart Charging and Power Distribution Grids

Recent research has extensively scrutinised the nexus between smart charging and power distribution grids. The study [87] asserted that smart charging, instead of unintelligent methods, can avert overload on the power system. Also, ref. [88] delineated the substantial adverse consequences of large-scale EV charging irregularities, such as transformer overload, power loss, and voltage departure. Furthermore, ref. [85] illustrated that uncontrolled electric vehicle charging amplifies the peak load of the power grid, underscoring the imperative for coordinated charging strategies. In a comprehensive study, ref. [89] explored the impacts of different charging approaches on the overall cost, grid losses, and voltage profiles, highlighting the potential advantages of coordinated charging in smart grids. By examining the effects of intelligent charging techniques on power distribution grids, the work in [90] provided insights and emphasised the need for practical solutions to lessen the grid's exposure to emissions from EVs.

Collectively, refs. [85,88–90] underscore the pivotal role of intelligent charging in alleviating the adverse impacts of EV charging on grids for distributing power. Coordinated and innovative charging strategies emerge as indispensable measures to forestall overload, curtail power losses, and uphold grid stability amid escalating electric vehicle integration. The review reveals a consensus regarding the critical importance of smart charging in navigating the dynamic interplay between EVs and power distribution grids, emphasising the requisite for well-coordinated and efficient charging strategies to uphold grid reliability and stability.

3. Electromobility Charging Infrastructure Smart Charging Evolution

Establishing electromobility charging infrastructure is pivotal in the shift towards sustainable transportation. The research output of [91] stresses the significance of aligning the layout of charging infrastructure with local government policies and urban planning, emphasising spatial considerations, construction quantity, and service area in diverse regions. The investigation by [92] documents the uniform price of EV charging in the U.S.A., underscoring the interplay between charging infrastructure characteristics and EV operating costs, thereby elucidating the economic ramifications of infrastructure development. Addressing technical challenges and perspectives, ref. [93] advocates for standardisation, charging time optimisation, demand policies, and regulatory procedures in EV charging infrastructure. By reducing the impact of EVs on transmission and distribution systems, smart charging can potentially reduce the requirement for additional generating equipment and distribution network reinforcement. This is demonstrated in the report [94]. The study output of [95] explores how EV fleets might be integrated into the architecture of intelligent grids, highlighting the relationship between the power grid and charging infrastructure.

Beyond technical and economic considerations, the geographic location of charging stations holds critical importance. The proposal of [96] for a multi-factor Geographic Information System (GIS) method for determining the best places to charge EVs offers decision support for strategically establishing a well-distributed charging infrastructure. Additionally, ref. [32] accentuates the effects of intelligent charging and battery storage on integrating EVs and photovoltaic solar panels into smart cities, highlighting the role of intelligent charging in urban energy systems. The studies reviewed underscore the imperative for comprehensive planning and optimisation of EV charging infrastructure, encompassing spatial layout, economic costs, technical challenges, and integration with the smart grid.

3.1. Comparative Analysis of Charging Station Development across Countries

Establishing EV charging stations is pivotal in fostering EV adoption and steering towards a more environmentally sustainable transportation system [14]. Examining EV charging station construction and operation methods contributes valuable insights into policy frameworks, as analysing how EV charging stations affect the electrical grids in nations such as Italy and the United States of America (U.S.A.) underscores the necessity for effective deployment and integration to mitigate power fluctuations and ensure grid stability [97–99]. Addressing optimal placement in urban areas and motorway infrastructure planning emphasises the complexity of station placement, necessitating advanced models to capture Plug-In Electric Vehicle (PEV) charging demands in diverse transport networks [100,101]. Deployment strategies such as multi-type fast charging stations in Europe and sustainable e-bike charging using solar energy showcase diverse global approaches, reflecting ongoing efforts to expand and innovate in charging infrastructure development [102,103]. Integrating charging stations with distributed generators and employing intelligent algorithms for optimal allocation of distributed electricity production and EV charging infrastructure highlights the interconnected nature of renewable energy integration and EV infrastructure planning [99,104]. Evaluating barriers to EV adoption in Indonesia and prediction of EV charging load in Shanghai contribute insights into challenges and future trends in EV infrastructure development, enriching our understanding of the global landscape of charging station deployment [105,106]. The comparative analysis of charging station development across different regions unveils the multifaceted nature of EV infrastructure planning [107], encompassing policy frameworks [28,68], grid integration [83], renewable energy [108], and future projections. Synthesising research from diverse countries offers a comprehensive overview of global challenges, strategies, and advancements in EV charging stations.

3.2. Factors Influencing the Development of Charging Infrastructure

The multifaceted construction of a charging infrastructure for EVs involves many influencing factors spanning technological, geographical, economic, and policy dimensions. The study of [109] underscores the significance of considering charging infrastructure types and models, their cumulative grid impacts, geographic location, and management. According to [110], the main obstacles to the expansion of EVs include battery technology constraints, poor infrastructure, a lack of public charging stations, incorrect positioning, and disorganised charging. The study of [111] identified the absence of infrastructure for public charging of EVs market development. At the same time, ref. [112] emphasises factors such as large-scale investment, unclear financing rights, a monopolised market, and interlinked risks contributing to the "absence" and "dislocation" of charging infrastructure. Similarly, ref. [95] assesses the effects of demand-side incentives and plug-in vehicle infrastructure on the adoption of EVs, emphasising the role of essential incentives and enabling variables on PEV adoption. The study of [113] stresses the consequences of charging patterns and infrastructure utilisation on local power grids, parking regulations, financial gains, and EV adoption. The experimental documentation of [114] demonstrates how explanatory variables predict EV charging behaviour in urban areas, providing implications for policymakers and planners aiming to optimise charging infrastructure types and sizes. The results of [115] conclude that fast-charging infrastructure works better than standard power charging stations when boosting EV sales. External factors such as government policies, consumer intentions, the environment, and the number of charging stations affect Tesla's profitability [116]. Additionally, ref. [117] highlights that mileage, electric vehicle distribution, and passenger distribution affect the location of EV charging stations. The construction of infrastructure for EV charging is intricately influenced by technological, geographical, economic, and policy-related factors. A comprehensive understanding of these factors' impact is imperative for successfully deploying and developing charging infrastructure to support the widespread adoption of EVs.

