

Review

Electric Vehicles in Modern Power Systems: A Critical Review of Technologies, Integration Challenges and System-Level Implications

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Abstract

Electric vehicles (EVs) are increasingly regarded as a key component of low-carbon mobility and the sustainable energy transition. However, their large-scale deployment raises challenges that extend beyond vehicle technologies and require a system-level understanding of interactions with power networks, energy resources and users. This paper presents a critical review of the literature published since 2012, examining EV development from an integrated energy perspective that includes vehicle technologies, charging infrastructure, power electronics, grid integration, renewable energy coupling and environmental implications. A structured methodology is used to identify and analyze peer-reviewed studies, with particular emphasis on high-impact review articles that consolidate knowledge across disciplines. The analysis shows that, despite significant technological progress, large-scale EV deployment remains constrained by infrastructure limitations, distribution grid readiness, charging coordination strategies, material availability and socio-technical factors. Simulation-based studies play a central role in anticipating these impacts and informing deployment strategies before real-world implementation. Rather than addressing individual components in isolation, this review highlights interdependencies between technologies, control approaches and energy systems. Based on this synthesis, key research priorities and high-level challenges are identified, providing guidance for future research and policy aimed at enabling EVs to effectively support sustainable ambient energy and mobility systems worldwide deployment.

Keywords: electric vehicle; energetic communities; fast chargers; raw materials; vehicle-to-grid



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1. Introduction

In recent years, the electric vehicle (EV) has been posited as one of the key solutions in the fight against pollutant transport dependent on fuel combustion [1,2], and as a promising way to manage surplus renewable energy by storing it in vehicle batteries [3]. Europe is leading this change, both at the legislative level, with regulations like Regulation (EU) 2019/631 [4] and the future Euro 7 [5], and at the political level, with limitations on the access of certain internal combustion engine vehicles (ICEVs) to historical and environmentally protected areas of large cities [6], reducing state and municipal taxes for acquiring and using EVs, and providing direct financial contributions (subsidies) for the acquisition of new ones [7]. Several factors are promoting the transition of transportation

systems towards completely, or almost completely, decarbonized solutions. The most noteworthy are the following:

- The costs of crude oil extraction have increased on the production side, having a higher impact on fuel prices on the consumer side [8]. Given this scenario, the International Energy Agency (IEA) has indicated there will be a progressive decrease in global production of fuels in the coming decades, with the only exception being the United States (US), which has invested significantly in fracking [9].
- The increased production of pollutants derived from the combustion of fossil fuels for electrical or transportation purposes. This has become locally toxic in large cities (non-breathable air) [10], with a high level of pollutants from tailpipes and factories. In some cases, due to a synergic combination with unfavorable weather conditions, these pollutants accumulate at low altitude in cities, causing situations of poor air quality and respiratory illnesses [11,12].
- A global concern about climate change, the primary cause of which is greenhouse gas (GHG) emissions, mainly associated with carbon dioxide (CO₂) production from fossil fuel combustion [13], with many authors reporting the effects of these emissions as the main cause of global warming [14,15]. The IEA proposes limiting the increase in global temperature to two degrees Celsius by 2050 [16]. The European Environment Agency (EEA) indicates that the transportation sector causes 15% of GHG emissions, with this percentage proportion reaching 27% in the European Union (EU) [17,18]. From this previous figure, a 20–54% reduction in GHG emissions is estimated within the EU between 2015 and 2050, achieved by using EVs and assuming decarbonization of the EU electricity production system [19].
- New paradigms in energy production, transmission and distribution, with a transition from the 20th-century centralized energy production model to a distributed one, in which EVs and renewable energies, wind power (WP) and solar power (SP), among others, are considered distributed energy resources (DERs). This gives rise to the possibility, depending on the case, of producing, consuming or storing energy in high mesh electric networks [20].
- Energy sovereignty. Although energy management at the country level has generally been considered a state issue, in recent years, many countries have bolstered the idea of energy sovereignty, promoting greater independence in energy production and the security of the electrical supply [21–23].

1.1. Problem Statement: A Successful Integration of EVs in Cities

The European Commission (EC) has set challenging objectives for 2030 to progressively substitute ICEVs with plug-in electric vehicles (PEVs) and battery electric vehicles (BEVs) to reduce CO₂ emissions (assuming the electric mix that feeds these vehicles becomes increasingly renewable, avoiding fossil fuel energy sources) [24]. The EC has also set Europe's 2040 climate target and path to climate neutrality by 2050, to build a sustainable, just and prosperous society [25].

Meeting the EC objectives, in technical terms, involves complete management of a decentralized electric network that will need to support a high penetration of two elements. One is the EV, which demands additional electricity from the electric network to charge its batteries, and the other is the sources of renewable electricity, such as WP and SP, which inject electricity into the grid at different points [26].

The electric power system will need to be prepared for the high penetration of these two elements, since, in the case of EVs, they will daily demand a large amount of electricity to recharge batteries, for which distribution facilities in cities have not been designed, generating problems with the quality and stability of the supply. Furthermore, when

vehicle-to-grid (V2G) technology becomes a reality, EVs will act as bidirectional sources of energy, transferring electricity from their batteries to the grid. This functionality, if well managed, will provide the means for great energy and emission reduction, but to reach that point, it must be noted that the electrical system was not designed to accommodate hundreds of thousands of EVs and renewable energy production systems, which will be intermittently injecting electricity into the grid. Managing this will be the greatest challenge in the integration of EVs into cities [27].

The European countries with the highest BEV shares at the end of 2023 were Denmark, where BEVs accounted for 7.1% of all passenger cars, Sweden (5.9%), Luxembourg (5.1%) and the Netherlands (5.0%) [28]; and they are starting to perceive some of the previously described consequences: harmonic injection, grid imbalances when electricity demand is high for fast charging and a low power factor. To address these situations, an important effort must be made for effective communication of distribution system operators (DSOs) with EV clients through the new stakeholder: aggregators. Additionally, high-speed chargers and strategies for controlling the charging process of a massive number of EVs should be improved [29].

Recent regulatory developments in the EU have introduced additional flexibility into the long-term decarbonization pathway of road transport. In December 2025, the EC proposed adjustments to the post-2035 regulatory framework for new passenger vehicles, reducing the requirement of zero tailpipe CO₂ emissions from 100% to 90%. This proposal would allow the continued commercialization of PHEVs and extended-range EVs beyond 2035, as well as the registration of ICEVs operating on synthetic fuels or bio-combustibles with net-zero emissions. These changes respond to the challenges faced by European manufacturers in terms of technological maturity, market adoption rates and international competitiveness. From a system perspective, this evolving regulatory context further underscores the need for flexible, technology-neutral and system-level approaches to EV deployment and long-term infrastructure planning [30].

1.2. Motivation and Main Aims

The motivation of this work stems from the increasing complexity of EV deployment, which involves not only advances in vehicle technologies but also their interaction with power systems, renewable energy sources (RESs), control strategies and urban planning constraints. While numerous studies have addressed these aspects independently, there is no comprehensive synthesis that critically examines their interrelations and collective impact. Accordingly, the main contributions of this critical review can be summarized as follows:

1. To propose a structured classification of the existing literature on EVs, covering technological developments, grid integration, control techniques, simulation approaches and emerging concepts, such as energetic communities.
2. To critically synthesize the findings of recent studies, highlighting common trends, methodological assumptions and performance limitations reported across different research streams.
3. To identify key compromises and unresolved issues that hinder the large-scale and sustainable deployment of EVs, particularly in urban environments.
4. To derive a set of future research challenges and directions grounded in the critical analysis of the reviewed literature, providing guidance for subsequent research efforts in the field.

Building on the foundation laid by [31], this study expands upon their systematic literature analysis. While this study quantified key technological aspects of EVs with a primary focus on grid impact, the present work develops the remaining dimensions that were previously unexplored. Many existing reviews on EVs focus on isolated components, such as

batteries, charging infrastructure or control strategies, providing limited integration across urban and power system contexts. In addition, these surveys are often descriptive and offer little critical assessment of methodological assumptions and reported compromises. This paper addresses this gap through a structured and critical review that synthesizes technological trends, identifies common limitations and contradictions, and outlines key challenges related to large-scale EV deployment, grid integration and sustainability.

1.3. Structure and Content

The paper is structured into five main sections. Section 1, the Introduction, presents the motivation, objectives, and the overall structure of the study. Section 2 (Materials and Methods) details the methodology used to assess the technical literature on EVs, including the selection of 40 prominent review studies from previous years and the development of a framework classifying these into categories. In Section 3 (Results), key content extracted from these 40 studies is organized into the predefined categories, encompassing the most significant aspects reviewed between 2012 and 2025, and is complemented by recent contributions that reflect emerging trends and regulatory developments. Section 4 provides an in-depth discussion of these results. Based on the findings, it identifies key challenges and outlines potential avenues for future research within this field. Finally, Section 5 presents the main conclusions of the study.

2. Materials and Methods

This work is conceived as a structured critical review rather than a fully systematic review, with the objective of synthesizing key technological trends and identifying cross-domain research challenges regarding EVs and their integration into modern energy and transportation systems.

2.1. Literature Search Strategy

The literature search was conducted using major scientific databases, including IEEE Xplore, Scopus and Web of Science. A core search strategy was first defined using targeted keyword combinations such as “electric vehicle” AND “electrical networks” and “electric vehicle” AND “renewable energy”, aimed at identifying review studies addressing EV technologies, charging infrastructure, power system integration, control strategies and urban mobility.

To ensure relevance and quality, the review focused on peer-reviewed journal articles and conference papers published from 2012 onward. Studies were considered eligible when they contributed to the technological development, system-level analysis or application-oriented evaluation of EV deployment. Because this work is conceived as a structured critical review rather than a fully systematic review, the screening process was designed to retain studies able to support an integrated and critical synthesis rather than to produce an exhaustive quantitative inventory of all publications on EVs. The qualitative criteria used to exclude records from the synthesis and to define the core analytical subset are summarized in Table 1.

These criteria were applied in a complementary way, since a single record could meet more than one exclusion reason. Consequently, the 215 excluded records are reported as an aggregate group in Table 2, rather than being retrospectively divided into mutually exclusive categories.

Applying the selection process summarized in Table 2, 95 studies were retained as the broader qualitative corpus of the review. Within this corpus, a focused subset of 40 journal articles, including systematic reviews, critical reviews and broad-scope studies, was selected as the core analytical foundation. These 40 papers should not be interpreted

as the complete set of references considered in the manuscript; rather they provide the analytical backbone used to organize the synthesis, compare methodological approaches and identify recurring assumptions, compromises, contradictions and research gaps across the main review categories.

Table 1. Screening and selection criteria applied in the review process.

Criterion	Application in the Screening Process	Role in the Review
Scope alignment	Studies had to address EV deployment in relation to power systems, charging infrastructure, grid integration, renewable energy coupling, environmental impacts, simulation, critical materials or system-level implications.	Exclusion/inclusion criterion
System-level relevance	Papers focused only on a narrow component, isolated algorithm, vehicle subsystem or highly specific local case were excluded unless they offered transferable implications for EV integration.	Exclusion criterion
Methodological transparency	Studies with insufficient description of data sources, assumptions, modeling boundaries, scenarios or evaluation conditions were not retained for qualitative synthesis.	Exclusion criterion
Technical depth	Mainly descriptive, editorial, preliminary or low-detail contributions were excluded when they did not provide substantive technical, analytical or methodological content.	Exclusion criterion
Non-duplication	Studies whose findings were largely duplicated or superseded by more recent, broader or technically complete works were not retained as core literature.	Exclusion/core-selection criterion
Transferability	Highly local regulatory, geographic or market-specific studies were excluded from the core subset unless they provided insights transferable to other EV deployment contexts.	Exclusion/core-selection criterion
Thematic contribution	Retained studies had to contribute substantially to at least one of the thematic categories used in the review.	Inclusion criterion
Core synthesis value	The 40 core papers were selected because they provided broad category coverage, methodological detail, technical depth, scientific relevance and capacity to support cross-category comparison.	Core-selection criterion

Table 2. Literature selection flow.

Stage	Number of Records	Interpretation
Records identified	420	Initial records retrieved from the database search using the defined keyword combinations.
Records after preliminary screening	310	Records remaining after removing duplicates and clearly unrelated items.
Records excluded	215	Records not retained for qualitative synthesis because they met one or more of the criteria reported in Table 1.
Studies included for qualitative synthesis	95	Broader qualitative corpus used to support the integrated review.
Core analytical subset	40	Studies selected as the main analytical backbone of the review.

The number of core articles was deliberately limited to balance analytical depth with representative thematic coverage. Priority was given to studies with sufficient technical detail, methodological clarity, scientific relevance and capacity to support cross-category comparison. The remaining studies included in the broader qualitative corpus were used selectively to contextualize results, support specific technical discussions and incorporate recent developments or emerging topics that extend beyond the scope of the core articles.

The remaining studies included in the broader qualitative corpus were used selectively to contextualize results, support specific technical discussions and address emerging or cross-cutting issues beyond the scope of the core articles. This complementary literature was particularly relevant for topics increasingly recognized as critical for large-scale EV deployment, such as cybersecurity, critical raw materials, energy communities, regulation and recent market developments. In this way, the review remains focused on the core

analytical synthesis while incorporating recent developments relevant to the evolving EV ecosystem.

Given the heterogeneity of the reviewed studies, numerical values reported across the literature were interpreted with caution and were not treated as universal benchmarks. This is particularly relevant for indicators such as harmonic distortion, charger-to-vehicle ratios and V2G economic benefits, which are highly dependent on the assumptions and boundaries of each study. Harmonic distortion values, for example, may vary according to charger topology, power level, point of measurement, grid strength, filtering strategies and charging simultaneity.

Charger-to-vehicle ratios depend on mobility patterns, availability of private charging, urban density and expected service levels, while V2G economic benefits are influenced by electricity prices, market rules, battery degradation assumptions, bidirectional efficiency and user availability. Therefore, when substantially different values are reported in the literature, they should be read as context-dependent results rather than as directly comparable or conflicting estimates. In this review, such numerical values are used mainly to illustrate ranges, sensitivities and qualitative trends.

Together, this structured use of the literature supports a coherent and transparent synthesis of results while preserving the critical and integrative focus of the review.

2.2. Classification of the Reviewed Literature

The selected literature was subsequently organized into thematic categories reflecting the main research dimensions identified in the field. This classification enabled a comparative and critical analysis both within and across categories, facilitating the identification of prevailing trends, shared assumptions and research gaps. Table 3 shows the main characteristics of the selected studies.

