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Review

Communications and Data Science for the Success of Vehicle-to-Grid Technologies: Current State and Future Trends

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Abstract: Vehicle-to-grid (V2G) technology has emerged as a promising solution for enhancing the integration of electric vehicles (EVs) into the electric grid, offering benefits, such as distributed energy resource (DER) integration, grid stability support, and peak demand management, among others, as well as environmental advantages. This study provides a comprehensive review of V2G systems, with a specific focus on the role of the communication, as they have been identified as key enablers, as well as the challenges that V2G must face. It begins by introducing the fundamentals of V2G systems, including their architecture, operation, and a description of the benefits for different sectors. It then delves into the communication technologies and protocols in V2G systems, highlighting the key requirements in achieving reliable and efficient communication between EVs and the different agents involved. A comprehensive review of communication standards is described, as well as the main communication technologies, which are evaluated in terms of their suitability for V2G applications. Furthermore, the study discusses the challenges and environmental implications of V2G technology, emphasizing the importance of addressing strong and reliable communications to maximize its potential benefits. Finally, future research directions and potential solutions for overcoming challenges in V2G systems are outlined, offering useful insights for researchers, policymakers, and administrations as well as related industry stakeholders.

Keywords: energy; communications; vehicle to grid; distributed energy resources; e-mobility; smart grids; grid integration

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1. Introduction

Nowadays, most electric vehicle (EV) fleets are conceived as devices that connect to the grid to charge their batteries when necessary. With the rise of electric mobility and EVs, batteries, considered as passive elements, are increasingly regarded as portable energy storage systems that can supply energy when needed, as a type of distributed energy resource (DER) and, more specifically, energy storage DER (ES-DER). This conception is especially relevant considering that studies indicate that vehicles are not in use for active transportation up to 95% of the time [1] In this scenario, the electric vehicle infrastructure, composed of electric vehicle charging stations (EVCS) or electric vehicle supply equipment (EVSE), is also conceived as a passive element, with a fixed and predetermined operation, whose planning, design, construction, and commissioning processes do not consider the potential network features and limitations, the density of the number of charging stations, and their simultaneous charging demand at each given time, among other issues. They also lack coordination with other installations such as renewable sources and storage devices. All these planning and operative conditions can alter the energy demand, power quality and communications in the grid. In addition, neither their design for the full life cycle nor their operation is aligned with environmental criteria.

Toward the energy transition and new forms of mobility, in which it is expected that EV sales will surpass gas-powered cars by 2040, the massive and fast deployment of charging points (CPs) is a fundamental pillar to supply an incipient demand in the mobility sector, with a global market impact expected to be over EUR 325,000 million by 2032 [2]. Only in the European context, in order to meet the environmental and carbon-neutrality requirements, at least 3.4 million operational public charging points will be necessary by 2030, in contrast to the 340,000 CPs currently installed [3]. That would require an acceleration from about 1600 installations of public CPs a week in 2021 to more than 10,000 a week in 2030 in Europe.

This massive deployment of EV CPs is a challenge, not only from the point of view of the electricity system itself but also from the impact on communications, and will make the requirements of EVSEs and other agents involved increasingly demanding and able to provide new services beyond classical 'plug & charge' charging, evolving towards active and collaborative elements. Hence, it will be necessary to apply strong and reliable communications and data techniques that guarantee their operation in an increasingly demanding context. As a result, communications will become a must for V2G. In addition, the inclusion of sustainability and circular economy concepts during the definition of the technology will generate a competitive advantage when implementing environmentally friendly charging systems, as these concepts are embedded in the technology from the early stages.

In this context, the concept of vehicle to everything (V2X) arises as a set of techniques encompassing the principle of smart charging and bidirectional power flows. Among them, options including Unidirectional Smart Charging (V1G), vehicle to grid (V2G), vehicle to building (V2B) and vehicle to home (V2H) can be found. The concept of V1G corresponds to the classical definition of charging, considering only one direction of energy flow from the grid to the vehicle, while the other techniques refer to a controllable energy flow both from the grid to the vehicle to charge the batteries and from the vehicle to another system: grid, buildings, and households, resulting in V2G, V2B, and V2H, respectively.

V2G currently generates the most research interest because of its potential and possibility to increase the cost-efficiency of charging, as well as an increase in grid efficiency. Since EVSEs are, nowadays, deployed in isolation and with local load control, without considering the nearby ecosystem of CPs (density and type of points, close load and generation, etc.) or the casuistry of the electricity grid itself (voltage drops, grid overloads, topology, phase imbalances, etc.), possible problems can be derived from these dynamics. In extreme grid events, the network could undergo supply shortages, grid asset overloading, inefficient behavior of the EVSEs (affecting, by extension, the EVs themselves and end users), compromising the quality and reliability of the electrical system, and resulting in higher energy losses. In addition, uncontrolled EV charging could lead to a substantial reduction in the lifetime of an EV battery, hence affecting the end user. Considering the extensive quantity and diverse variety of EVSEs installed, from multiple manufacturers which incorporate different technologies, ensuring the interoperability becomes crucial to guaranteeing the success of V2G techniques, as well as to secure investments and user satisfaction.