3.3. Interoperability and Standardisation in Smart Charging

Interoperability and standardisation play a pivotal role in intelligent charging for EVs. Integrating smart metres, charging interfaces, and smart grid applications necessitates standardised languages to ensure seamless interoperability [118]. Recognising the significance of addressing interoperability issues in the smart grid, literature, particularly in the context of EV charging, has emphasised the need for standardised approaches [119]. To achieve interoperability in the context of smart cities, standards like {O-MI (Open Messaging Interface)/(O-DF) (Open Data Format)} (O-MI/O-DF) have been detailed, specifically in electric vehicle charging [120]. A global standard for electric vehicle charging has been identified as an obstacle to expanding charging infrastructure, underscoring the paramount importance of standardisation and interoperability in this domain [121]. Moreover, research has delved into optimal vehicle grid integration strategies, incorporating user behaviour prediction and scalability considerations, essential elements for achieving interoperability in intelligent charging systems [122]. Initiatives such as workshops and frameworks, exemplified by those from the National Institute of Standards and Technology (NIST), have played a crucial role in addressing intelligent grid interoperability testing and certification, highlighting the ongoing endeavours to establish standards in this field [123]. NIST emphasises the critical role of interoperability and standardisation in intelligent charging for EVs. This underscores the necessity for standardised languages, practical standards, and global frameworks to effectively address interoperability challenges, enabling the smooth integration of charging infrastructure for EV charging into the smart grid. The architecture for interoperability presented by [124] presents a reference architecture for interoperability testing of EV charging systems. The study likely delves into the design and implementation of a framework that facilitates testing the compatibility and effectiveness of various EV charging technologies, aiming to enhance the interoperability and efficiency of charging infrastructure.

Importance of Interoperability in the Electromobility Network

Interoperability is a pivotal element within the electromobility network, facilitating seamless information and service exchange among diverse network components. The timely and actionable exchange of information is deemed indispensable for the effective operation of the power system, especially for EVs, where interoperability ensures the efficient integration of the electricity grid with the infrastructure for charging, addressing challenges like disparate charging demand and infrastructure utilisation [123,125]. The interoperability of EV charging infrastructure emerges as vital for grid modernisation and the widespread adoption of EVs, significantly influencing the success and extensive use of electric vehicles [126]. This importance extends to intelligent grid automation/load distribution, where interoperability in data sharing and future device and system integration is imperative for effective infrastructure planning and policy considerations related to EV charging [127]. Additionally, the interoperability of electric vehicle supply equipment is a concern for consumers, as limited charging points and interoperability issues linked to smart charging can impede the broad adoption of EVs [121].

Furthermore, the interoperability of EV knowledge graphs and the development of ontologies for EVs, charging infrastructure, and electric transmission networks contribute to reusability and interoperability, underscoring the importance of interoperability in enabling seamless integration and information exchange within the electromobility network [128]. Interoperability is central in the electromobility network, influencing various facets such as grid modernisation, infrastructure planning, consumer concerns, and the electrical grid's integration with EV charging infrastructures. Addressing interoperability challenges is indispensable for fostering the widespread adoption of EVs and ensuring the efficient and seamless functioning of the electromobility network. Interoperability is a broad paradigm that applies to numerous contexts and levels of analysis. Data interchange interoperability refers to the capacity of two or more entities to manage and maximise the goal by exchanging and processing information as needed by anyone and with whatever is required. As demonstrated, data interchange interoperability in the provided context can be viewed as a two-level task, as Figure 2 illustrates.

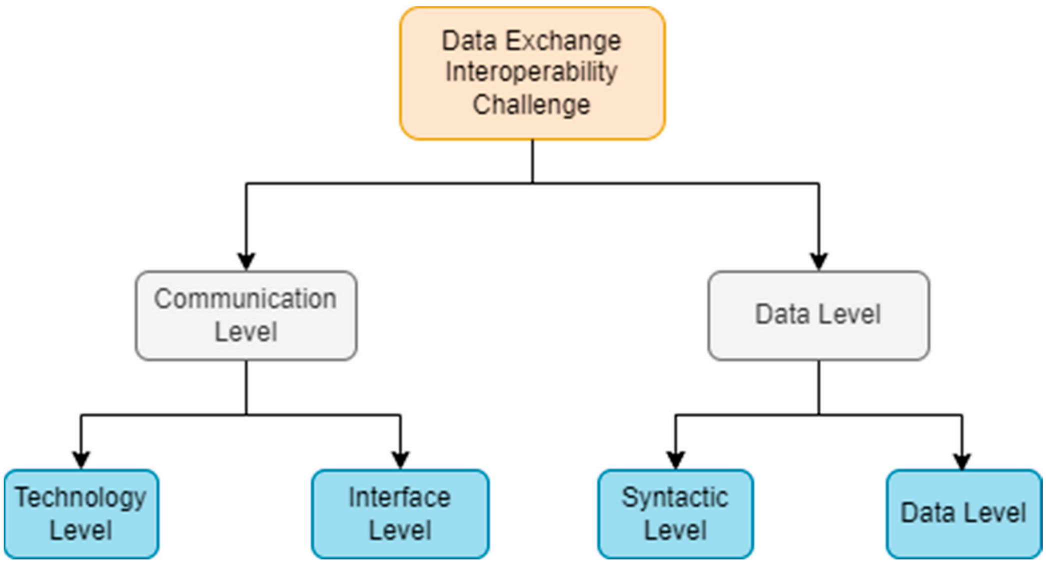

Figure 2. Data exchange interoperability challenge.

4. Smart Charging Algorithms and Optimisation

The escalating demand for reliable and sustainable energy management in EVs has underscored the significance of intelligent charging algorithms and optimisation. An array of authors has evaluated multifaceted exploration, encompassing charging infrastructure planning, energy management, optimisation algorithms, and the impact of EV charging on the power grid. The research of [110] offers an overview of EV charging infrastructure planning, emphasising the importance of home charging and optimisation algorithms to address placement challenges. Similarly, ref. [129] delves into energy management optimisation for microgrids and electric vehicle aggregators, focusing on collaborative optimisation and control of EV charging processes. The influence of EV charging on the distribution network is further explored in the literature, which records that EV charging models can be optimised using an augmented particle swarm optimisation technique to minimise the adverse impacts of disorderly charging on the power grid [130]. The authors of [85] compare decentralised and centralised algorithms in large-scale power systems to enhance PEV smart charging strategies, while [131] addressed the issue of EV charging at resource-constrained stations while adhering to customer satisfaction standards. The optimisation of EV charging is intricately linked to battery management systems (BMS) and renewable energy integration. Ref. [132] focuses on intelligent charging methodology for EVs to optimise total costs in isolated systems heavily reliant on renewable energy. Additionally, the literature addresses charging stations' location and capacity determination, as exemplified by [133], who suggests predicting charging load using an energy-equivalent technique and evaluating economic and user convenience. The literature analysis on optimisation and intelligent charging algorithms highlights the increasing importance of creating algorithms for Building Management System (BMS) strategies, cooperative energy management, EV charging, and incorporating renewable energy. These aspects are pivotal in addressing challenges associated with EV charging and ensuring efficient and sustainable energy utilisation.