Table 3. Selected review articles (A1–A40) organised by year and main author.

Article (year)	A1 (2012)	A2 (2013)	A3 (2013)	A4 (2014)	A5 (2014)
First author	Murat Y. [32]	David B. Richardson [33]	Wei Gu [34]	Ahmed M.A. Haidar [35]	Pranav Maheshwari [36]
Article (year)	A6 (2014)	A7 (2015)	A8 (2015)	A9 (2015)	A10 (2016)
First author	Xianjun Zhang [37]	Liansheng Liu [38]	Salman Habib [39]	Jia Ying Yong [40]	Junjie Hu [41]
Article (year)	A11 (2016)	A12 (2016)	A13 (2017)	A14 (2017)	A15 (2017)
First author	Abdul Rauf Bhatti [42]	Kang Miao Tan [43]	Ashique, R. H [44]	Ahmad, A. [45]	Sovacool, B. K. [46]
Article (year)	A16 (2018)	A17 (2018)	A18 (2019)	A19 (2019)	A20 (2019)
First author	Thompson, A. W [47]	Shepero, M. [48]	Hoarau, Q. [49]	Collin, R. [50]	Pagany, R. [51]
Article (year)	A21 (2019)	A22 (2019)	A23 (2020)	A24 (2020)	A25 (2020)
First author	Li, Z. [52]	Barone, G. [53]	Mohammad, A. [54]	Arias-Londoño, A. [55]	Fachrizal, R. [56]
Article (year)	A26 (2020)	A27 (2021)	A28 (2021)	A29 (2021)	A30 (2022)
First author	Ding, Z. [57]	Aretxabaleta, I. [58]	El-Bayeh, C. Z. [59]	Eltoumi, F. M. [60]	Rahman, S. [61]
Article (year)	A31 (2022)	A32 (2022)	A33 (2023)	A34 (2024)	A35 (2024)
First author	Metais, M. O. [62]	Safayatullah, M. [63]	Barman, P. [64]	Ahmed, S. [65]	Das, Bhat & Sajith [66]
Article (year)	A36 (2024)	A37 (2025)	A38 (2025)	A39 (2025)	A40 (2025)
First author	Arévalo P., Ochoa [67]	Santinha, G. [68]	Santos, R. C. O. [69]	Razzaque, M. A. [70]	Xylia, M. [71]

Considering the impact of high EV penetration on distribution grids, which is a challenge extensively documented in the recent literature [72–74], six thematic categories were established to cover various aspects of EV integration. These categories were defined to synthesize and integrate the scientific findings reported over the study period.

1. **EV technologies.** This category includes the technological aspects of the EV related to its internal functioning, but also to its external functioning, by means of the connection with the electric grid. Four subcategories were selected: *Types of EVs*, describing the main typologies of EVs; *battery technology, remanufacturing and recycling*, which deals with the types of batteries, capacity, and aspects of recycling; *powertrain*, which includes operative characteristics of the engine; and *charging infrastructure, power electronics and V2G integration*, explaining the advances in these elements and their interactions with the electric network.
2. **Charging infrastructure, power electronics and V2G interaction.** This section examines the core technological and regulatory pillars of electric mobility. It provides a comprehensive analysis of the subcategories: *charging infrastructure and standards*, alongside the latest advancements in *fast and ultra-fast charging systems*. Furthermore, the discussion covers *wireless charging technologies*, the evolution of *power electronics for charging and grid interfaces*, and the implementation of *bidirectional energy exchange and V2G interaction*.
3. **Environmental management aspects.** This includes two subcategories: 1. *Local pollutants*, covering the studies that propose energy savings and pollutant reductions in relation to ICEVs—unburned hydrocarbons (HCs), nitrogen oxides (NOx), particles, etc.; and 2. *emission reduction management*, including the studies that conclude CO₂ emissions are reduced when ICEVs are substituted with EVs, considering both global and local scenarios, and without using RESs to support the electric system.
4. **Integration of EVs into renewable-based smart grid (SG): Operational frameworks, energetic communities and cybersecurity aspects.** This section explores the integration of decentralized energy systems, and the digital frameworks required for their operation. Specifically, it addresses the studies dealing with control and information and communication technology (ICT) to manage complex smart electric grids with multiple renewable producers and elements with storage capacity, such as EVs. Furthermore, this category includes articles on the relation between the incorporation of RESs into the electric network, and the positive consequences for EV penetration in the same network. Five subcategories were selected: *Interaction between EVs and RESs*, split into *wind*, including the scientific results of integrating EVs and WP in the same electric grid, and *solar*, performing the same analysis with EVs and SP; the development of *energy communities*; the design of *smart-grid architectures and control strategies*; and the critical importance of *cybersecurity for smart chargers and grids* to ensure resilient and secure energy networks.
5. **Simulation tools and system-level studies.** This category includes studies that use simulation methodologies to calculate future effects for certain scenarios of interest. Not only technical but also economical simulations are carried out to predict optimal solutions. Four subcategories were selected: *Long-term*, for simulations to predict results on timescales of several days to years; *short-term*, for simulations ranging from milliseconds to hours; *optimization algorithms*, for simulations intended to calculate different solutions for cost reduction strategies in relation to the optimal percentage of penetration of renewable energies; and *PHEV/EV penetration and electric system capacity*, in which calculations seek to determine the acceptable number of EVs that the electric distribution system can manage for each use case.

6. **Raw materials and component production. Economic and environmental challenges. Strategies to face them.** This section examines the production of raw materials and critical components, and the challenges posed by mineral scarcity and supply chain risks. It analyzes the feasibility of large-scale electrification given current resource constraints.

It is important to clarify that these categories are not intended to be mutually exclusive. Many topics addressed in this review are inherently connected. For example, charging infrastructure and V2G can be discussed as part of EV technology when the focus is on vehicle components, onboard converters, batteries or bidirectional capabilities. However, they are addressed in a dedicated category when the focus shifts to external chargers, charging standards, power electronic interfaces, fast and ultra-fast charging, and the practical exchange of energy between vehicles and the grid.

Similarly, renewable integration, smart grids and control strategies are grouped together when the analysis concerns how EVs are coordinated with distributed generation, energy communities, communication systems and grid operation. Simulation tools are treated separately because they are mainly used to test scenarios, estimate grid impacts, evaluate charging demand and compare planning or control strategies before real deployment. Therefore, the classification should be understood as a thematic framework based on the main perspective from which each topic is analyzed, while preserving the cross-cutting links between categories.

This review employs a multidimensional categorization that integrates technological, operational, and systemic aspects to analyze their mutual interdependencies. This transparent and structured framework facilitates a balanced synthesis of the literature and a comparative analysis of how advances in vehicles and control strategies impact grid integration and sustainability outcomes.

3. Results

This section presents the main findings of the review, focusing on the key technological and systemic aspects that shape EV development and deployment.

3.1. EV Technologies

This section provides an overview of EV technologies, starting with a classification of the main types of EV.

3.1.1. Types of EV

ICEVs are vehicles propelled by an internal combustion engine, being the traditional vehicles based on the combustion of fossil fuels [38]. PEVs are defined as those using an external source of electricity to recharge batteries carried on board and that allow an electric motor to be moved. PEVs can be divided into two subsets:

- BEVs, which are vehicles that work exclusively with an electric battery and motor, being charged through the electrical grid, and whose discharged batteries can be replaced by charged ones in potential operating models. This paper only addresses the external electric charge of these vehicles, without battery replacement.
- PHEVs have a battery, which, apart from electricity, can be charged using other energy sources, such as fossil fuel through a combustion motor, an electrical motor acting as a generator, and power electronics [36]. For an EV to be considered a PHEV, it must have at least a 4 kWh battery with which it can cover a minimum distance of 16.1 km in electric-only mode [4]. A 10 kWh battery, depending on the mass of the vehicle and driving conditions, can provide a range of 16.1 km to 96.6 km [35]. An example is the

2024 Toyota RAV4 Plug-in PHEV, with an 18.1 kWh battery, which allows it to travel 75 km in electric mode. It can be charged by cable through a wall box [75].

Other types of vehicles that partially use electricity for their operation are indicated. The mild hybrid electric vehicle (MHEV) consists of a combustion engine plus a small electric motor that provides starting assistance with a small battery. The electric motor is not capable of moving the car on its own, but reduces fuel consumption and therefore emissions (around 5%) at start-up [76]. Hybrid electric vehicles (HEVs) have a larger battery and higher-capacity electric motors, which assist the combustion engine, but can only operate in electric mode for a limited time depending on road conditions and battery charge. They are not loaded externally. The battery is recharged from the combustion engine and regenerative braking [77]. For the purposes of this study, the term EVs refers to PEVs, specifically focusing on BEVs and PHEVs operating in electric mode. In economic terms, BEVs are more expensive than an equivalent ICEV, although prices are expected to converge between 2025 and 2028 [78].

3.1.2. Battery Technology, Remanufacturing and Recycling

EVs are heavier than their ICEV equivalents, since a platform is designed with a specific compartment to house batteries (around 250 kg depending on the model), which maintains a very low center of gravity, improving dynamic behavior in curves. The batteries are usually located in a metallic frame with structural capacity that makes the assembly rigid and protects it against impacts. The lower part of this type of vehicle typically has a metallic or polymeric plate to protect the batteries, and at the same time, to provide an aerodynamic fairing to the assembly, which improves its top speed [79].

Batteries can be composed of cells of two types: prismatic [80] or cylindrical [81]. These cells are organized to provide around 400 V and capacities from tens to more than one hundred kWh. Battery conductors (power wires) are normalized to orange in color, and can be handled with safety gloves up to 1000 V. Typically, three types of connectors that enter/exit the battery are found: (1) power connector, which goes to the engine block; (2) heating and/or cooling connector, which is electrical in some vehicles, and in others, according to specifications, can be a liquid or a gaseous fluid, to thermally condition the batteries through electrical devices controlled by electronics; and (3) control system connector, to send messages to the vehicle control networks and to constantly be informed of the battery status. Additionally, the battery may have a high-amperage fuse (around 200 A, depending on the vehicle model) [82].

The authors of [40,41] exhaustively review the path from lead–acid (Pb-acid) batteries to the most recent lithium (Li) ones. They highlight that their selection depends on lifetime, power density, efficiency and operation temperature. Pb-acid batteries are the most traditional and most widely studied batteries, with a lower charge density (unsuitable for EVs) and a lower cost, constituting a baseline for comparison with respect to other options. Nickel–cadmium (Ni–Cd) batteries have a low energy density, although they are appropriate for low temperature ranges (below 0 °C) and are expensive. Nickel–metal hydride (Ni–MH) batteries are used as a lifetime model for assessing the impact of a specific operating scheme of a battery. Additionally, the Li-ion battery and Li-polymer battery are available on the market. EVs use Li-based batteries because of their high energy density (the highest on the market) and long lifetime [32,34,35].

The authors of [47] present an extensive review of the fundamentals of the technologies of the different types of batteries, reporting that from 2008 to 2017 their costs reduced fourfold, while from 2009 to 2015 their energy density multiplied by the same factor. In addition, the work performs an in-depth analysis of battery degradation mechanisms, some of the most important being temperature, time, state of charge (SoC), charge rate

(C-rate), depth of discharge (DoD) and ampere hour (Ah). Mathematical models have been developed to predict the life of batteries, although this is a complicated question because validating them requires empirical tests of ten or more years, while, in this time, the technology continues to advance [59,63]. The authors of [58] compile an extensive updated table of the autonomy of commercial EVs, from which it can be concluded that, depending on a multitude of variables (mass, driving style, orography...), the current approximate consumption ranges are between 0.11 kWh/km and 0.24 kWh/km.

It should be mentioned that V2G-type services, as a counterpart, present a reduction in the useful life of the battery compared to if it is only used for driving [42–44]. Honda provided figures on the warranty period for the battery, indicating that the loss of useful life for driving was 8%, and an additional 2% had to be added for V2G services. In general terms, a battery is considered to be at the end of its useful life when it reaches 70% or 80% capacity, although it can still be used in this state [46].

Regarding the near future, ref. [50] indicates that the current nominal charge voltage of batteries (300 V to 420 V) could be increased to a DC bus of 800 V, reducing the weight of the conductors and the size of batteries for the same power target. Ref. [52] reports that, according to the Association of European Automotive and Industrial Battery Manufacturers (EUROBAT), it is intended that the efficiency of the three main types of batteries will be improved by 2030. In terms of efficiency, Li-ion batteries could reach 95%, with power densities of 1100 Wh/L, making it possible to recycle up to 90% of their components and improving their lifetime to values above 10,000 cycles. In that time, the price of these batteries is expected to continue to drop, improving their cost competitiveness. Regarding this point, the same authors reported a battery cost of \$156/kWh in 2019 and forecasts of \$100/kWh for 2024 and \$61/kWh for 2030. Other authors complement these data, indicating that in 2010 the price was \$1100/kWh, while in 2020 it had been reduced to \$137/kWh [62].

Battery design remains a critical factor for large-scale EV deployment, particularly in terms of cycle life, energy density and end-of-life management. Recent studies emphasize that advances in battery performance must be accompanied by sustainable recycling strategies capable of recovering critical raw materials and reducing long-term supply risks [83]. New types of batteries are currently under development and close to market. Some examples are solid-state batteries (SSBs), solid electrolytes over organic liquids [47] and sodium-ion batteries [84].

In summary, the reviewed literature reflects a consolidated transition toward lithium-based technologies, highlighting a drastic trend in cost reduction and energy density improvements which, alongside the development of 800 V architectures and solid-state cells, define the technical roadmap for the coming decade.

3.1.3. Powertrain

The powertrain of an EV is made up of three elements:

- **Power module**, which, depending on the vehicle brand, may have a different name. It is usually located where the cylinder head of a combustion engine would go. Its mission is to distribute power to the EV systems, when needed, and it can act as a power switch if there is a problem. In some vehicle models, it works by managing the current that enters the socket when the EV is charged.
- **Inverter**, which works together with the power module and can transform the direct current (DC) from the battery into three-phase alternating current (AC), which is necessary for the motor to work. Depending on the EV model, this step can be performed in the power module or through a hybrid connection between both. The inverter performs a task that is exclusive to it, converting three-phase AC into DC

when regenerative braking is used (disc brake braking or motor braking), such that the battery can be charged. It is made up of insulated-gate bipolar transistor (IGBT)-type power semiconductors. In thermal terms, it is the hottest point of the EV.

- **Motor generator**, which is made up of a brushless electric motor, which can be a permanent magnet or fully wound (rotor/stator) and is usually cooled by a liquid that is a conventional motor coolant (glycol-type or similar). Initially, working with permanent magnets would allow the motor to cool better than using a double winding. It also reduces battery size with respect to using the latter, as when the former are used, the assembly is compacted. Permanent magnets are usually solidly installed in the rotor part, and variable magnetic field windings are arranged in the stator. These motors are, with equal power, typically much smaller than industrial ones, since the latter are cooled by natural or forced air convection, while the former are cooled by a liquid refrigerant circuit, improving the heat evacuation. In the case of permanent magnet motors, temperature control is essential, since if the temperature rises too high it could demagnetize the magnets, making the motor unable to provide movement to the EV [85].

The authors of [35] indicate that motors with permanent magnets behave better in overload transients at constant speed. Furthermore, the peak efficiency of synchronous brushed motors is lower than that of motors with permanent magnets, maintaining high efficiency in a wide range of operation. Reluctance motors present better performance with overloads at high speed. Finally, the efficiency of the reluctance motor decreases rapidly at low speed but allows for control in high-speed operation. The mechanical power leaves through a set of gears in which there is no gear change, transmitting the engine revolutions directly from the stationary state up to the nominal maximum. What exists is a gearbox that goes from high revs in the engine to low revs in the wheels, so that the maximum number of revs of the engine limits the speed. In general, the casings of these three elements are made of aluminum. The inside part of the motor, for obvious reasons, needs to be ferromagnetic.

The servo brake is an element that electronically regulates the amount of energy that is dissipated in braking by means of mechanical brakes (discs and pads), or by means of the engine brake of the electric motor. In some models, the user can configure this value, allowing more braking energy to be converted into charging for the batteries, reducing wear on the brake pads [38,40].

Overall, the literature underscores that current powertrain design prioritizes compactness and thermal stability, with permanent magnet motors leading in efficiency while relying on advanced cooling and electronic regulation to maximize performance across the entire speed range.

3.2. Charging Infrastructure, Power Electronics and V2G Interaction

Charging infrastructure and the associated power electronics constitute the physical and functional interface between EVs and the electrical grid, determining not only charging performance but also power quality, grid interaction and the feasibility of bidirectional energy exchange.

3.2.1. Charging Infrastructure and Standards

An EV can be charged with AC or DC, using the first for slow or medium charges, and the second for fast or ultra-fast charges [32,35]. In the first case, the current is transformed into DC inside the vehicle before going to the battery (which only works on DC); and in the second, the charger directly injects DC to the battery connectors [41,42]. All connectors have a communication cable that ensures the plug is well connected before transmitting current and that the battery is receiving charge in appropriate conditions, so that the amount of

current is controlled in order to avoid overheating in the battery [38,39,45]. At all times, whether charging in AC or DC, the car communicates with the charging station to indicate the current that it can accept safely and that all the cells are charged equally [36].

To standardize the different charging systems and connections, a set of international standards for EVs was developed. The authors of [40] and, as an update, [58], worked to create an exhaustive compilation of such standards, listing the main ones, namely, Society of Automotive Engineers (SAE)—United States, International Electrotechnical Commission (IEC)—International, CHArge de MOve (CHAdeMO)—Japan, GB/T—China, and CNS—Taiwan. The standards are organized internally by load level, with the lowest levels being the least powerful and the highest being the most powerful. Table 4. shows those that are currently the most significant.

Table 4. Standards for EV chargers. The data in row 3 is used with the charging points in Appendix AA, BB and CC of the IEC 61851-23:2014 [86].

Standard	Charging Level	Max. Voltage (V)	Max. Current (A)	Power (kW)
SAE J1772 [87]	1	120-AC	16	1.92
	2	240-AC	<80	19.2
	3	240-AC	>80	19.2
	1	450-DC	80	36
	2	450-DC	200	90
	3	600-DC	400	240
IEC 62196-2:2016	1	250-AC	32	8
	2	250-AC	70	17.5
	2 (3-phase)	480-AC	63	30.24
	3	250-AC	70	17.5
	3 (3-phase)	480-AC	63	30.24
IEC 62196-3:2014	4 (AA)	600-DC	200	120
	4 (BB)	750-DC	250	187.5
	4 (EE)	600-DC	200	120
	4 (FF)	1000-DC	200	200
	4	1000-DC	500	500
IEC 61851-23:2014	4	1500-DC	300	450
IEC 61851-1:2020 [88]	1	25-AC	16	4
	1	480-AC (3-phase)	16	7.68
	2	250-AC	32	8
	2	480-AC (3-phase)	32	15.36
	3	250-AC	32	8
	3	480-AC (3-phase)	32	15.36

Regarding the SAE EV standard, AC level 1 (120 VAC single-phase power network) is useful for overnight charging, with an average charging time of 17 h. In the case of AC level 2, the estimated charging time is about 22 min for a small-capacity PHEV. DC charging levels can charge up an EV to an SoC of 80% in less than 30 min.

The CHAdeMO standard, CHArge de MOve (CHAdeMO) [60], has been reviewed. It was published as the Japanese national standard in October 2012, introducing the DC fast-charging standard designed for EVs to alleviate range anxiety among EV drivers. In its first version, it was able to recharge a battery to 80% SoC in less than 30 min, working with a 50 kW DC charging power (around 500 V and 100 A). Ref. [44] indicates that it establishes a secure communication between the EV management system (EVMS) and charger control units. Furthermore, the CHAdeMO standard supports bidirectional power flow for V2G applications. Since the beginning of 2014, CHAdeMO has been included in

the IEC EV standard, adopting IEC 61851-23 [86] for the charging system, IEC 61851-24 [89] for communication and IEC 62196-3 [90] for the connector.

Further to the previous studies, ref. [62] makes contributions related to the IEC standards. Regarding IEC 62196-2 [91], it describes three levels of EV connections in AC, adding a fourth one (IEC 61851-3 [92]) working in DC, which is able to fully charge an EV in ten minutes, and mentions that the differences in charging time, between a few minutes and up to 20 h, depend on the activity of the EV. In the case of home EV charging, no ultra-fast charging or special facilities are needed (97% of the time the EV is stopped) and 90% of the trips do not exceed 80 km. An EV with a range of 200 km allows daily trips to be completed. If the journeys are long, fast charging points are necessary, or ICEVs might continue to be the option for this type of situation until the autonomy and charging speed of EVs are comparable to those of ICEVs. Such situations are a part of the social barrier that exists for the acquisition of EVs, not only of a technical nature [50,63].

The authors of [40,61] provide several battery charging strategies to optimize different variables: 1. Constant-voltage (CV) charging, which charges the battery while maintaining a constant voltage, adapting the current based on the internal resistance of the battery and the voltage converter. This system optimizes battery life. 2. Constant-current (CC) charging, which always forces a constant current into the battery, speeding up the charging rate but decreasing battery life. 3. A combination of CC and CV charging. This is a hybrid method and is more commonly used in commercial chargers. It uses the advantages of each system, starting with a CC load until a certain predefined SoC, and from there changing to CV until the load is finished. Battery life and charging speed are optimized.

There are two other methods: 4. Constant-power, and 5. multistage-current charging. The aim of these is to control the temperature of the battery, which avoids impairing its useful life. In on-board AC converters, trickle charging with low power and current is used to minimize the size of electronic equipment and maximize conversion efficiency. The preferred charging method is CC-CV, which typically takes 10–12 h. Ref. [64] classifies smart charging methods for EVs based on alignment with renewable generation patterns, detailing four approaches: network charging synchronized with grid load and renewable production, shifting charging to periods of high renewable output, excess renewable charging triggered by surplus production, and on-site renewable charging directly coupled to local generation. These strategies are supported by pilot programs utilizing time-of-use tariffs and variable pricing to encourage charging behavior aligned with grid-friendly patterns. These strategies are validated through pilot programs in the USA using economic incentives, such as flat residential rates, between \$30 and \$50 monthly; or price differences, up to \$0.40/kWh in summer versus \$0.14/kWh in winter.

Ref. [71] quantitatively analyzes methodological trends in charging infrastructure demand estimation. It is indicated that over 60% of the reviewed studies rely on user behavior or mobility-based modeling approaches, while around 40% employ spatial or GIS-based methods. However, fewer than 25% of the analyzed works explicitly link charging demand estimation with distribution grid constraints. The authors also report order-of-magnitude variability in charger-to-vehicle ratios across studies, reflecting the strong dependence of infrastructure requirements on local assumptions regarding driving behavior, charging preferences and service levels.

In conclusion, the data demonstrates a complex landscape of international standards (SAE, IEC, CHAdeMO) that categorize charging into AC and DC levels, where the selection of CC-CV strategies remains essential to balance the trade-off between ultra-fast charging speeds and the preservation of battery cycle life.

3.2.2. Fast and Ultra-Fast Charging Systems

Fast and ultra-fast chargers are the solution the market demands to avoid range anxiety due to EVs' lack of autonomy, and to be competitive with petrol-based transportation. According to [50], it would be necessary to be able to charge an EV in 5 to 10 min, and according to their calculations, the transferred power should be around 5.4 MW. It is not possible to achieve this enormous value, but a minimum Level 3 charger with 50 kW fast chargers can charge a 60 kWh battery in 1 h and 15 min. To reach these power levels, charging must be performed directly in DC without electronic converters in the EV, since they would be too large [58,60]. Currently, and as seen in Table 4, fast chargers of hundreds of kilowatts are standardized. Continuous increases in power charging entail technological challenges, such as large external power converters, a larger conductor section, battery overheating problems and the physical limitation of the diffusion of Li ions in the electrodes, which slows down as the thickness of the layer formed increases.

Fast battery charges decrease battery life [63]. Ref. [45] indicates that a fast charger can charge 50% of a battery in 3 min and 80% in 15 min, and coincides with previous work in stating that a careful charge control strategy, finely adjusting voltages and currents, is necessary to enhance battery life. The authors of [61] present a classification in which fast charging is equivalent to a time of 180–240 min to go from 20% to 80% of the SoC of a battery. On the other hand, rapid/superfast charging can reduce that time to 20 min. Additionally, these authors deal with various technologies for precise thermal control of temperature in batteries, providing solutions such as air cooling, liquid cooling and even phase change materials, with the clear objective of avoiding breakdowns and increasing the useful life of the battery. Finally, the authors of [62] provide interesting data on charger costs. For a Level 2 charger, it is estimated at \$3000, on the other hand, a DC fast charger can cost up to nine times more. There are already apps for users, e.g., “A better route planner” [93], which tells them where there are chargers, how to travel, and planning the trip from home and its approximate cost.

Ultimately, the findings reveal a stark contrast between market demands for 5-to-10 min charging and current technical realities, where the high costs of DC infrastructure (up to nine times that of Level 2 chargers) and physical limitations in Li-ion diffusion remain the primary hurdles for large-scale implementation.

3.2.3. Wireless Charger Technologies

Wireless power transfer (WPT) chargers are devices that allow electrical energy to be transferred to EVs for battery charging without physical contact between the two systems, with a small air gap between them. The main advantage is that cables and plugs are eliminated. It is a booming research trend [63]. The authors of [50] carry out an in-depth analysis of this technology, classifying these systems as inductive or capacitive based on their operating principle, and as static (vehicle stopped) or dynamic (vehicle in motion) based on their mode of operation. In the inductive case, a magnetic coupling occurs between the coils of the charger and the EV. Several examples of power transmission between 50 kW and 100 kW are provided at frequencies from 22 kHz to 25 kHz, calculated to achieve resonance between coils to minimize energy losses, and at distances of 12.7 cm, with transmission efficiencies of 96%.

Capacitive charging is performed by capacitive coupling at higher frequencies between a roadway plate and an EV onboard one. Indicative figures are 884 W and 91.3% efficiency, with a transmission frequency of 13.56 MHz and a 12 cm air gap, reaching a power density of 29.5 kW/m². Honda has designed solutions of 180 kW circulating at 156 km/h and 250 kW at 200 km/h. In Sweden, there are several real wireless charging demonstrators. The authors of [43] reference another example in the form of the implementation in Málaga

(Spain) of bus route 16 in 2014, operating at 200 kW and 35 kHz; they provide an extensive collection of WPT standards. Some of the most relevant are the IEC-61980-1 standard [94], defining WPT and a supply of 1000 V (AC) or 1500 V (DC), and its equivalent in SAE, which is the SAE TIR J2954 standard [95]. These findings highlight a maturing technology supported by international standards and successful pilot projects, demonstrating the feasibility of both static and dynamic charging as cable-free alternatives for urban mobility and public transport.

3.2.4. Power Electronics for Charging and Grid Interface

Advanced electronic systems and controllers are used to charge PEVs when demand is low and at night [32,34,39]. AC is converted to DC by means of AC/DC electronic converters [42], whose size for low- and medium-speed loads means it can be carried on the EV itself [43,45], while it is large and external when the power is greater than 50 kW [50]. The EV charging strategies previously seen [60] need advanced electronic systems that affect the electrical system as little as possible while respecting the life of the batteries [44,60]. One of the biggest impacts on power grids is derived from the significant production of harmonics in the power systems of electronic converters [35].

Switching processes on electronic elements generates harmonic distortion, which can reduce the available energy for electrical systems, referencing studies in which the total harmonic distortion (THD) is measured, with this being the quotient between the sum of the powers of the harmonics with respect to the fundamental frequency. Early studies showed that THD from conventional EV charging (around 1%) does not seem to be significant in the power grid [40]. The same authors referenced other studies in which few units of EV fast-charging stations were responsible for injecting significant harmonics into power grids, reaching a THD of 11.4%.

Considering the EN 50160 standard [96], THD up to the 40th harmonic should be less than or equal to 8%. Furthermore, they indicated that other studies obtained a THD around 45% with few EVs charging at peak demand hours, while in other studies its value was minimal [40]. It seems that, depending on the type of simulation and how electronic converters are modeled, discrepancies are explained. In any event, the electronic market has filtering devices to deal with this problem. The authors of [63] report that fast-charging stations produce harmonic distortion and supra-harmonics. For the first case, they find that a specific charging station has a THD range between 9.3% and 30.7% in CV charging mode, while it has a THD of 11% in CC mode. In the second case, to reduce the size of passive components in fast-charging stations, work is performed with increasingly higher frequencies, generating supra-harmonics (2–150 kHz), producing heating and lifetime shortening. A correct electronic and filtering design reduces these problems.

To facilitate visual comparison, Figure 1 summarizes the THD values and ranges reported in the studies discussed above, organized according to their corresponding charging and grid-interface context.