4.1. Charge Scheduling Algorithms for Smart Charging

The advancement of smart charging algorithms in electromobility is essential to streamlining the EV charging procedure and ensuring the efficient utilisation of charging stations. Various studies have proposed scheduling algorithms to address this challenge. The research by [134] introduced an intelligent scheduling system based on reinforcement learning, considering average speed, battery level, distance travelled, nearby recharge stations, and other appointments. Similarly, ref. [135] presented a hierarchical, uncooperative optimal charging scheduling algorithm to level the charging stations' utilisation rate and make the most money for charging stations and EVs. Additionally, ref. [136] highlighted reducing generation and charging costs in intelligent environments using reinforcement learning in EV scheduling.

Furthermore, integrating renewable energy sources (RESs) for EV charging has been recognised as a viable way to handle related energy issues. This aligns with the focus on environmental sustainability and energy efficiency in the electromobility sector. The communication channel between EVs and smart grids has been characterised, emphasising the significant fluctuation effects of EV users' charging and discharging behaviour on the power grid load. Furthermore, the proposal of using the Internet of Things (IoT) to control EV charging/discharging methods indicates the potential for IoT-based solutions to control the charging procedure.

The escalating adoption of EVs necessitates a comprehensive review of scheduling algorithms for efficient charging management. Various approaches have been postulated to address the difficulties related to EV charging. The authors in [137] introduced a two-stage optimal scheduling strategy for large-scale EVs, mitigating the detrimental effects of unregulated charging on the grid. Similarly, ref. [138] developed a dynamic scheduling algorithm based on road conditions to address challenges like "difficult charging" and uneven spatial distribution of charging piles in urban areas, aiming to optimise charging schedules and enhance grid stability. The research output of [139] attempted the electromobility scheduling and optimal charging problem similar to what is illustrated in Figure 1, emphasising scheduling complexity and the need for exact and heuristic approaches. Hybrid optimisation techniques employed by [140] allowed multi-aggregator-based charge scheduling using a graph-based multi-objective heuristic approach that considers EV owners' willingness. Reinforcement learning has been applied to scheduling algorithms for EV charging, as shown in Figure 3. An arrival time-based priority charging schedule algorithm was implemented. The research outputs of [141,142] proposed reinforcement learning-based scheduling methods, optimising the charging and load of large-scale EVs and leveraging artificial intelligence to optimise charging schedules based on real-time data adaptively. Beyond optimising charging schedules, studies have delved into specific applications such as electric bus scheduling [143,144], coordinated schedule optimisation for buses' vehicles and charging [145], and the electric vehicle routing problem [146], addressing unique challenges associated with different EV types and operational requirements. The exploration of renewable energy source integration into EV charging has been addressed. The author [147] studied reducing the cost of charging stations using solar energy, underscoring the importance of optimal control of EV charging schedules in the context of renewable energy integration. These scheduling algorithm reviews underscore various scheduling algorithms for charging EVs, encompassing mathematical optimisation, heuristic approaches, reinforcement learning, and incorporating sustainable energy sources. Together, these studies aid in creating sustainable and effective charging plans for the growing fleet of EVs.

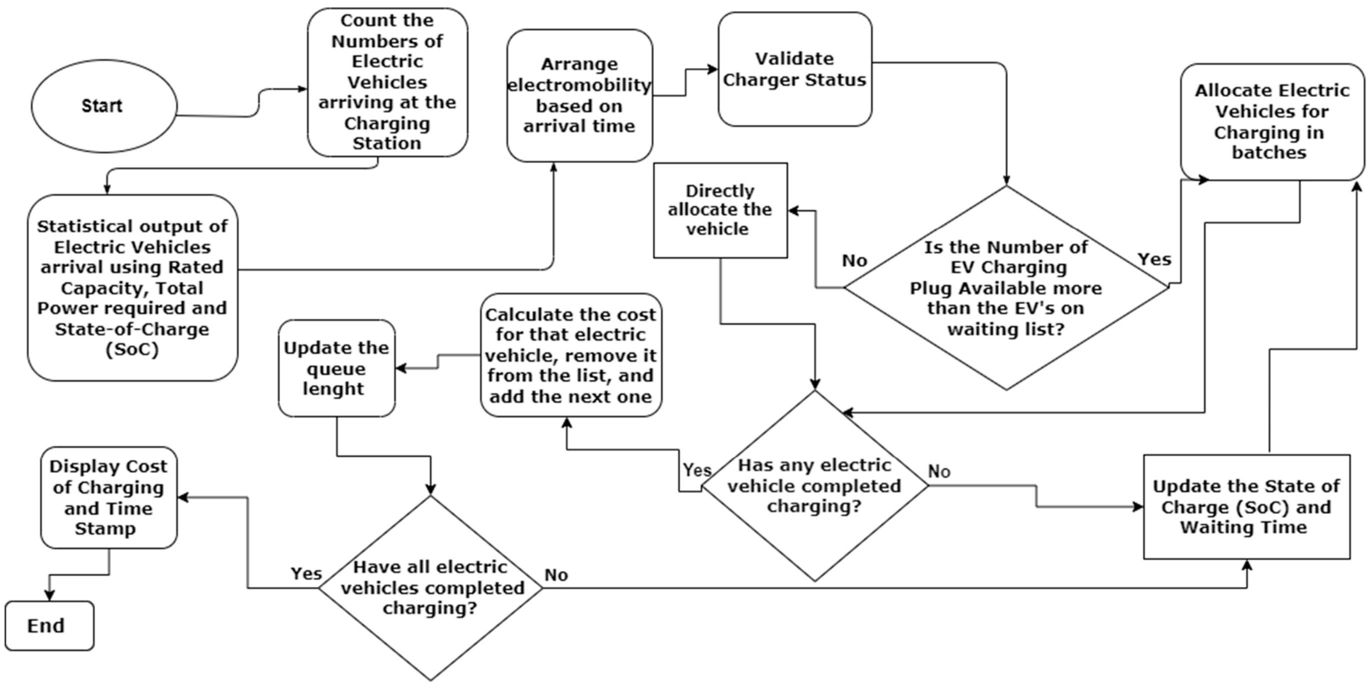

Figure 3. Flowchart of arrival time-based priority charging schedule algorithm.

4.2. Survey of Charge Management Optimisation Methods

The study of electromobility charging and charge optimisation management methods yields valuable insights from several pertinent references. The study of [137] introduced a two-phase optimal scheduling strategy for large-scale EVs, emphasising mathematical and distributed optimisation management in EV charging. Similarly, ref. [148] presented a real-time EV charging scheduling method for parking lots, utilising approximate dynamic programming for efficient parking lot charging management. Additionally, ref. [149] developed a protocol for cooperative EV-to-EV charging that is adaptable in energy management, emphasising a convex quadratic programming framework for optimising the charge patterns of EVs. Regarding energy storage optimisation, ref. [150] discussed the optimal modelling of energy storage systems, mainly focusing on size optimisation to net present cost. Similarly, ref. [151] examined capacity optimisation methods for electrochemical energy storage systems, showcasing substantial improvements in system capability through optimisation technologies.

In addition, ref. [152] created a configuration model for the Integrated Energy System (IES) that optimises energy storage while considering several constraints and aiming for the lowest annual system life cycle cost. Regarding battery energy storage, ref. [153] talked about how to optimally size battery energy storage systems for managing demand charge in EV fast charging stations. They emphasised the need for research on better size based on several goals. Furthermore, ref. [154] suggested the best way to distribute capacity in a multivariate composite energy storage system, focusing on capacity optimisation through time series simulation technology. These references collectively offer a comprehensive overview of charge management optimisation methods, covering EV charging scheduling, energy storage system modelling, and battery energy storage optimisation. The synthesis of these references contributes to a holistic understanding of the current research landscape in charge management optimisation.

Reinforcement learning has garnered considerable attention in intelligent scheduling for EVs. Numerous studies have delved into using fundamentals from reinforcement learning to optimise scheduling and energy management in the EV domain. The introduction of a batch reinforcement learning method for scheduling domestic electric water heaters and smart home energy management was highlighted by [155]. Likewise, ref. [156] provided an overview of deep reinforcement learning's application in the optimal scheduling of EVs, highlighting recent developments. The application of reinforcement learning to hybrid electric tracked vehicles was investigated by [157], focusing on learning transition probability matrices from specific driving schedules.

Furthermore, ref. [158] suggested a charge change load optimal scheduling approach based on (Soft-Actor-Critic) deep reinforcement learning for electric car aggregators, showcasing the versatility of reinforcement learning in addressing scheduling and energy management challenges in the EV context. The research outputs of [159] presented a reinforcement learning framework for battery scheduling issues, highlighting the relevance of reinforcement learning in improving the performance and longevity of EV components and prolonging the life of EV batteries. In order to improve fuel efficiency, ref. [160] created a real-time energy management system for hybrid EVs based on reinforcement learning. This underscores the potential of reinforcement learning in addressing real-time energy management challenges in the EV context. Additionally, ref. [161] investigated the use of reinforcement learning algorithms in the energy management strategy of power-split hybrid EVs, highlighting the relevance of reinforcement learning in optimising energy utilisation in EVs. These reinforcement learning studies collectively illustrate the potential of reinforcement learning techniques to optimise EVs' performance, energy utilisation, and longevity.

4.3. Security Analysis of Smart EV Charging Systems

Given that EVs are increasingly being integrated into smart grids, research on the security analysis of EV charging is essential. The advent of technologies like 5G, autopilots, and intelligent charging has exposed cybersecurity gaps demanding thorough consideration [31]. These gaps introduce vulnerabilities at the intersection of the smart grid and EV charging, necessitating robust security measures [37,162]. Recent research has delved into the effects of cyberattacks on EV chargers and suggested safety precautions for EV charging systems [163]. Innovative approaches have emerged to address these concerns. Notably, the significance of safe authentication techniques is shown by CableAuth, a biometric second-factor authentication system for EV charging [164]. Additionally, the introduction of EVchain, an anonymous blockchain-based system, offers a multi-party security system between EVs and service providers, eliminating the reliance on third-party platforms [165]. Furthermore, the literature emphasises the integration of intelligent charging into city energy systems, stressing sectoral coupling and efficient energy scheduling [166]. This integration is pivotal for optimising power grids using smart metre data, reflecting EV charging behaviours, and supporting decision-making for utility operators [167]. Cloud computing's use of smart grid communications has also been explored for EVs' efficient charging and discharging [168]. Integrating innovative technologies like biometric authentication, blockchain systems, and cloud computing, alongside optimising smart charging strategies, is necessary to guarantee the safe and effective functioning of EV charging within the smart grid.

5. Research Gap in Electromobility, Future Trends, and Research Directions

The electromobility charging system is crucial in transitioning towards decarbonisation and clean energy sources in the transportation sector. Challenges such as slow deployment of charging infrastructure, competing standards, and reliability issues in power converters are being addressed to ensure efficient grid integration [169,170]. Studies focus on the interaction of electric vehicles with local energy systems, analysing charging profiles based on mobility patterns and peak load flow for households, emphasising the need for adequate infrastructure to meet future demands [171]. The development of charging stations plays a pivotal role in electromobility growth, supporting energetic infrastructure and maritime transportation in countries with vast geographical distances [1]. Probabilistic models are being explored to accurately predict the impact of electromobility on the power grid, using polynomial regression for simulations and discussing potential applications and extensions. Table 3 typifies some of the various research gaps, methodologies, and research contributions of various researchers in the field of electromobility charging, respective research aims, and some suggestions for future research direction in the field of electromobility charging systems. Figure 3 shows a review of current research trends, research gaps, and proposed future directions according to various works in the electromobility charging niche as a research thematic area.

Table 3. Selected Research Gaps in Electromobility Charging System.