To further address the harmonic distortion problem, international standards, such as IEEE 519 [97] and EN 61000-3-2 [98], to limit harmonic voltages and currents [58] have been developed. A systematic review of global charging demand research indicates that infrastructure efficiency metrics (e.g., EVs-per-charger ratio) could be optimized significantly beyond present deployment levels. The large variations observed across studies emphasize the critical need to standardize assumptions regarding charging behaviors when planning future infrastructure, ensuring alignment with realistic usage patterns rather than generalized estimates [71].

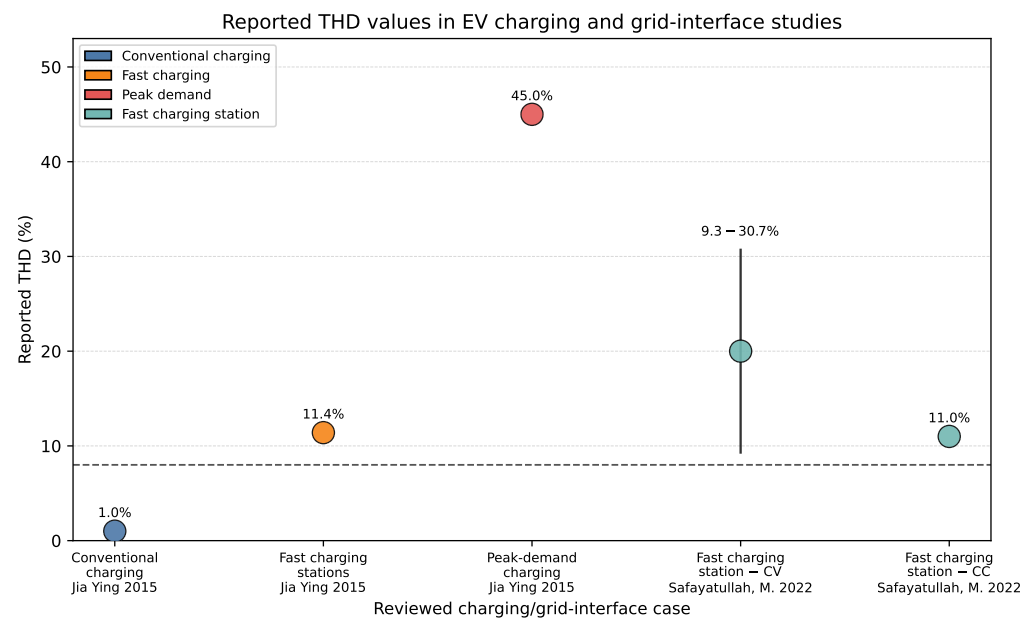


Figure 1. Reported THD values and ranges in EV charging and grid-interface studies discussed in Section 3.2.4, including data from Jia Ying (2015) [40] and Safayatullah, M. (2022) [63]. Bubbles represent single reported THD values or midpoint values of reported ranges, while vertical bars indicate minimum–maximum intervals where available. The dashed line indicates the EN 50160 reference level of 8% up to the 40th harmonic, as cited in the manuscript. The figure should be interpreted as a context-dependent synthesis of reported power-quality results.

Ultimately, the findings highlight that the push for faster charging and more compact converters is introducing new challenges, such as supra-harmonics that can lead to equipment overheating, underscoring the need for superior electronic design and standardized infrastructure planning to align charging demand with grid capacity.

3.2.5. Bidirectional Energy Exchange and Vehicle–Grid Interaction (G2V, V2G, V2H, VGI)

This section deals with the V2G concept from a technological perspective. As shown in previous sections, the concept of V2G (an abbreviation for vehicle-to-grid) services has been defined in the scientific literature. Other associated concepts exist, such as vehicle-to-home (V2H), vehicle-to-building (V2B), vehicle-to-load (V2L), and vehicle-to-vehicle (V2V). This study combines all these concepts under vehicle-to-grid/home/vehicle (V2GHV), in which BEVs/PHEVs are capable of transferring electricity from their batteries to the grid, buildings, vehicles or other loads, acting as energy storage systems (ESSs), not only to fulfill their functions as means of transport, but to transfer it, when needed, to other locations or devices [41,43,62].

A simpler way to condense the previous acronyms is vehicle-to-everything (V2X). All previous definitions are examples of vehicle–grid integration (VGI), which is a concept related to strategies, technologies, and policies to benefit both the electric grid and drivers' mobility needs, through the management of variables such as power level, charging time and charger location for EVs [39,40,47].

The common method of energy transfer from the grid to an EV is specifically called grid-to-vehicle (G2V). Today, in generalized charging stations, transmission of energy between the network and the vehicle, depending on the technology, can be carried out in V0G mode, in which there is no load control, sometimes referred to as “behavioral or manual control”; and in V1G mode, conventionally called “unidirectional smart charging”, in which not only power is transmitted but also information, such as SoC, voltage level, current and time to full charge. In vehicles, charge management is carried out by power

electronic converters, while when energy transfer is carried out in an intelligent building, this information is managed through an energy management system [36].

The last level, V2G (and G2V), involves a bidirectional flow of electricity produced between the two smart systems, charging the vehicle battery in G2V mode, and smart discharging and transferring energy to the network in V2G mode [38,59]. The authors of [50,53] proposed that EV batteries could be used to provide emergency power to homes or other vehicles in case of natural disasters, in direct connection or through an aggregator.

To implement a V2G system, the following elements are necessary: 1. Energy resources and an electric grid; 2. a system operator and an aggregator; 3. charging infrastructure; 4. bidirectional energy flow and smart communication between the aggregator and BEV/PHEV; 5. intelligent control and metering (on/off-board); and 6. battery charger and the BEV/PHEV [32]. The need for V2X arises from the direct association between the objectives of the challenge of RES penetration (WP and SP) by 2030, and the associated problems of faults and quality in the network [37].

Through the capacity of smart charging and electrical accumulation derived from V2X in EVs, curtailments can be significantly solved or limited, increasing the profitability of RESs; meaning that the greater the EV battery capacity, the greater the WP and PV penetration in the national system [33,34]. EV manufacturers and grid operators are expected to have greater interest in solutions that integrate V2G, EV and RES production in a seamless way [60].

Regarding the technology, V2X still does not have the necessary maturity, and further research is required on the control of charging stations, which integrate renewables, and on the operation of V2H. On the other hand, the rapid discharge of batteries can reduce their useful life in V2X, causing concern among EV owners [46,63], although users who voluntarily participate in V2G could be compensated for the degradation of the battery [54].

In relation to the wireless charging previously evaluated, WPT can provide a transmission of electricity between an EV and the grid in a simple way, using wireless communication devices that always detect the charging situation needed [45]. It is worth recalling that, at the level of the previous standards, CHAdeMO is designed to work with bidirectional power flow for V2X applications [44].

In economic terms, based on the previous context and that below, it is necessary to design new electricity market rules that implement V2G satisfactorily [35]. It should be noted that in 2012 and the previous years, the payback of a BEV with respect to a small ICEV was expected to be 20 years, foreseeing that their prices would equalize in 2030 [33]. The same authors calculated total economic impacts from the use of V2G, obtaining a result of \$300 to \$4600, with the majority of values from \$100 to \$300 per vehicle per year. A recent review documents the techno-economic considerations and research gaps, such as the costs of adapting charging systems to smart modes and accounting for impacts like battery lifespan under V2G within expansion planning [69].

Another recent review explicitly examines EV charging and V2G operation from the perspective of citizen expectations and perceptions. Ref. [68] report that these perceptions have been assessed through empirical studies involving survey-based and mixed-method approaches, with sample sizes ranging from several hundred to more than one thousand respondents, predominantly in European countries. The analysis shows that technological and functional concerns are recurrent across the reviewed literature, particularly regarding battery degradation, vehicle range limitations, system reliability and uncertainty over charging and discharging control. Economic aspects also play a decisive role, with several studies reporting higher willingness to participate in V2G schemes when clear financial incentives or electricity cost reductions are offered. In parallel, psychosocial factors, such as trust, subjective norms and perceived behavioral control, are identified as relevant

drivers of acceptance, while environmental motivations related to emission reduction and sustainability goals are frequently mentioned, although often in qualitative terms.

Despite the technical feasibility of bidirectional charging, the gap between V2G/V2X potential and real deployment is explained by specific implementation barriers. The first is economic: V2G profitability depends on whether revenues from price arbitrage or grid services exceed battery degradation costs, efficiency losses and the additional cost of bidirectional infrastructure. Recent life-cycle analyses show that regions with large peak–valley electricity price differentials can make V2G profitable, whereas regions with narrow price spreads may not provide sufficient incentives [99].

The second barrier is the lack of mature business and market arrangements. Although V2G can technically provide services such as demand response, frequency regulation, voltage support, reserve capacity and emergency power, the reviewed literature indicates that business schemes remain unclear, particularly regarding who pays for these services, how revenues are distributed among EV owners, aggregators, and grid operators, and how battery degradation is valued [100].

The third barrier is system coordination: V2G requires coordinated operation among vehicles, bidirectional chargers, communication protocols, aggregators, grid operators and electricity markets. Ref. [101] describes V2G integration as a system-level problem involving EVs, aggregators, grid operators, markets and end users, with unresolved issues related to infrastructure readiness, standardization, incentives and cybersecurity.

Recent systematic reviews also report that deployment remains largely confined to pilot projects because of revenue uncertainty, regulatory gaps, user resistance and grid unreadiness [102]. Therefore, V2G/V2X should be interpreted as technically feasible but commercially and institutionally immature, with scalability depending on clear remuneration, battery-warranty protection, interoperable communication, aggregator recognition and grid-operation procedures.

The findings highlight that bidirectional charging offers clear economic potential, but its large-scale adoption is currently hindered by technical concerns over battery degradation, system reliability, governance aspects, data privacy and transparency of energy management processes, which remain insufficiently addressed, despite being repeatedly identified as potential barriers to large-scale V2G adoption.

3.3. Environmental Management Aspects

3.3.1. Local Pollutants

EVs avoid dependence on fossil fuels, reducing local emissions of polluting gases such as NO_x and sulfur oxides (SO_x), even more so when they use only RESs [33,39] as the energy source. One study indicates that using an EV together with V2G reduces NO_x emissions by 31% [32]. The authors of [40] address this topic from three points of view:

1. Powertrains, which are the electromechanical configurations for the transmission of power from the engine to the wheels. It is concluded that their designs in EVs and HEVs improve energy efficiency compared to ICEVs.
2. Uncontrolled EV charging generates higher costs due to the increase in primary energy and associated losses, but if controlled, these costs can be reduced by 60%, and may be higher if RESs, specifically WP, are added.
3. Although the investment in an EV is greater than that for an ICEV, due to subsidies and electricity prices, this cost can be amortized, even yielding profits in the long term compared to the ICEV option.

Other authors, without considering the integration of RESs into the grid, report that a study was carried out in Europe showing that reducing local emissions is one of the key benefits when shifting from ICEVs to EVs. Additionally, it is concluded that EVs

are more efficient at dissipating heat compared to ICEVs, and thus the authors calculate that, in an urban setting, the energy needed for air conditioning would be reduced by 14.4 million kWh [48]. As mentioned, there is a psychological cost in changing an ICEV for an EV, due to the range and time required to charge the vehicle. Various basic models have a range of 200 km (the new models are gradually increasing this, as well as reducing the price) and charging times vary from tens of minutes to more than 20 h on very slow chargers. In general, these values would be sufficient for many users since 90% of cases involve less than 80 km/trip (in the USA, this value is somewhat higher), and vehicles are parked most of the time, and so may be charging batteries. Although this is true, the user experiences a certain anxiety, which is an initial barrier to changing their ICEV for an EV [62]. Currently, GHG calculations are made assuming driving ranges of 550 km, which are realistic for EVs and fully demonstrated [21].

Finally, the authors of [52] indicate that an ICEV is less energy efficient than a PEV, since the latter, apart from having better electric motor and battery efficiencies, has a regenerative brake that, together with the previous elements, can increase the efficiency of a BEV by 60% to 70%. In the case of Europe, the next step towards net-zero emissions is the implementation of the Euro 7 regulation, which is entering into force in 2027 or 2029, depending on the type of vehicle, and is intended to reduce emissions of NO_x, HC, particles and carbon monoxide (CO) to minimum levels. However, these vehicles reduce not only these emissions but also those of particles derived from tires and brakes. The emission values achieved under this regulation should be maintained for a set distance or time (200,000 km or 10 years in cars) [103]. Overall, the findings highlight that EVs not only reduce GHGs but also improve urban thermal management and align with upcoming Euro 7 standards, which aim to minimize both tailpipe emissions and non-exhaust particles from tires and brakes.

3.3.2. Emission Reduction Management

Using EVs for transportation reduces local CO₂ emissions [34]. Several studies show that PEVs reduce CO₂ emissions compared to other equivalent transportation alternatives, reducing them by 7% to 21% compared to HEVs. If V2G technology is used, the reductions are even more significant [32,39]. One of the most important benefits when comparing EVs and ICEVs is that with the first option, local emissions are avoided, which is essential for improving air quality in large cities [48]. On the other hand, VGI could be considered effective in reducing GHG emissions, although it is estimated that the greatest benefit, in terms of emissions, comes simply from the use of an EV rather than from its grid integration. Some studies reveal that CO₂ emissions can be reduced by an average of 42% when using a PHEV instead of a gasoline ICEV. Additionally, it has been suggested that, by 2030, the reduction in CO₂ emissions from using PEVs instead of ICEVs could reach 62–65% in the United Kingdom.

Finally, it is stated that, despite the different operating conditions, PEVs can appreciably reduce GHG emissions [46]. Thanks to life-cycle analysis (LCA), it is possible to quantify the environmental impact during the entire life cycle of a product. An LCA-specific parameter for EVs is “wells-to-wheel” (WTW) emissions, which compares the CO₂ emissions of EVs from the power source (well) to the point of use (wheels), which allows comparisons to be made between different types of vehicles, including all emitted and embedded emissions [40]. Typical measurement parameters are grams of CO₂ equivalent/km (gCO₂eq/km) and liters of gasoline equivalent/100 km (l_{gas}eq/100 km).