Paper	Research Summary	Research Results	Method Used	Contributions	Research Aim	Research Gaps
[1]	Charging stations are pivotal for electromobility development, especially in countries with advanced road infrastructure. They support energetic infrastructure and show similar patterns in electromobility development across analysed countries.	• Charging stations are pivotal in electromobility development in developed countries. • Similar electromobility development patterns in analysed countries.	• SLR variation based on Scopus database queries. • Tabular comparison and K-means clustering algorithm.	• Integrates research perspectives for theoretical and practical implications. • Focuses on electromobility development and charging station infrastructure calculations.	• Present electromobility development through charging stations and infrastructure calculations. • Explore the relationship between charging stations and electric vehicle numbers.	• Knowledge gap in definitions used in scientific papers. • Taxonomic gap addressed by ranks in different aspects.
[169]	The paper discusses the critical role of EV charging infrastructure in decarbonisation, highlighting various charging technologies for different EV classes and their impact on grid integration.	• The paper provides an overview of the existing charging infrastructure ecosystem. • It covers different charging technologies for different EV classes and their impact on the grid.	• Provides an overview of the existing charging infrastructure ecosystem. • Covers different charging technologies for different EV classes and its different impacts.	• Overview of existing charging infrastructure ecosystem and technologies for different EV classes. • Discussion on the impact of charging infrastructure on the power grid.	• Decarbonisation through EV charging infrastructure. • Enhancing grid integration for renewable energy sources.	• Slow deployment of charging infrastructure. • Competing charging standards.
[170]	The charging infrastructure for electromobility involves various technologies for different EV classes, impacting the grid and enabling flexible grid integration for increased renewable energy utilisation.	• The paper provides an overview of the existing charging infrastructure ecosystem. • It discusses the impacts of current charging technologies on the grid.	• The paper provides an overview of the existing charging infrastructure ecosystem. • It discusses the impacts of current charging technologies on the grid.	• Overview of existing charging infrastructure ecosystem and technologies for different EV classes. • Discussion on the impacts of current charging technologies on the grid.	• Grid-forming control research for chargers. • Charging pathways performance analysis for different.	• Grid-forming control research gaps in charger management. • Need for more research on distributed control and stability.
[171]	The paper discusses utilising travel demand models to create charging profiles for electric vehicles, analysing peak hour load flow, and assessing infrastructure adequacy for future electromobility demands.	• Analysed charging demand and peak hour load flow for households. • Studied the adequacy of existing infrastructure for future electromobility demand.	• Travel demand model for charging profile generation. • Analysis of peak hour load flow for households.	• Analysed electric vehicle interaction with local energy systems in Stuttgart. • Studied infrastructure adequacy for future electromobility demand.	• Analyse electromobility interaction with local energy systems. • Determine adequacy of existing infrastructure for future demand.	• Future research gaps in IoT electromobility infrastructure were identified. • The study focused on existing infrastructure adequacy for future demands.

Table 3. *Cont.*

Paper	Research Summary	Research Results	Method Used	Contributions	Research Aim	Research Gaps
[172]	Modelling electromobility charging behaviour using polynomial regression simplifies grid impact predictions. The paper proposes a probabilistic power grid readiness model based on weighted random choices and polynomial regression.	• Proposed simple probabilistic model using polynomial regression for electromobility charging behaviour. • The model was verified using open data, with applications and extension discussions.	• Polynomial regression on probability density functions • Weighted random choice variables for modelling charging behaviour	• A simple probabilistic model using polynomial regression is used for electromobility charging behaviour. • Verify using open data and discuss applications and extensions.	• Create a simple probabilistic model for electromobility charging behaviour. • Analyse effects on the power grid and prepare for expansion.	• Polynomial regression for electromobility charging behaviour modelling. • Verification using open data for model validation.
[173]	An interoperability framework for electromobility (INFRA) focuses on creating guidelines for interoperable charging infrastructure for EVs, aiming for accessibility "anywhere, anytime" across the EU.	• INFRA study analysed layers for interoperability in electromobility. • Guidelines and recommendations for interoperable charging infrastructure are elaborated.	• Analysis of four layers: organisational, semantic, technical, and legal. • Development of guidelines and recommendations for an interoperability framework.	• Guidelines for interoperable charging infrastructure for EVs. • Analysis of existing barriers and recommendations for an interoperability framework.	• Develop guidelines for interoperable charging infrastructure for EVs. • Enable charging "anywhere, anytime" for all.	• Analysis of the existing interoperability framework in the electromobility sector. • Identification of barriers and guidelines for interoperability in each layer.
[174]	The safety system monitors hazardous gases from lead-acid or lithium-ion batteries during charging in an electromobility laboratory. It provides real-time values, alarms, and email notifications for remote monitoring.	• The safety system monitors dangerous gases emitted by batteries in the lab. • Real-time values are displayed on a Liquid Crystal Display (LCD) with source and light alarms.	• Monitoring hazardous gases emitted by lead-acid and lithium-ion batteries. • Real-time values are displayed on LCD, sound, light alarms, and email notifications.	• The safety system monitors dangerous gases emitted by batteries. • Offers real-time values, alarms, and email notifications for monitoring.	• Design and test safety systems for monitoring hazardous gases. • Provide real-time values, alarms, and notifications for dangerous gas situations.	• Implementation of machine learning (ML) for predictive gas monitoring. • Integration of additional sensors for comprehensive gas detection coverage.
[175]	The paper discusses integrating EV chargers with urban electrified transportation systems like trans, trolleybuses, and metro to utilise regenerative braking energy for charging.	• The study shows that every supply section of the trolleybus system in Gdynia can install a fast-charging station. • Installing charging stations in the trolleybus system provides opportunities to expand the charging network in Gdynia.	• Connecting charger to traction overhead supply line. • Feasibility analysis for trolleybus traction supply system in Gdynia.	• Use of EV charging stations to prevent grid instability. • Feasibility assessment of using a trolleybus power system to supply EV charging stations.	• Analyse the feasibility of using a traction power supply for charging EVs. • Develop criteria for assessing the capability of the traction supply system.	• Integrating feasibility in other urban traction systems. • Impact of charging stations on different traction supply parameters.