The authors of [38] carried out interesting research incorporating RESs and performing various simulations, obtaining notable reductions in emissions. The authors of [52] conducted similar studies on the WTW of EVs with RESs. Multiple integrated LCA studies in

the literature report a substantial environmental advantage for EVs over ICEVs. Systematic evidence shows that BEVs can achieve up to 97% lower CO₂-equivalent emissions compared with petrol vehicles and about 70% lower emissions compared with diesel vehicles across the entire life cycle, provided electricity generation is supplied from relatively clean sources. The most significant contribution to EVs' environmental impact arises from battery production, a process that demands high energy input, but this initial carbon "investment" is typically recouped during the operational phase due to the higher energy efficiency of electric drivetrains [66].

Ref. [67] concludes that quantitative analyses show that integrating EVs and ESSs into microgrid energy management can reduce CO₂ emissions by approximately 57% over a decade compared to scenarios without such integration. This integration, which increases renewable energy use and decreases reliance on fossil fuels, also leads to a cumulative operational cost reduction of about 21%, with a further 20% saving possible by using second-life EV batteries in stationary storage.

In summary, the literature underscores that WTW emissions are significantly lower for EVs, with projections suggesting a 62% to 65% reduction in carbon footprint by 2030 as power grids decarbonize and VGI becomes more prevalent.

3.4. Integration of EVs into Renewable-Based SGs: Operational Frameworks, Energetic Communities and Cybersecurity Aspects

The integration of EVs with RESs cannot be addressed in isolation, as it strongly depends on SG architectures, control strategies and demand-side management approaches that enable coordinated and flexible system operation. The classic problem of the global electricity system is the great difficulty in energy accumulation. While work has been done with plants that function with rotating machines that regulate themselves, the inertia of such machines has favored productive stability [32], but with the increasing incorporation of RESs into the electrical system to avoid CO₂ emissions and produce clean energy, the uncertainty in the unpredictable nature of renewable production needs to be seriously addressed, without failures, due to supply necessities [38–40]. EVs with RESs ease two problems. On the one hand, they are able to absorb excess renewable production and store it in EV batteries. On the other hand, when V2G technology is developed and implemented, and there is no renewable production due to weather conditions, EVs are able to supply their stored energy to the grid [41,43,52].

Ref. [64] provides a detailed synthesis of charging infrastructure elements in the context of RES integration, analyzing existing renewable sources such as WP and SP, which combined are expected to meet more than 35% of global electricity demand by 2050, and highlights that EV charging demand drives an increase in overall power demand of approximately 4% by 2030 due to EV stock growth. On the other hand, quantitative data on EV charging's energy consumption is indicated: passenger BEVs and PHEVs are cited as consuming between 500 kWh and 4350 kWh annually, while heavy-duty electric buses and trucks require approximately 0.56–3.34 kWh per mile.

Based on U.S. National Renewable Energy Laboratory (NREL) projections, the total energy demand for EV charging in the U.S. is expected to increase to around 300 TWh by 2030, highlighting the massive scale of demand growth relevant to grid and renewable planning. Ref. [64] identifies several critical technical barriers to scaling the integration of RESs with EV charging infrastructure, emphasizing that extensive grid renovation is required, especially for highway charging zones situated beyond urban networks. Therefore, the large-scale integration of EVs and RESs has been identified as a key enabler for future low-carbon energy systems. In particular, recent reviews highlight the role of SP and EVs as flexible assets capable of enhancing self-consumption, reducing grid stress and supporting system stability when properly managed [104].

EVs offer significant potential as mobile storage to enhance microgrid stability through advanced control strategies, but current research identifies critical barriers. Specifically, the lack of component interoperability and the absence of holistic optimization frameworks, integrating pricing, stability and renewables, remain major gaps for effective system coordination [67]. A recent review notes that if planning does not incorporate smart charging and renewables together, additional EV load can overload existing infrastructure [69].

3.4.1. Interaction Between EVs and RESs: Wind

The penetration of RESs contributes to gradually eliminating the production of energy through fossil fuels and the associated production of pollutants, but the instability and unpredictability of RESs in time and place makes their use difficult. In previous years, several authors have opted for the use of ESSs locally in buildings as an element of storage and management of demand and consumption. Currently, the progressive and unstoppable uptake of EVs is causing these to become the elements that store renewable energy without other specific storage equipment for buildings [55].

WP is an energy source that has been implemented for decades and with ambitious penetration targets, but whose production is unpredictable and discontinuous, as it depends on weather conditions. Its implementation requires large areas of land where wind turbines (WTs) can be installed, with these typically being integrated away from cities due to the space required and because buildings generate wind energy losses and instability. Since its output is more unstable than other sources, like SP, it is typically less attractive for EV charging [44]. Several authors have concluded that, when V2G becomes a reality, a positive result is expected to be obtained from the association of PEVs with WP [32,43]. Multiple studies with simulations of the penetration of WP in the electrical system have been carried out [33]. The results are reviewed in Section 3.5.

Some authors have studied how WP surpluses are capable of supplying half of the energy demand of EVs, concluding that the relationship between WP generation and EVs can enhance the penetration of the latter in the market in the short term, and EVs can help WP in regulating its intermittent production in the long term. Another study referenced by the same authors obtains similar conclusions when integrating EVs, V2G and WP, concluding that EV charging significantly improves RES fluctuations in the distribution network [39,40]. The authors of [59] provide different combinations for centralized/decentralized distribution planning and large-scale integration of EVs and WP.

The following authors suggest that the technical literature has focused more on the integration of EVs with WP than with SP. It is concluded that EVs mitigate the intermittent effect of RESs, being able to store more than 50% of the excess annual renewable energy produced. The future use of V2G, when technical problems are solved (investment in technology, smart metering and communication, high degradation of battery due to cycling, etc.), is intended to provide the full potential of the synergy between EV and RESs [34,41]. Once RESs have been integrated into the local EV charging network, the adjustment between production, storage and consumption is greatly benefited by the use of SGs, which, thanks to their two-way communication, allow for the execution of corrective actions in a fast and efficient way [38].

Overall, the findings highlight that while EVs can store over 50% of excess annual renewable production, a significant gap persists in holistic optimization frameworks; current research underscores that without interoperable control strategies and coordinated planning, the growing power demand from EVs could overload existing distribution networks.

3.4.2. Interaction Between EVs and RESs: Solar

In contrast to the authors in the previous section, there are others who consider SP the most viable solution among RESs for joint use with EVs due to the fact that, although solar irradiation at a specific place and time is a meteorological variable and therefore non-deterministic, there is greater meteorological control and predictability of its production. This makes it possible to better anticipate its generation and make joint plans with the accumulation possibilities offered by EVs. Furthermore, photovoltaic (PV) modules have an increasingly lower cost and are easy to install, both on land and on roofs. In addition, production coincides with the peak of electricity demand, when the energy costs are higher for the user, and maintenance is low [41,44].

Several authors are more specific in determining the solar production peak, making it possible to store the energy that occurs a few hours before the consumption peak in EVs, to be used a few hours later, when it is most needed [32,56]. The incorporation of SP over parking lots and the charging of the EVs that are situated below was studied for the latitude of New Jersey using 14%-efficiency PV panels. Values of 0.84 kWh/m² in summer and 0.252 kWh/m² in winter were obtained. Another study was conducted for an area of Japan, examining the use of heat pumps to produce hot water when there was an excess of SP production. It was concluded that the incorporation of 5 million EVs, together with the same number of heat pumps, could assimilate the excesses of 10 TWh of annual production [33].

In this sense, the authors of [61] agree with the previous authors and conclude that SP is a good option to flatten the demand peak, but its production begins to decrease when the demand of users begins to increase. They thus propose the installation of ESSs that store SP energy when it is at its maximum and release it when most needed. Good management of EVs is essential to perform this function. SP research in residential environments, community car parks and on islands has shown good results, allowing EVs to be partly charged with RESs, and reducing daytime demand peaks, in the same way as with WP, allowing surpluses to be accumulated. Consequently, although SP and EVs are technologies that are independent of each other, a greater penetration of SP in the production system is possible as the penetration of EVs increases [39,40]. The authors of [48], in addition to reinforcing this concept, present in detail the elements required to take into account irradiance modeling and SP behavior in cities.

The authors of [49] study the technical and economic subfactors related to the optimization of the SP/EV combination, as well as all kinds of spatial configurations, describing specific ones, from single-family houses to entire territories. At the level of installation typologies and associated technologies, the authors of [42] extensively present and describe the implementation of PV in different locations. The authors of [52,53] proposed various configurations to seek to achieve the goal of a net- or near-zero-energy building using SP and EV to store and manage energy. Various simulation strategies were used to obtain energy optimization results and economic analyses. This is discussed in more detail in Section 3.5.

The studies reviewed by [67] show that a residential microgrid with 6 kWp PV capacity and approximately 20 kWh battery storage can supply around 23% of daily BEV charging demand and 68% of daily PHEV charging demand entirely from local renewable generation, underscoring the importance of scaling PV output and storage capacity to support EV charging in decentralized energy systems. In temporal terms, the benefits of linking local SP production to storage in PHEVs/EVs can be divided into short-term and long-term benefits. In the first case, the electronics associated with SP may cause harmonics that can be absorbed by the EVs, thus not being injected into the grid, where they would cause

quality and stability electrical problems. In the case of the long term, EVs can store the discontinuous production of SP and release it continuously when needed [34,38].

Several authors have proposed the use of roofed parking facilities in which PV panels are installed, such that an infrastructure that is already built would be used to provide shade and PV production in countries with high solar irradiation, thus respecting the aesthetics of the city but installing technology. A study carried out in a medium-sized Swiss city using the above concept concluded that between 14% and 50% of the energy needed for public electric transport could be provided with SP [44]. Other authors promote EV charging stations being powered by SP to avoid CO₂ emissions problems. A great part of the research in this regard is focused on residential systems, and much study is needed to find adequate solutions and strategies [54,55].

DSOs indicate that the “time” variable is the most relevant in avoiding uncontrolled demand on the distribution side, such that SP and EVs working together must be planned, both in terms of the number of EVs, SP size and the scheduling load. The same authors indicate that, although much research has been performed on the sustainability of the EV and SP combination, there is a lack of detailed studies on guidelines to solve the specific problems of this combination. Certain combinations for centralized/decentralized distribution planning and large-scale integration of EVs have been provided [59]. Maintenance of PV installations is minimal, which makes this type of configuration more attractive for working jointly with EVs [43,57].

In summary, SP offers high predictability for integration with EVs, allowing stored energy to flatten demand peaks; however, the literature highlights a need for detailed operational guidelines and planning to manage charging loads effectively across diverse configurations.

3.4.3. Energetic Communities

Apart from the review articles studied thus far, a small review by several authors actively working on the concept of “energetic communities” is included, which is of great interest for distribution networks in the near future. An energetic community is a type of collaborative economy within the energy sector in which an economic profit is obtained due to the sharing of electrical storage capacity between different entities, which are normally a group of neighbors or sets of people sharing with a company [105]. It must serve a social group whose members live geographically close to each other (e.g., same locality) [106]. The objective is mainly economic, storing energy when costs are cheaper, with advantageous prices making investment in electricity storage capacity profitable, optimizing community energy storage [107]. A key aspect to consider when designing an energetic community is its optimal size to reduce costs and maximize benefits, and how energy resources should be allocated to each participant [108].

Fostering energy communities is necessary to boost SGs, which are key elements for making the former feasible. A positive impact of this concept is the generation of new production models based on an advantageous energy economy for the members of such a community [109]. The negative impacts are similar to those related to multiple energy producers and storage facilities in a network that would have to be managed through a high volume of real-time communications, with intelligent strategies to match supply and demand, which, if not managed, produce phase imbalances and other stability issues. Another negative impact is congestion, which could occur in the transmission grid due to the existence of many generators in the distribution grid. Possible solutions would be dynamic price increases that indicate network saturation, or local strengthening of the infrastructure only at those points that need it [110]. The implementation of this concept necessarily involves considering potential regulatory barriers in the management

of agreements and techniques, how to predict advantageous prices, monitoring and how to invoice energy flows [111].

EVs, in the context of energetic communities, should not be interpreted only as additional electrical loads. Their distinctive contribution lies in their capacity to operate as controllable demand resources and, when bidirectional charging is available, as mobile storage assets that can support local balancing, renewable self-consumption and flexibility services. Recent case-study-based research illustrates this role through three complementary mechanisms. First, the operation of an industrial microgrid within an Italian renewable energy community shows how photovoltaic generation, battery storage, EV charging infrastructure and V2G-capable delivery vehicles can be jointly coordinated through an energy management system. In this case, EV fleets contribute to renewable self-consumption, self-sufficiency and energy sharing among heterogeneous community members [112].

Second, an experimental local energy community composed of residential photovoltaic prosumers and an EV owner demonstrates how smart metering and a central aggregator can shift EV charging toward periods of photovoltaic surplus. This transforms EV demand into a controllable flexibility resource that increases collective self-consumption and improves the economic performance of the community [113].

Third, local electricity market models based on prosumer-to-vehicle transactions show that EV users can obtain locally generated renewable electricity from neighboring prosumers, linking EV charging with peer-to-peer exchange, aggregation and community governance [114].

These studies suggest that the value of EVs in energy communities emerges through three main pathways: technical flexibility, renewable self-consumption and local market coordination. Technical flexibility is achieved when EV charging and discharging are coordinated with community-level energy needs. Renewable self-consumption increases when EV charging absorbs local photovoltaic or renewable surplus that would otherwise be exported or curtailed. Local market coordination becomes possible when EVs participate in community transactions as flexible demand units or distributed storage resources. In this sense, EVs can operate as an interface between mobility patterns and local energy management.

However, these benefits are not automatic. They depend on sufficient charger availability, adequate dwell time, user participation, controllable charging points, ICT infrastructure, aggregators, suitable tariff or incentive schemes, regulatory permission for local energy exchange and explicit consideration of battery degradation under V2G operation. From a system-level perspective, energy communities are therefore not a peripheral topic, but a local operational framework through which EV technologies, renewable generation, smart-grid control, storage, user behavior and governance mechanisms can be jointly implemented.

Overall, the literature underscores that despite the clear economic and social potential of energy communities, regulatory barriers regarding price prediction, monitoring and legal agreements must be addressed to unlock their full benefits for future low-carbon distribution networks.

3.4.4. Smart-Grid Architectures and Control Strategies

At the operational level, an SG is a local electrical network that can detect disturbances, analyze them and act to resolve them quickly by incorporating smart devices, monitoring capabilities, communications and a control system for processing, managing and actuating [35]. EVs can be incorporated, and their batteries controlled, through the communications network, acting as storage elements or electricity sources to the network [36,39].