Table 3. *Cont.*

Paper	Research Summary	Research Results	Method Used	Contributions	Research Aim	Research Gaps
[176]	A novel distributed EV charging system based on Pumps as Turbines (PATs) utilises excess water pressure in a water distribution network to support sustainable micromobility.	• Proposed EV charging system using PATs • Bi-level methodology to design and optimise EV charging station systems.	• Proposed EV charging system based on pumps used as PATs. • Bi-level methodology to design and optimise EV station systems.	• Use of PATs in water distribution networks for EV charging. • Bi-level methodology to optimise EV stations for micromobility.	• Shift to renewable energy for eco-friendly EV charging. • Design and optimise EV charging stations for e-bikes and e-scooters.	• Shift towards renewable energy for eco-friendly EVs. • Design and optimise e-charging stations using PATs for micro-mobility sustainability.
[177]	The authors discuss an intelligent infrastructure for EV charging stations empowered by PV-based microgrids, promoting sustainable urban electromobility through efficient energy management and societal integration.	• Defines intelligent infrastructure for EV charging stations. • Highlights requirements and feasibility of implementations	• Multidisciplinary framework for technical-economic-environmental evaluation methodology. • Study case on requirements and feasibility of IIREVs implantation.	• Defines intelligent infrastructure for EV charging stations. • Highlights the need for a systemic approach.	• Define intelligent infrastructure for EV charging stations in urban areas. • Encourage stakeholders to develop IIREVs that are in line with societal expectations.	• A systemic approach is needed for efficient IIREV implantation. • Multidisciplinary framework for technical economical–environmental evaluation methodology.
[178]	Large-scale electromobility infrastructure can function as a profitable virtual electricity storage plant, addressing power grid instabilities with spare EV capacity and offering an economically feasible solution for investors.	• The paper presents a concept and case study for a large-scale integrated EV charging infrastructure system. • The system is economically feasible for more prominent investors and has a low visual impact.	• Virtual power plant utilising spare EV capacity. • Integrated system for large-scale EV charging infrastructure.	• Implementing large-scale electromobility infrastructure. • Creating a profitable virtual electricity storage plant.	• Implement large-scale EV charging infrastructure. • Create a profitable virtual electricity storage plant using EV spare capacity.	• Widespread EV adoption versus charging infrastructure availability. • Economic feasibility for more prominent investors in EV charging infrastructure.
[179]	The authors discuss the challenges of establishing a sustainable charging infrastructure for EVs, emphasising the complexity of integrating electromobility into the transport sector.	• The authors discuss the influencing factors and complexity of charging infrastructure establishment. • Focuses on sustainability and challenges in electromobility development.	• Factors influencing charging infrastructure. • The complexity of establishing sustainable charging infrastructure.	• Influencing factors of establishing charging infrastructure. • Complexity of a successful and sustainable establishment.	• Analyse influencing factors in establishing charging infrastructure. • Discuss the complexity of sustainable charging infrastructure establishment.	• Factors influencing successful charging infrastructure establishment. • The complexity of adapting vehicle value chains for electromobility.

In the contemporary discourse on electromobility, ref. [180] delves into the emergent trends in the Smart Green Internet of Vehicles (IoV), particularly spotlighting Vehicle-to-Everything (V2X) communication within the electric vehicle (EV) era. The study meticulously scrutinises the developments, challenges, and potential uses of V2X technology in sustainable transportation systems, accentuating the assimilation of EVs into the burgeoning IoV milieu. Meanwhile, ref. [181] elucidates the strategic research and innovation agenda concerning the IoT, underscoring the pivotal integration of IoV and the Internet of Energy (IoE) as quintessential components shaping the trajectory of intelligent transportation and mobility applications. Their discourse traverses the intersection of IoV and IoE, delineating their prospective influence on the era of electric vehicles and the evolution of V2X communication systems. Furthermore, ref. [182] expounds on the application of machine learning technologies to fortify secure vehicular communication within the IoV. Their inquiry likely elucidates recent strides and pragmatic implementations of machine learning in ensuring the security and efficacy of V2X communication, grappling with the imperative of establishing swift and robust communication among heterogeneous vehicles and smart devices in the IoV ecosystem. In a complementary vein, ref. [183], presents a scholarly discourse on an Intelligent Traffic Management System predicated on the IoV for envisaged Smart Cities. Their research posits a novel traffic management paradigm leveraging Vehicular Ad hoc Networks (VANET) and IoV to bolster traffic dynamics, alleviate congestion, and prioritise emergency vehicle traversal. The scholarly endeavour unveils an adaptive algorithm conducive to enhancing average waiting times and vehicle servicing, thereby evincing the prospective efficacy of the proposed system in the futuristic Smart City landscape.

5.1. Potential of V2G Integration in Smart Charging Systems

Integrating EVs into smart charging systems, mainly through V2G technology, has attracted much attention because of its potential to improve the smart grid's dependability and efficiency. By enabling bidirectional energy transfer between EVs and the grid, V2G technologies turn EVs into dispersed energy resources. [184] This capability influences various aspects of the smart grid, including frequency regulation, ancillary services, and reliability enhancement [185–188]. Additionally, V2G integration can contribute to effectively managing renewable energy sources and optimising energy trading within the smart grid [189–191]. The successful implementation of V2G systems necessitates addressing technical and operational challenges, such as developing efficient charging control techniques for grid-to-vehicle (G2V) and vehicle-to-grid frameworks [192]. Optimisation of V2G behaviour is crucial to mitigate battery ageing and ensure grid stability [191]. Privacy-preserving energy trading schemes and reliability evaluations are also essential for secure and dependable V2G network operation within the smart grid context [193,194].

Furthermore, the potential of V2G integration extends to economic and environmental considerations. Techno-economic evaluations of regulation services from EVs in intelligent microgrid systems emphasise the benefits of managed charging and V2G scenarios for improving smart grid operation [195]. Additionally, an analysis of intelligent charging methods and emissions from EVs highlights the bright future of intelligent charging-integrated electric power distribution networks, indicating potential environmental sustainability [90,196]. The significant potential of V2G integration lies in its ability to enhance intelligent charging systems within the smart grid context by enabling energy transfer between EVs and the grid in both directions, improving grid stability and energy management. The synthesis of studies reveals multifaceted benefits, spanning technical advancements, operational enhancements, and contributions to economic and environmental sustainability.