More specifically, an SG is an electrical grid that uses automation and computer-based remote control to increase the efficiency, reliability and sustainability of the energy supply. The incorporation of ICT into the electrical grid provides communication between the utility and the elements that make up the network, establishing bidirectional communication not only of information but also of power, thus enabling interaction with users, who can configure the use they make of their electricity. At a global level, the ICT part of the SG is made up of the following: 1. Sensors and smart meters that retrieve data from every important/critical location of the grid in real time; and 2. monitoring control with intelligent and even autonomous capabilities to monitor all the aspects of the grid, integrating demand response (DR) capabilities. The configuration of an SG is so dispersed that it is highly resilient in the event of a failure/attack or disaster in one of its parts, with the rest of the parts capable of being autonomous and taking corrective actions if necessary [45,59].

At the construction level, an SG is planned to have the following elements: 1. Advanced metering infrastructure (AMI), made up of electronic devices that retrieve real-time data from customer use. Users can use the information from these devices to access updated information on their consumption; 2. supervisory control and data acquisition (SCADA), consisting of a system with a set of functionalities, such as database servers, programmable logic controllers, sensor interface devices, switches and relays to send data and control orders; 3. a home area network (HAN), which is a local network infrastructure at home that allows different electrical devices to be interconnected under the same communication protocols, managing their activity, with the possibility of receiving market information; 4. DR, previously explained, where customers can participate under certain possibilities of consumption/billing, selecting the one that most benefits them; 5. distributed generation, in which a large number of small consumers/producers (prosumers) and storage facilities are distributed across the territory; and 6. V2G, previously discussed, which allows bidirectional power and communication fluxes between EVs, consumers and producers (renewables), working as an ancillary service for the stability of the grid [32,37,44].

For correct implementation of an SG, it is necessary to work with a broadband communication network, allowing for real-time information on the status of assets, load flows and price information [38,61]. Other authors consider it essential to have an advanced communication infrastructure if the focus of the SG is centralized [56,57]. Various authors mention the EV fleet operator, which provides management services to a fleet of EVs, and which could be equivalent to the previously discussed figure of the aggregator [41]. Currently, practically almost all charging systems are unidirectional and do not have advanced communication systems to ensure proper use of V2G [43,44].

Ref. [67] points out that when EVs and ESSs operate as both load and DERs, they contribute to grid stability by participating in peak shaving, load shifting and frequency regulation. The literature reports improved efficiency and resilience in microgrid operations under high-renewable-penetration conditions when coordinated EV/ESS control strategies are applied. New systems that integrate artificial intelligence (AI)-based control algorithms can be trained to optimize decision making in the management of EV batteries, and how to stabilize the network as much as possible and optimize costs for all stakeholders [63]. Advanced control strategies incorporating AI, such as adaptive neuro-fuzzy inference and reinforcement learning, significantly enhance system performance. For instance, reinforcement learning applications in microgrid control reduce power losses by around 61% and peak load demand by 17% compared with baseline control strategies under fluctuating renewable generation scenarios [67].

Ref. [64] also details the communication and control architectures needed for intelligent coordination between EVs, charging stations and DSOs. It highlights that smart charging ecosystems increasingly rely on the Open Charge Point Protocol (OCPP) to enable

bidirectional communication between EV supply equipment, central management systems and DSOs. The study reports that the OCPP is extensively used in over 148 countries and supported by more than 65,000 active EV charging stations, illustrating the practical scale of standardized communication deployment. Ref. [64] further highlights that real-time load forecasting remains constrained by the insufficient deployment of smart meters and sensing equipment, while the lack of standardized energy-conversion frameworks continues to hinder interoperability across heterogeneous power sources and charging systems. Additionally, the study notes that market mechanisms for flexibility services remain underdeveloped, and successful implementation is further challenged by the shortage of skilled personnel for specialized maintenance.

A recent review on charging demand identifies a critical need for universal metrics to support infrastructure deployment, noting that existing frameworks often fail to account for how diverse charging behaviors impact the distribution grid. Establishing standardized protocols is increasingly urgent as the sector moves toward integrated, smart-grid solutions to manage peak demand and prevent localized transformer overloads [69].

The findings highlight that despite the widespread use of communication protocols like the OCPP, significant operational gaps remain due to insufficient smart meter deployment and underdeveloped flexibility market mechanisms, hindering interoperability across diverse power sources and charging systems.

3.4.5. Cybersecurity of Smart Chargers and Grids

In the first review study, in 2012 [32], reference was already made to the importance of considering the implementation of secure communication between aggregators and PEVs. In the case of [63], the importance of cybersecurity is underlined, both in the vehicle and in the charging infrastructure, since data such as the vehicle owner, location or payment data can be captured. It is possible to access the vehicle by performing remote cyber-attacks.

The authors of [115] studied this topic, indicating that the network stabilization services provided by EVs require a significant transmission of information, which can be attacked by various methods, such as man-in-the-middle, data intrigued, denial of charging, etc. Potentially, there are many weak points in each of the actors that make up the system. Authors have described the concept of smart charging management systems, potential vulnerabilities and cybersecurity measurements that can be taken to prevent attacks that could cause significant damage. In this sense, authors such as those of [110,115] propose a more decentralized energy management, which reduces dependence on a centralized system, since information processing is carried out at various points in the network rather than just at one, so the system's resilience against cyber-attacks is increased.

Some authors are investigating machine learning systems designed to identify cyber threats in EVs by analyzing controller area network traffic data, which can suggest possible abnormal patterns that may be indicative of cyber threats [116]. Ref. [64] points out that inherent delays and security vulnerabilities (e.g., reliance on web protocols like HTTP/FTP) remain a concern, which motivates the development of secure techniques such as multimodal authentication and message authentication codes. Cyber-physical system perspectives suggest that advanced digital and control frameworks are necessary for integrating V2G securely within smart grids, highlighting that cybersecurity challenges are integral to smart-grid deployment [70].

A systematic analysis of 134 studies on the cybersecurity of EVs concludes that integrating EVs into grid ecosystems via V2G technology introduces complex, system-wide risk vectors. This necessitates robust, holistic cybersecurity approaches. However, the analysis reveals a predominant focus on safeguarding EVs and charging stations, overlooking significant vulnerabilities in physical access, control systems, user behavior and

emerging threats from AI and blockchain integration. Notably, there are major gaps in the management of recovery aspects within the cyber-risk life cycle, which highlights the urgent need for a broader scope of research to ensure the resilience of V2G operations [70].

Cybersecurity in EV charging systems also affects data-driven operational functions such as short-term charging demand forecasting. Ref. [117] recently proposed GenS2-P, a generative multi-task self-supervised learning framework for cyber-attack-resilient EV charging demand prediction. Their work highlights that EV charging demand forecasting is essential for real-time traffic management, route optimization and charging station utilization planning, but that forecasting models relying on IoT devices and communication networks may be degraded by cyber-attacks. In particular, the authors model two adversarial scenarios: data poisoning attacks, simulated by adding Gaussian noise to node features; and denial-of-service attacks, simulated by randomly masking nodes to represent interrupted data transmission between charging stations and a central server.

GenS2-P addresses these conditions by combining a denoising/reconstruction AutoEncoder with graph neural network encoders and decoders, followed by a spatio-temporal prediction architecture based on graph attention and multi-head attention mechanisms. Using real-world EV charging data from 247 traffic zones and 18,061 public charging piles, the study shows that GenS2-P obtains a lower mean average error and root mean squared error than several benchmark forecasting models under different data corruption levels and prediction horizons. This contribution is relevant for EV integration because it extends cybersecurity from the protection of chargers and communication channels to the resilience of AI-based forecasting and operational decision-support systems used for charging infrastructure management.

Cybersecurity directly conditions the feasibility of smart charging and V2G/V2X operation. The relevant attack surface is distributed across several architectural layers. At the EV–EVSE interface, ISO 15118-compliant [118] vehicle-grid communication supports charging negotiation, vehicle identification, Plug & Charge authentication and bidirectional power-exchange capabilities [119]. At the EVSE–backend or EVSE–aggregator interface, OCPP-type management protocols are used to authorize sessions, monitor charger status, apply tariffs, update firmware, manage faults and send smart charging commands [119]. Smart meters and backend platforms then provide the measurements and transaction records required for billing, settlement, aggregation of flexibility and grid-support verification. Consequently, compromised authentication, manipulated meter data, unavailable communication links or malicious control commands may propagate beyond an individual charger; they can distort payments, reduce user trust, interfere with aggregator dispatch, misrepresent available flexibility and affect local grid operation [117].

The recent literature therefore frames EV charging cybersecurity as a system-level requirement involving charging stations, communication protocols, backend systems, V2G interfaces and grid-integration technologies [120]. Secure authentication, protected data exchange, intrusion and anomaly detection [120], and resilient forecasting/control models [117] are consequently needed to ensure that smart charging and V2G services remain trustworthy and operationally reliable.

Overall, the literature underscores that although cybersecurity is integral to smart-grid deployment, significant gaps remain in managing the recovery phase of the cyber-risk life cycle, necessitating broader research into AI and blockchain integration to ensure the long-term resilience of V2G interactions.

The smart-grid perspective therefore acts as a system-level framework that connects several dimensions discussed in previous sections: charging infrastructure, V2G interaction, renewable integration, energy communities, aggregators, ICT-based control and cybersecurity. However, the operational feasibility of these interactions cannot be assessed from a

purely descriptive perspective. It requires modeling approaches capable of testing how EV penetration, renewable variability, charging behavior, control strategies and grid constraints interact under different temporal and spatial conditions. This connection provides the natural transition to the simulation-based studies reviewed in the following section.

3.5. Simulation Tools and System-Level Studies

Simulation tools and system-level models can be understood as the analytical counterparts of the smart-grid concepts discussed above. While smart grids define the operational architecture required to coordinate EVs, distributed renewable generation, storage resources, aggregators and communication infrastructures, simulation models allow these interactions to be quantified, stress-tested and compared before implementation. In this sense, simulation studies are not an isolated research stream, but a methodological bridge between technological possibilities and practical grid-planning decisions.

The reviewed literature shows that simulation models are used to examine different but interconnected layers of the EV–energy system. Long-term models evaluate infrastructure needs, renewable penetration, fleet growth and investment requirements; short-term models capture load peaks, voltage deviations, congestion, harmonic effects and operational constraints; optimization algorithms explore coordinated charging, V2G scheduling, cost reduction and renewable energy matching; and EV penetration models estimate the hosting capacity of distribution networks under alternative mobility and charging assumptions. Together, these approaches provide the quantitative support needed to assess whether smart-grid strategies can operate reliably and economically at scale.

3.5.1. Long Term

Some authors have carried out simulations on transmission networks in the US, incorporating up to 50% PHEVs, concluding that this could increase WP penetration by up to 6%. Other simulations estimate that, when V2G becomes a reality, from 30% to 75% more WP can be integrated into the grid. These estimations were obtained by simulations run for the year 2000 to 2100 [33].

Other authors have considered that to analyze the impact of EVs on the distribution and transmission networks it is necessary to use mathematical models that include the size of the territory and the operating conditions. The behavior of many EVs incorporated into a network has been studied. The authors indicated that it is important to correctly simulate the charging dynamics of the vehicle, and therefore its SoC, so the dependence on voltage is considered to capture the operating dynamics of EVs as their penetration increases in the system. It must be possible to simulate and configure the behavior of users and charging schedules in order to obtain realistic scenarios. Meanwhile, V2G simulations are a topic of enormous interest in simulations [35].

Some authors have simulated scenarios in which conventional generation and RESs enter only when necessary, using data on the travel schedule of users' EVs and arrival at their homes. Coordinated vs. uncoordinated loads are compared over 52 weeks of simulation with a mixed-integer problem setup. Other authors have simulated the reduction in CO₂ emissions with different numbers of RESs and EVs, simulating EV penetration from 0% to 100% and progressive incorporation of RESs. The EnergyPLAN (v12) tool was used for the simulations [38].

The authors of [53] researched different types of microgrids between EVs and buildings that can achieve the goal of net- or near-zero energy consumption. They used simulations with a code developed using MATLAB (vR2018a) to obtain energy and economic results. EVs provide and store energy, transmitting it between different buildings and managing SP energy flows. Three scenarios are simulated: a single-family house associated with a

small office building in which the EV connects both buildings, verifying that the building-to-vehicle-to-building (V2B2) concept obtains good results in terms of energy efficiency through energy flows between buildings, concluding in this case that the key to this success is the use of the EV as an energy vector between different types of buildings. They report that their long-term simulations obtain energy savings of between 45% and 77%. It is essential to consider the different rates of electricity prices. In the future, these researchers intend to work to increase the size of their microgrid and perform sensitivity analyses.

The authors of [61] studied the result of many simulations to assess how EV penetration growth impacts distribution networks. It was concluded that factors such as load imbalances in parallel lines, EV load distribution, sources and location are important. They also showed how grid stability is affected by varying levels of EV penetration, relative to different demand curves for California. A review of other similar studies from around the world was performed.

In summary, long-term simulations indicate that high EV penetration could enable a significant increase in WP integration, up to 75%, provided that mathematical models accurately capture voltage-dependent charging dynamics and diverse user behavior patterns to ensure realistic grid-stability assessments.

3.5.2. Short Term

Studies have been carried out to evaluate whether electrical systems in which BEV-type loads are incorporated, with the possibility of using V2G, are capable of withstanding wind shortage. It was concluded that there is no capacity for more than two hours [32]. Based on the previous study, the authors of [35] highlighted that, in order to obtain realistic long-term conclusions, it is necessary to integrate dynamic models that include storage effects with small time steps.

The same result is obtained from the analysis carried out by the authors of [53], whose model to obtain long-term conclusions was carried out in detail, taking into account dynamic behaviors and small time steps to capture variations in the short term. The authors of [61], similarly to the previous cases, performed dynamic models with small time steps to capture essential information such as variability of renewable energy, capabilities of EVs to provide ancillary services, microgrid structure of the distribution system and random EV loads.

Ultimately, the short-term findings reveal critical stability limits, such as the grid's inability to withstand wind shortages for more than two hours even with V2G support, highlighting the urgent need for dynamic models that account for storage effects and random charging loads.