The study by [170] examines charging-dispatch tactics and V2G technology for electric vehicles in distribution networks, elucidating the multifaceted capabilities of V2G systems. The research highlights the two-way energy flow by describing how V2G systems enable EVs to collect power and then release it back into the grid, as seen in Figure 4. This dynamic functionality presents avenues for grid stabilisation, peak shaving, and demand response, whereby EVs function as a portable energy source unit, bolstering grid reliability and efficiency. Furthermore, the pivotal role of V2G communications in facilitating seamless coordination between EVs and the grid is underscored. Leveraging advanced communication protocols, EVs can adjust their charging or discharging patterns in response to grid conditions and demand fluctuations, thus optimising energy management. This bidirectional exchange of information enables EVs to capitalise on low electricity prices for charging while supporting grid operations during peak demand periods. Ultimately, the study accentuates the significance of V2G technologies and charging-dispatch strategies in augmenting the integration of EVs into distribution networks, underscoring their potential to benefit both individual EV owners and the broader power grid ecosystem through intelligent vehicle-grid communications.

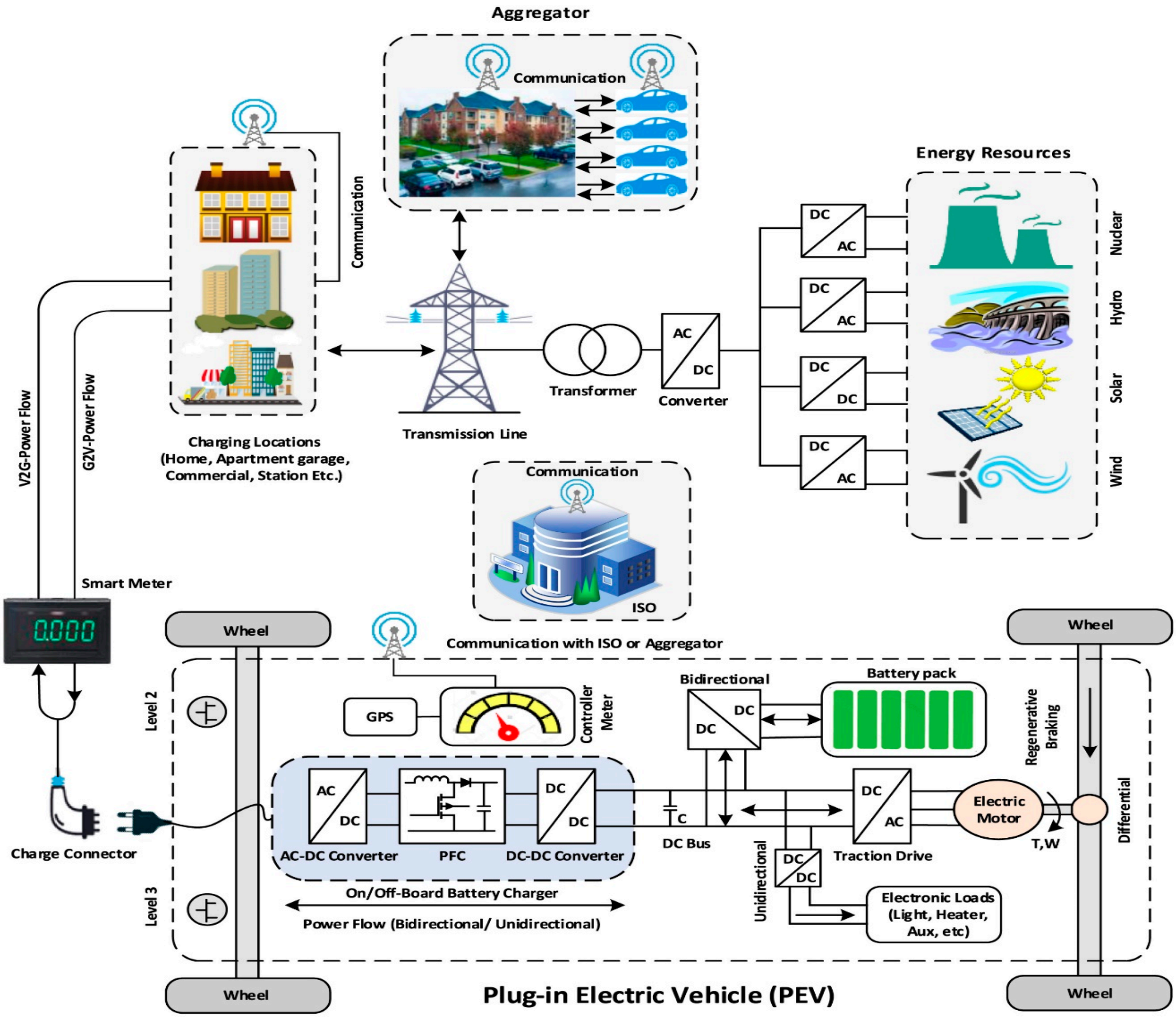

Figure 4. An outline of a V2G system's components and power flow grid communications [170].

5.2. Role of IoT and Virtual Sensors in Smart Charging

Studies on the role of the IoT and virtual sensors in smart electromobility charging reveal a growing interest in optimising charging infrastructure to advance electromobility. Countries with established road infrastructure and maritime transportation recognise the significance of developing compatible EV charging infrastructure, a responsibility often shouldered by governmental bodies overseeing infrastructure projects [1,197]. The integration of Wireless Sensor Networks (WSNs) within the Industrial Internet of Things (IIoT) has demonstrated efficiency gains in manufacturing industries, suggesting similar applications in the electromobility sector [198]. Virtual sensors within an IoT framework are acknowledged for their enabling role in smart industries, with potential applications in optimising charging processes and improving system efficiency within the electromobility sector [199]. Developing intelligent and connected EVs aligns with emerging technologies like decentralised energy trading, artificial intelligence applications, and intelligent EV charging, all relevant to integrating IoT and virtual sensors in electromobility charging [200]. A reliable communication system in smart grids is a crucial component for the effective implementation of electromobility charging infrastructure, facilitating real-time data exchange between charging stations, EVs, and grid operators to optimise charging schedules, manage grid congestion, and ensure seamless integration of EVs into the energy ecosystem [201]. Additionally, optimal scheduling of EV charging in intelligent grid networks emerges as a critical consideration, emphasising the relevance of IoT and virtual sensors in the broader context of electromobility [202].

5.3. Future Research Directions in Electromobility Charging Infrastructure

As the adoption of EVs accelerates globally, the need for advanced and efficient charging infrastructure becomes increasingly critical. Addressing electromobility's technical, economic, and operational challenges requires continuous innovation and research. This section outlines critical areas for future research that aim to enhance the integration, efficiency, and reliability of charging infrastructure, ensuring it can meet the growing demands of EV deployment while contributing to the stability and resilience of smart grid systems.

For future research into electromobility charging infrastructures, ref. [203] recommended investigating prosumers' flexibility of demands and time-variation constraints within the proposed peer-to-peer energy trading and sharing (P2P-ETS) model. Additionally, ref. [203] suggests exploring the impact of time-coupling constraints on optimising energy and communication resources in P2P-ETS, which would provide valuable insights. Integrating additional factors such as demand flexibility and time-varying constraints is also suggested to enhance the efficiency of the proposed model in future studies.

To enhance charging infrastructures, subsequent investigations should implement isolation techniques, such as those utilised in ABB Terra HP 150 or Porsche's fast charging park. Additionally, shifting transformers to higher frequencies through isolated DC-DC stages can improve voltage and power ratings by incorporating more submodules. Investigating the role of vehicle chargers in virtual inertia strategies is essential for enhancing grid integration and stability. Addressing the impacts of current charging technologies on the grid, particularly in the context of large-scale deployment and the potential for providing grid services with existing infrastructure, is crucial. Exploring the potential of chargers as grid assets and developing standard-compliant non-isolated chargers for future applications are also critical areas for future research [169]. These studies will contribute significantly to the advancement and efficiency of electromobility charging infrastructure.

Additional investigation is necessary to tackle the control issues related to grid-forming processes. Accumulating operational experience will be essential to recognise and address possible problems resulting from the intrinsic complexity of grid-forming control systems as integrating EV charging infrastructure into electrical grids becomes more widespread. Moreover, targeted innovation efforts are anticipated to alleviate safety concerns and enhance the overall efficiency of charging systems. These advancements hold promise for optimising the seamless incorporation of electromobility solutions while ensuring the resilience and reliability of power networks [174]. Pursuing such research avenues is poised to catalyse the development of robust, secure, and cost-effective charging infrastructures, thereby fostering the large-scale adoption of electric transportation and its concomitant environmental benefits [204].

Furthermore, there is strong research potential to examine the inter-organisational networks that support the implementation and upkeep of EV infrastructures. For the successful large-scale implementation of electromobility solutions, it is essential to have a thorough understanding of the intricate relationships, collaborations, and interdependencies among various stakeholders, including energy providers, automotive manufacturers, regulatory bodies, and local governments. By investigating these complex networks, scientists may spot bottlenecks, exchange knowledge, and create cooperative relationships that will eventually speed up adopting environmentally friendly transportation options [205].

Additional evaluations should consider intricate details like the expenses of particular services to augment comprehension of the system's economic viability. Examining how EV plug-in locations differ in residential and commercial settings will enable the infrastructure to be practically adjusted to various contexts [178]. Furthermore, examining the potential for incorporating cutting-edge municipal services into the system can improve its effectiveness and functionality. These study paths will yield important information about optimising the infrastructure for electromobility best charging to satisfy a range of requirements and improve system efficiency.

To improve interoperability in the electromobility industry, future research must zero in on putting the INFRA study's guidelines and suggestions into practice. More investigation into the determined minimum requirements is required to implement an interoperable charging infrastructure for electric vehicles throughout the European Union [172]. Ongoing thorough examinations of the literature will support the development of critical elements needed to achieve interoperability in charging networks. It is essential to keep up with the changing conversation around electromobility by looking into the most recent developments in the EU. Addressing current obstacles in the organisational, semantic, technical, and legal facets at each tier of the interoperability framework requires cooperation with stakeholders [172].

As the number of Plug-In Electric Vehicles (PEVs) increases and their impact on distribution networks increases, future research should concentrate on the deployment of Wireless Vehicle-to-Grid (W-V2G) systems [12]. Moreover, air-gap problems in Wireless Electric Vehicle Charging Systems (WEVCSs) must be resolved by creating and utilising In-Wheel Wireless Charging Systems (IW-WCSs) for stationary and dynamic applications. IW-WCS technology has reduced air gaps and is more efficient than the current dynamic WEVCS, so further research and development are necessary [12]. To achieve effective static and dynamic IW-WCS, careful design and optimisation of the power supply, internal structure, and wireless transformer coils are essential [12].

Future research should focus on improving EV charging systems to ensure that the integration of EVs is advantageous for intelligent grid infrastructure rather than burdensome. Improving EV integration requires investigating bidirectional Vehicle-to-Grid (V2G) solutions integrating smart metering, security, and communication between EVs and the smart grid. It is essential to look into ways to use EVs in an intelligent grid architecture to reduce power variability from renewable energy sources and preserve system efficiency and stability. Furthermore, to minimise energy losses during charging, future research should concentrate on improving the efficiency of wireless power transfer systems by refining coil designs, resonance matching, and control algorithms [206]. These research avenues will significantly enhance the integration and effectiveness of the infrastructure needed for electromobility charging.

6. Conclusions

The comprehensive study review provides an all-inclusive elucidation of the intelligent electromobility charging system, underscoring its pivotal role in the transition to electric vehicles. The review is well structured with clear research objectives and scope, encompassing diverse aspects such as user acceptance, technical potentials, grid impact, infrastructure development, interoperability, intelligent algorithms, renewable energy integration, and future trends. The overview of smart charging systems furnishes a foundational understanding by delineating definitions, key features, benefits, and challenges. User acceptance factors, derived from empirical studies, discern key influencers and trends. Technical potentials, functionalities, and integration with the smart grid are meticulously reviewed, providing nuanced insights into capabilities and applications. Examining how smart charging affects power distribution networks while concentrating on interactions and mitigation strategies offers a comprehensive understanding of the systemic effects. The global comparison of charging station infrastructure development and the factors influencing it illuminates the landscape of charging infrastructure. Additionally, exploring in-city EV charging station siting and interoperability addresses critical infrastructure planning and system compatibility.

Reviewing smart charging algorithms and optimisation methods, including charge scheduling, reinforcement learning, optimisation considering driver priorities, and security analysis, offers a comprehensive understanding of technical aspects and security considerations. Examination of smart charging's integration with renewable energy emphasises distributed resource utilisation, its impact on renewable energy integration, and the emergence of smart grids, providing insights into sustainable energy integration. Real-world insights from case studies and pilot projects, including an analysis of the COVID-19 impact on electromobility development, offer practical implications and lessons learned. Finally, outlining future trends and research directions encompassing vehicle-to-grid integration, the IoT role, and research challenges guides future endeavours in the field.

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