3.5.3. Optimization Algorithms

The authors of [34] propose that when the energy market is well established, with all the actors, such as aggregators and PHEV customers, the rescheduling of the charging period strategies can be optimized through mathematical formulation to smooth out the effects of power demand. Several authors have carried out simulations assimilating EVs as if they were batteries that can absorb the energy of the wind peaks, collected statistically. They have also worked on optimizing the behavior of the network through economic dispatches, assuming that in the future part of the population will allow their vehicles to be used in V2G mode. Other optimization studies concluded that charging providers can increase their operational profit by 7.9% by adding RESs to a network. Some authors have focused their effort on simulating how aggregators in charge of EV charging can maximize their profit, while other authors have sought to maximize profit for the producer of a virtual WP farm with EV charging. Other simulation studies have worked to minimize

the cost of recharging EVs for the user, considering only WP. Other types of optimization are based on minimizing electrical costs with variations in RESs and response demand. The minimization of the recharge cost as the penetration of RESs and EVs increases has been studied by other authors. Work has been performed with optimization in microgrids to maximize the use of RESs and EVs, minimizing electricity cost. Other authors have used RESs and EVs, optimizing the operation of WP and the SoC of the EVs. Other authors, based on historical data on vehicle-user travel behavior and EV control possibilities, have maximized the use of RESs [37,38,42].

Strategies such as Lyapunov optimization were implemented to find stable and optimal performance points when using EVs with PV and WP plus V2G strategies [40]. The authors of [41] carried out an exhaustive review of mathematical simulation procedures to optimize the control strategies of a fleet operator. These can be centralized, transactive or price control of EVs. The authors of [49] carried out an in-depth study of optimization of the use of SP and EVs and the associated technical–economic variables. They studied the majority of possible use cases, from small scale (houses) to larger territories, in which, selecting a PV capacity, the objective was to minimize electrical cost for a selected number of EVs [48].

Regarding charging station location, the authors of [51] describe two possible ways to address this issue. The first is to use optimization approaches considering the road and driving network to find the best places. The second is to calculate the spatial distribution of demand and position the charging stations there. The fundamental problem of charging infrastructure planning is the optimization of its size and location [55,57]. The authors of [62] proposed different conclusions in terms of methods for optimizing the location of EV charging stations, incorporating a figure that summarized all the information. In [53], the authors optimize the use of a single SP installation, rather than two, which serves a house and a small office building. An EV is used as an energy vector for energy storage and distribution. An optimized demand management solution allows both customers to be served.

The authors of [56] collected research on the advantages and disadvantages of centralized and distributed smart charging systems, concluding that the optimal solution for the use of power grid capacity with RESs is a combination of both strategies. Other authors investigated a complete set of strategies to optimize the grid performance with EVs so as not to increase peak demand, taking into account V2G and EV randomness [44,47,61]. Finally, ref. [65] summarizes outcomes from studies using machine learning and mathematical models for EV optimization. These models often incorporate traffic flow, charging station distribution, and in-vehicle energy management data to derive optimized routes and charging schedules. Examples include the following: Route-planning algorithms that reduce total congestion and energy consumption in simulation environments, and data-driven strategies that stabilize power distribution systems under stochastic load.

These findings highlight a transition from simple Lyapunov-based stability models to advanced machine learning applications that integrate traffic flow, energy management and stochastic load data to optimize both route planning and real-time grid stabilization.

3.5.4. PHEV/EV Penetration and Electric System Capacity

It has been found that for a Level 1 load, EV penetrations of 10% increase peak demand by 17.9%. On the other hand, penetrations of 20% increase the demand peak up to 35.8%. A Danish study indicates that the penetration of 1 million EVs would mean the additional installation of 10 GW of WP [32]. EV penetration is limited by power imbalance if charging is not scheduled, which must consider generation structure, emission level and power supply/demand and dispatch. The above points, in addition to the DR and economic dispatch decision-making strategies, allow for a better management of the EV's

storage, stabilizing the network and favoring greater vehicle penetration. To maximize EV penetration, two main strategies are used: rescheduling of the charging period, shifting the charge to other times of lower demand; and rescheduling the charging power, modifying the power delivered to vehicles [34].

To plan high EV penetration, it is necessary to perform simulations with dynamic models, which include human driving behaviors, hourly demand and SoC [35,39]. The authors of [36,41] coincide in concluding that it is necessary to carry out smart load management, especially in times of high demand and when PEV penetration is high. The authors of [37] indicate that the monthly electric bill can increase by 22%, even with 10% PEV penetration, if the charging is uncontrolled. The closer-to-customer services that aggregators can provide are only sustainable as a business model if EV penetration is high, and for this purpose the simulation of their controlled load must be a prerequisite for this structure to be real [44,48]. High penetration of EVs requires simulating the problems related to the load imbalance between the three phases of a distribution network; otherwise, voltage imbalances between phases may occur [53]. Although the charging system can be centralized or decentralized, in areas where high EV penetration is desired, it is suggested that it is better to use the first option because the availability of network and vehicle status information is faster [49,55].

The authors of [60] indicate that the incorporation of PV and EVs in the network has to be designed, controlled and foreseen. Using tools such as scheduled load, this penetration can be increased. The authors of [61] researched the impact of increased EV penetration, concluding that all network systems are affected, and the use of simulation tools allows corrective proposals for these impacts to be anticipated and proposed. The authors of [69] quantitatively classify the literature on EVs in power system expansion planning. The authors report that over 70% of the analyzed studies model EVs solely as additional electrical loads, while less than 30% explicitly consider EV flexibility, coordinated charging or V2G capabilities. In methodological terms, approximately two-thirds of the reviewed works rely on deterministic optimization models, whereas stochastic or robust formulations remain limited. Furthermore, fewer than one quarter of the studies adopt an integrated generation–transmission–distribution planning perspective, indicating that system-wide interactions involving EVs are still insufficiently addressed.

In summary, even low EV penetration can increase peak demand by 18% if uncontrolled, necessitating smart rescheduling and stochastic modeling to prevent voltage imbalances. However, a significant gap remains in system-wide planning, as over 70% of studies still treat EVs as static loads, underscoring the urgent need for integrated models that explicitly account for flexibility and V2G capabilities to ensure grid resilience.

These findings illustrate that the relevance of simulation results depends not only on the reported numerical outcomes, but also on the assumptions, model boundaries and system conditions considered in each study. For this reason, the main methodological approaches identified in the reviewed literature are critically compared in Table 5, with particular attention to the assumptions and prerequisites that condition the interpretation of optimization and simulation results.

The comparison highlights that each modeling approach captures only part of the EV–energy system. Long-term simulations support strategic planning but normally sacrifice local technical detail, whereas short-term operational models provide detailed grid-impact assessment but have limited transferability. Optimization models add decision-making capacity, but their value depends on whether practical constraints, such as user participation, charger controllability, battery aging and market incentives, are explicitly represented. This distinction is important because technically optimal charging schedules or V2G strategies may not be feasible under real deployment conditions if users, tariffs, ICT infrastructure or distribution-grid constraints are not aligned. Therefore, the main contribution of

these models is not to define universally optimal solutions, but to identify the conditions under which different EV integration strategies become technically, economically and operationally viable.

Table 5. Critical comparison of modeling and simulation approaches for EV–grid integration.

Methodological Approach	Main Purpose in the Reviewed Literature	Typical Temporal/System Scope	Foundational Assumptions	Required Prerequisites	Critical Limitations and Interpretation
Long-term simulations	EV growth and infrastructure planning.	Days–years; fleet or regional scale.	Adoption, demand and energy-mix trends.	Scenarios, mobility and policy data.	May hide local grid constraints.
Short-term operational simulations	Voltage, congestion and power quality.	Milliseconds–hours; feeder or station scale.	Loads, topology and charging simultaneity.	High-resolution demand and network data.	Precise but highly case-specific.
Optimization algorithms for charging coordination	Optimal cost, peak or RES schedules.	Minutes–days; chargers, fleets or aggregators.	Flexibility, prices, forecasts and constraints.	Smart chargers, ICT and tariffs.	May overestimate coordination benefits.
EV/PHEV penetration and hosting-capacity models	Acceptable EV penetration levels.	Feeders, transformers or urban districts.	Penetration, charger power and simultaneity.	Local grids and load-growth assumptions.	Strongly dependent on topology.
Charging-infrastructure demand models	Charger number, type and location.	Urban, corridor or regional networks.	Mobility, dwell time and service level.	Travel, GIS and parking data.	Demand may exceed grid capacity.
V2G economic and flexibility models	Flexibility value and bidirectional revenues.	Household, fleet or market scale.	Availability, participation, prices and aging.	Bidirectional chargers and market access.	Sensitive to regulation and aging.
Renewable-aligned smart-charging models	Match charging with renewable output.	Microgrids, communities or smart grids.	RES profiles, forecasts and flexibility.	Forecasts, smart meters and controllability.	Limited by mobility-generation mismatch.
Cyber–physical smart-grid simulation models	EV interaction with ICT-enabled grids.	Smart grids and distributed control.	Communication, interoperability and cyber-resilience.	ICT platforms and security protocols.	Often idealizes communication risks.

3.6. Raw Materials and Component Production, Economic and Environmental Challenges, Strategies to Face Them

Although distinct from powertrain or grid technology, the production of critical components is subject to material availability risks. Considering these raw-material constraints is crucial for a comprehensive understanding of the EV ecosystem and the feasibility of large-scale renewable energy integration. In 2021, the IEA carried out what is arguably the most extensive study to date. Titled “The Role of Critical Minerals in Clean Energy Transitions”, it showed the need for government action “to ensure reliable, sustainable supplies of elements vital for EVs, power grids, WTs and other key technologies” [121]. For the construction of EVs, certain essential critical minerals are needed, among which are Li, copper, nickel, cobalt, and neodymium.

The IEA makes recommendations in six key areas to avoid risks in the availability of minerals or artificial variations in their price in the ongoing energy transition process. The study reports that six times more minerals are needed for an EV than for a conventional ICEV. It also suggests that, in climate-driven scenarios, the amount of minerals necessary to produce batteries may increase at least 30 times by 2040.

Given this context, the IEA makes some recommendations to all governments: 1. Adequate and diversified investment in new supplies; 2. promoting R&D on both the demand

and production sides for a more efficient consumption of materials; 3. increasing recycling to reduce waste and the demand for minerals; 4. strengthening standards of transparency, social and environmental regulations and resilience of the supply chain; 5. strengthening of international collaboration between consumers and producers; and 6. the extraction of minerals for EVs produces GHG emissions, although, according to the IEA, the emissions are half those of an ICEV vehicle in its entire life cycle. Regarding Li resources identified in the world, the US Mineral Resources Center in its 2022 report [122] publishes the following: Bolivia: 21 Mt, Argentina: 19 Mt, Chile: 9.8 Mt, USA: 9.1 Mt, Australia: 7.3 Mt, China: 5.1 Mt, Congo (Kinshasa): 3 Mt, Canada: 2.9 Mt, Germany: 2.7 Mt, Mexico: 1.7 Mt, Czechia: 1.3 Mt, Serbia: 1.2 Mt, Russia: 1 Mt, Peru: 880 kt, Mali: 700 kt, Zimbabwe: 500 kt, Brazil: 470 kt, Spain: 300 kt, Portugal: 270 kt, Ghana: 130 kt, Austria: 60 kt, and Finland, Kazakhstan, and Namibia: 50 kt each.

The author of [123] indicates that if all the lithium extracted were used to manufacture EVs, according to his estimations, 8 million EVs could be manufactured per year. If the annual production of cars were 80 million, at that rate, the current demand could not be met. On the other hand, there are estimated to be 1400 million cars in the world. At a rate of 8 million EVs/year it would take 175 years to replace all of them and Li would be depleted in that time. This type of calculation, with the current information, raises doubts about the supply of Li, and would mean that if the electrified mobility model continued, a possible scenario in which the development of other types of batteries, containing other types of more abundant minerals, although with similar charge densities, should be addressed. Additionally, according to his calculations, 2 million vehicles are currently manufactured per year, accounting for EVs, HEVs and PHEVs. Neodymium production is also limited. Cobalt is needed for batteries to be of a feasible size for a vehicle. Copper production has reached a maximum and it seems it can rise no further.

According to the report by the United Nations Development Program for Latin America and the Caribbean, “Lithium prices increased 11-fold in the last 2 years” [124], which means a general rise in EV prices due to the increase in raw-material prices, and a greater cost for the acquisition of an EV by citizens. Efforts by all the stakeholders involved: producers, technicians, politicians, legislators, etc., must be oriented in the same direction in order for a progressive substitution of ICEVs and acquisition of EVs to be possible. Raw-material limitations are not only occurring with Li. Since 2010, the EU has published a list of critical raw materials; in that year, there were 14, but this increased to 34 in 2023. Most of these are necessary for the manufacture of EVs [125]. Furthermore, the recycling of materials from a vehicle that should be carried out does not recover valuable metals. These are lost as waste in the non-recyclable fractions of the vehicle, with only 75% of materials being recovered. This percentage does not cover critical minerals, which must be replenished when manufacturing a new EV, producing a “downcycling” effect instead of “recycling” [126]. In view of the previous point, a number of authors are already engaged in serious research to improve the efficiency of EV materials, concluding that the process of disassembling parts should be improved, and that other materials that are not scarce should be used. Recycling should be based on metallurgy, designs should be rethought, and old cars should be used to make new cars [127].

In summary, the transition to electric mobility requires six times more minerals than conventional systems, which, coupled with lithium price volatility, raises significant concerns regarding long-term supply viability. The findings underscore that current recycling processes result in ‘downcycling’ rather than critical mineral recovery, highlighting the urgent need to diversify investments into alternative chemistries and redesign metallurgical recovery to ensure a true circular economy.

4. Discussion: System-Level Implications, Cross-Domain Interactions and Research Priorities for Large-Scale EV Deployment

The analysis in the previous sections indicates that, notwithstanding significant technological progress, the large-scale and sustainable deployment of EVs is still limited by a set of interrelated technical, infrastructural and systemic factors. These constraints arise not from individual components, but from the complex interactions between vehicle technologies, charging and control strategies, user behavior and power system operation. Building on this evidence, this section provides a critical discussion of six cross-cutting themes that synthesize the main limitations and open research questions identified in the literature, and outline the conditions required for EVs to effectively support sustainable energy and mobility systems.

4.1. From Component-Level Optimization to System-Level Performance Limits

The results presented in Section 3 confirm that substantial technological progress has been achieved at the component level of EVs, particularly in battery energy density, power electronics efficiency and motor performance. Battery costs have decreased by an order of magnitude over the last decade, while energy densities and cycle life have steadily improved. Similarly, advances in power electronics and thermal management have enabled higher charging powers and more compact drivetrain architectures.

However, the literature consistently indicates that these improvements do not scale linearly at the system level. Many studies implicitly assume that advances in individual components will automatically translate into overall system performance gains, yet the reviewed evidence suggests that new constraints emerge as EV penetration increases. For instance, higher charging powers exacerbate grid stress, harmonic distortion and local congestion, while battery degradation becomes more pronounced under fast charging and V2X operation. This highlights a key limitation of reductionist approaches and underscores the need to shift from component-level optimization toward holistic system-level assessment frameworks that explicitly capture cross-domain interactions between vehicles, grids, control strategies and user behavior.

4.2. Charging Infrastructure as the Main Bottleneck for Scalable Electrification

Across the reviewed literature, charging infrastructure emerges as one of the most critical bottlenecks for large-scale EV deployment. While standards such as IEC, SAE and CHAdeMO have enabled interoperability and technological convergence, the practical deployment of fast and ultra-fast chargers remains constrained by cost, grid capacity and power-quality issues. Quantitative results show that DC fast chargers can cost up to nine times more than Level 2 alternatives, while ultra-fast charging scenarios introduce technical challenges related to lithium-ion diffusion limits, thermal stress and accelerated battery aging.

Moreover, studies addressing charging demand estimation reveal substantial methodological divergence, with order-of-magnitude differences in charger-to-vehicle ratios, depending on assumptions about user behavior and spatial distribution. Less than a quarter of the reviewed studies explicitly integrate distribution grid constraints into charging infrastructure planning, which limits the reliability of many of the demand forecasts. These findings suggest that charging infrastructure planning cannot be treated as a purely spatial or mobility-driven problem but must be tightly coupled with distribution network analysis and smart charging strategies to avoid inefficient over-dimensioning or critical grid bottlenecks.

4.3. EVs as Flexibility Assets: Opportunities and Unresolved Constraints of VGI and V2X

VGI, including V2G, V2H and broader V2X concepts, is widely presented in the literature as a key enabler for enhancing grid flexibility and renewable energy integration. Quantitative studies report potential economic benefits ranging from approximately 100 to 4600 USD per vehicle per year, depending on market design, participation level and grid services provided. At the system level, EVs are shown to be capable of absorbing a significant share of renewable energy surpluses and mitigating curtailment, particularly in high-wind and high-solar-penetration scenarios.

Despite this potential, the reviewed evidence indicates that V2X technologies remain far from large-scale deployment. Technical challenges related to bidirectional charger availability, interoperability and control complexity remain, while battery degradation concerns continue to act as a major deterrent for EV owners. Empirical studies on user perception further reveal that acceptance of V2G schemes depends strongly on transparent financial incentives, trust in DSOs and clear governance frameworks. These socio-technical barriers suggest that VGI should not be framed solely as a technical optimization problem, but rather as a coordinated market, regulatory and behavioral challenge.

4.4. Environmental Benefits Under Conditional Assumptions: Emissions, Pollutants and Rebound Effects

The reviewed literature consistently demonstrates that EVs offer substantial reductions in local pollutants and GHG emissions compared to ICEVs. Reported values include reductions of up to 31% in NO_x emissions through controlled charging strategies and life-cycle CO₂ reductions ranging from 42% to over 90% under favorable electricity-mix conditions. However, these benefits are highly conditional and depend strongly on grid decarbonization, charging behavior and vehicle usage patterns.

Several studies emphasize that while EVs eliminate tailpipe emissions, upstream emissions associated with electricity generation and battery manufacturing can offset part of these gains, particularly in regions with carbon-intensive power mixes. LCAs indicate that battery production represents a significant initial carbon footprint, which is typically amortized during the operational phase, but only under sufficient annual mileage and clean electricity supply. Furthermore, rebound effects related to increased electricity demand and potential shifts in mobility behavior remain underexplored, pointing to the need for more integrated environmental assessments that account for system-wide and behavioral feedbacks.

4.5. SGs, Renewable Integration and the Governance Gap

The integration of EVs into renewable-based SGs is identified as a central pillar for achieving sustainable electrification. Quantitative projections indicate that EV charging demand could reach hundreds of terawatt-hours annually by 2030 in large economies, representing a non-negligible share of total electricity consumption. Smart charging strategies aligned with renewable generation profiles have demonstrated the potential to reduce peak loads, increase self-consumption and improve grid stability.

Nevertheless, the literature reveals a persistent governance and coordination gap. While technical solutions for SGs, advanced metering and ICT-based control architectures are well documented, their deployment is often fragmented across regulatory jurisdictions and stakeholder responsibilities. The absence of standardized optimization frameworks that jointly consider pricing mechanisms, grid constraints, renewable variability and user participation limits the effectiveness of current approaches. This gap suggests that future research should increasingly focus on integrated planning and governance models rather than isolated technical solutions.

4.6. Material Criticality, Socio-Technical Acceptance and Long-Term Sustainability

Beyond operational and grid-related challenges, the reviewed studies highlight emerging concerns related to raw-material availability, supply chain resilience and long-term sustainability of EV manufacturing. Lithium, cobalt and rare-earth elements are identified as critical resources, with potential supply constraints that could limit large-scale electrification. While advances in recycling technologies and second-life battery applications show promise, current recovery rates and economic viability remain insufficient to fully mitigate these risks.

At the same time, socio-technical acceptance emerges as a cross-cutting issue influencing multiple dimensions of EV deployment, from charging behavior to participation in V2G schemes. User concerns regarding battery degradation, data privacy, system reliability and transparency recur across multiple studies, indicating that technological maturity alone is insufficient to guarantee adoption. Addressing these challenges requires interdisciplinary research that combines engineering, economics, policy analysis and social sciences to ensure that EV deployment pathways are not only technically feasible, but also socially acceptable and resource-efficient in the long term.

4.7. Critical Assessment of Divergent Findings in EV–RES Integration

Some apparent contradictions in the reviewed literature should be interpreted as context-dependent findings rather than mutually exclusive conclusions. This is particularly relevant in the discussion of EV integration with renewable energy sources, where different studies may reach different conclusions depending on the assumptions adopted for generation profiles, charging behavior, grid constraints and control strategies. The debate on whether wind or solar power is more suitable for EV integration illustrates this issue.

Solar generation may be more favorable when charging can be shifted to daytime hours, when workplace or public charging is available, or when local photovoltaic production is coordinated with smart charging. In contrast, wind generation may be more advantageous in systems where wind output coincides with evening or nighttime charging, where residential overnight charging dominates, or where storage and V2G allow temporal shifting between generation and demand. Therefore, the relevant question is not whether wind or solar power is intrinsically superior for EV integration, but under which system conditions each resource provides higher value. The key boundary condition is the temporal and spatial alignment between renewable generation and EV charging demand. This alignment depends on the dominant charging location, user mobility patterns, tariff incentives, controllability of charging points, local renewable availability and the presence of storage or bidirectional charging.

Studies that assume unmanaged evening charging may favor renewable resources available outside solar hours, while studies that assume workplace charging, daytime flexibility or local PV self-consumption may favor solar integration. Similarly, conclusions obtained at national or annual energy-balance scales may differ from those obtained at distribution-feeder or hourly operational scales.

This interpretation also applies to other divergences identified in the literature. Fast and ultra-fast charging improves user convenience, but its benefits are constrained by charger cost, battery thermal stress, grid capacity and power-quality impacts. V2G can provide flexibility and support renewable integration, but its value depends on user availability, market access, bidirectional charger deployment and compensation for battery degradation. Smart charging can reduce peaks and improve renewable matching, but only if user behavior, communication infrastructure and tariff structures allow sufficient flexibility. Thus, contradictions across studies often originate from different boundary conditions rather than from incompatible evidence.

4.8. Actionable Research Agenda for Large-Scale EV Deployment

Building on these boundary conditions, the final step is to translate the identified limitations into concrete research actions. To enhance the practical relevance of the review, Table 6 presents an actionable research agenda that organizes the cross-cutting challenges discussed in Sections 4.1–4.7 according to their expected implementation horizon, distinguishing between short-, medium- and long-term research directions.

Table 6. Research roadmap and implementation horizons for EV integration into modern power systems.

Research Gap	Engineering Challenge	Future Research Direction	Expected Impact	Implementation Horizon
Limited coupling between charger siting and grid capacity	Mobility-based planning often ignores feeder constraints.	Co-optimize charger location, power level and hosting capacity.	Lower reinforcement costs and fewer network bottlenecks.	Short term
Fast charging constrained by battery aging	High C-rates increase thermal and electrochemical stress.	Develop battery-aware fast-charging protocols.	Shorter charging times with controlled degradation.	Short term
Uncertain V2G feasibility	Benefits depend on aging, vehicle availability and market access.	Validate degradation-aware V2G business models.	More realistic flexibility and revenue assessment.	Medium term
Weak interoperability of smart charging systems	Chargers, EVs, aggregators and DSOs use fragmented protocols.	Test interoperable ISO 15118 [118]/OCPP-based architectures.	Scalable smart-charging and V2G deployment.	Short term
Simplified user flexibility assumptions	Models often assume ideal charging availability.	Include plug-in time, mobility requirements and user acceptance data.	More realistic smart-charging outcomes.	Short term
Limited EV–RES temporal matching	Annual balances frequently hide hourly mismatches.	Couple PV/wind forecasts with charging-control strategies.	Higher renewable energy utilization and lower curtailment.	Short term
Underdeveloped EV role in energy communities	Community models often treat EVs as passive loads.	Validate EMS, aggregator and P2V/V2G mechanisms.	Higher self-consumption and local flexibility provision.	Medium term
Insufficient power-quality evidence	THD and supra-harmonics strongly depend on local conditions.	Measure high-power chargers under comparable operating conditions.	Better filtering strategies, standards and grid compliance.	Short term
Simulation models lacking field validation	Results remain scenario-dependent and difficult to transfer.	Calibrate models using pilot-project and metering data.	Improved reliability and transferability of results.	Short term
Cybersecurity treated as secondary	Communication risks are commonly idealized.	Test secure EV–charger–aggregator–DSO communication architectures.	More resilient smart-grid operation.	Medium term
Environmental benefits depend on assumptions	LCA results vary according to electricity mix and usage patterns.	Use location-specific and dynamic life-cycle assessments.	More robust decarbonization estimates.	Medium term
Raw-material and recycling uncertainty	Battery scaling increases supply-chain pressure.	Integrate recycling and second-life scenarios into planning frameworks.	Lower material risk and life-cycle impacts.	Long term

Table 6 translates the cross-cutting limitations identified in this review into an implementation-oriented research agenda. The proposed horizons distinguish between short-term actions, defined as those that could realistically be addressed within the next three years; medium-term actions, expected to require up to seven years; and long-term actions, whose full implementation would likely extend beyond seven years.

Short-term priorities mainly concern issues that can be advanced using existing technologies and datasets, such as charger siting and grid-capacity co-optimization, battery-aware fast-charging protocols, interoperability testing, realistic user-flexibility assumptions, EV–RES temporal matching, power-quality measurements and field validation of simulation models. Medium-term directions involve more complex coordination and market structures, including degradation-aware V2G business models, EV participation in energy communities, cyber-secure communication architectures and dynamic life-cycle assessment.

Finally, long-term research is mainly associated with raw-material availability, recycling and second-life integration, because these challenges require industrial-scale deployment, mature circular-economy pathways and stable regulatory frameworks.

5. Conclusions

This review has examined the evolution, current state and future challenges of EV development from a system-level perspective, integrating technological, environmental and power system dimensions. By critically analyzing the scientific literature published over the past decade, the study highlights that the feasibility of large-scale EV deployment no longer depends primarily on individual component performance, but on the coordinated interaction between vehicles, charging infrastructure, electricity networks, RES and user behavior.

The literature shows that substantial progress has been achieved in core EV technologies, including batteries, power electronics and charging systems, enabling higher efficiencies, improved performance and reduced costs. However, these advances alone are insufficient to guarantee sustainable deployment at scale. The results consistently indicate that charging infrastructure availability, grid readiness and control strategies represent limiting factors that may offset technological gains if not addressed through integrated planning approaches.

From an environmental perspective, EVs demonstrate a clear potential to reduce local pollutants and GHG emissions, yet these benefits are strongly conditioned by electricity generation mixes, charging patterns and life-cycle considerations. The findings underline that electrification of transport must progress in parallel with power system decarbonization and demand-side management to achieve its full environmental potential.

The review further confirms that EVs can play a strategic role as flexibility assets within SGs, supporting renewable energy integration through coordinated charging and bidirectional power exchange. Nevertheless, widespread implementation of V2G solutions remains constrained by technical maturity, regulatory uncertainty, economic incentives and user acceptance, emphasizing the socio-technical nature of this transition.

Beyond operational aspects, emerging challenges related to critical raw materials, supply chain resilience and recycling raise fundamental questions about the long-term sustainability of current EV production pathways. These issues reinforce the need to broaden the analytical scope of future research to include resource availability and circular-economy principles alongside performance metrics.

Overall, this review demonstrates that the transition toward electric mobility is not a purely technological shift, but a complex systemic transformation. Future research and policy efforts should therefore prioritize integrated, interdisciplinary frameworks that jointly address technical performance, infrastructure planning, environmental impacts and societal dimensions. Such approaches are essential to ensure that EVs effectively contribute to resilient, low-carbon energy and mobility systems in the decades ahead.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating current
BEV	Battery electric vehicle
C&S	Cost, energy, and pollution savings using EV instead of ICEV
CO	Carbon monoxide
CO ₂	Carbon dioxide
CSP	Charging service provider
DC	Direct current
DER	Distributed energy resource
DR	Demand response
DRP	Demand response program
DSO	Distribution system operator
DSR	Demand-side response
E	Emissions reduction management in relation to ICEV without RES
EC	European Commission
ESS	Energy storage system
EU	European Union
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
G2V	Grid-to-vehicle
GHG	Greenhouse gas
GI	Grid impact
HC	Hydrocarbon
HEV	Hybrid electric vehicle
HVAC	Heat, ventilation and air conditioning
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
IoT	Internet of Things
KPI	Key performance indicator
LCA	Life-cycle analysis
Ni-MH	Nickel–metal hydride
NO _x	Nitrogen oxides
OCPP	Open Charge Point Protocol
PEV	Plug-in electric vehicle
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaic energy
R	Electrical resistance
RES	Renewable energy source
S	Simulation
SG	Smart grid
SoC	State of charge
SP	Solar power
T	Technology
TSO	Transmission system operator
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
V2G	Vehicle-to-grid
V2GHV	Vehicle-to-grid/home/vehicle
V2H	Vehicle-to-home

VGI	Vehicle–grid integration
WHO	World Health Organization
WP	Wind power
X	Electrical reactance

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