Additionally, distribution system operators (DSOs), in charge of managing and operating these active electricity grids, are expected to face technical challenges and increased complexity in grid operation derived from the massification of electric mobility and deployment of renewable generation. In fact, EV charging is one of the main future challenges in distribution, due to the wide range of phenomena that it can cause [4], as previously indicated (such as displacement of the demand curve, overloading of lines, increased energy losses, imbalances and voltage drops, increased harmonics, investments in grid reinforcements and expansion, etc.). Therefore, techniques such as V2G can help to minimize these negative impacts on the grid in terms of cost, quality, and security of the energy supply when significant penetration levels of these resources are adopted, and which, in turn, contemplate the business models, roles, and functions defined for all agents involved in EV charging (DSO, charging aggregators/managers, end users, battery manufacturers, etc.). V2G is also a promising way to store energy in the grid, especially needed during the transition to renewable energy, since leveraging a two-way flow of electricity from EV battery storage to balance power supply and demand could also help global efforts to integrate more renewables into the power mix [5]. Currently, EU passenger EVs would have up to three terawatt-hours of available battery capacity, which is equivalent to 40% of the EU's daily average energy demand [3].

From the point of view of effect over communications, it has been demonstrated that power converters located within CPs generate a high level of electrical noise and emissions, which are transmitted through the electrical cable. Since the noise and emissions are located at the frequencies used by power line communications (PLCs), communications can be affected. In a scenario with thousands of CPs connected in the same sector of the power grid, the impact on communications will be multiplied. Last but not least, another perspective addressed in this review is the consideration of environmental challenges as a whole, as the impact minimization should be understood not only from the electricity system and communications perspectives, thus providing a transversal view of the challenges that V2G will face in the coming future.

The key innovative insights that this study presents can be summarized as follows:

- Dynamic convergence of V2G technology with latest advancements in communications and data science, exploring how the latter can revolutionize energy management and optimization.
- Transformative role of data science in enhancing grid resilience and efficiency through machine learning algorithms and data processing techniques, providing insights into proactive V2G strategies.
- Sustainability challenge assessment by evaluating the environmental implications of V2G integration, including several perspectives, such as batteries' issues, grid and charging systems, and users themselves.
- Emerging trends and future directions towards V2G success, envisioning a roadmap for continued advancements in communications-enabled V2G systems, data-driven decision making, and sustainable energy solutions.

This study contributes to the existing related research with key insights about data, communications, and the current challenges of V2G, aiming to help administrators, researchers, and relevant stakeholders (utilities, manufacturers, etc.) towards the adoption and improvement of V2G systems in the coming years.

The document is structured as follows: Section 2 revises the V2G concept as well as the main benefits and future considerations; Section 3 comprehensively reviews V2G communications and standards, while Section 4 highlights current and future V2G challenges and how data and communications can help to tackle them; finally, Section 5 compiles the main conclusions of the work and highlights relevant considerations for the future of V2G.

2. Overview of Vehicle to Grid

2.1. Description of Vehicle to Grid

The term V2G encompasses the systems, techniques, and technologies that allow EVs to interface with the power grid to provide demand response services by delivering bidirectional electricity exchange [6]. The concept of V2G goes back to the late 1990s, where the first insights of the value of power flowing from vehicle to utility were identified [7]. From then on, different approaches and demonstration experiences have been developed to illustrate the possibilities and potential benefits of the V2G concept to overcome various technological, economic, and market barriers. Currently, rising electricity demand, concerns about climate change and sustainability, as well as the challenges involved in the management of intermittent renewable energy, have highlighted once again the advantages and opportunities of V2G techniques [8]. The potential benefits of V2G are especially related to the provision of grid services, such as reductions in load consumption for small periods of time (peak shaving), the movement of load consumptions to off-peak periods of time (load shifting), and potential revenues for EV owners from grid services provided by their vehicles. In addition, V2G can play and important role in the energy transition by offering a grid resource when required.

The main actors of the EV charging ecosystem can be seen in Figure 1, in which the EV connects to the EVSE for charging and discharging purposes. The DSOs also play a crucial role in this context, not only because they operate the grid to which EVSEs are connected and supply the power but also because the electric energy that is required for charging EVs can lead to problems in the electricity grid in areas where the electric grid is not scaled for EV electrification [9]. Hence, time-shift energy techniques including V2G can benefit DSOs and help to smooth out peaks in the electricity grid and fill in valleys. Another two key agents are the Charging Point Operators (CPO) and the e-Mobility Service Providers (eMSPs). The CPOs are responsible for the physical infrastructure, for the monitoring and control of the energy supply, and they handle technical communication related to the operation and maintenance of the charging infrastructure. eMSPs offer EV charging services towards EV users, including fleet management, the billing and transaction management, and handles user-related communication and software platforms. The role of eMSPs is especially relevant in public charging, where there is the necessity of enabling customers from one party to use an EVSE of another party, enabling interoperability. Their roles could differ depending on the country and their mutual agreement.

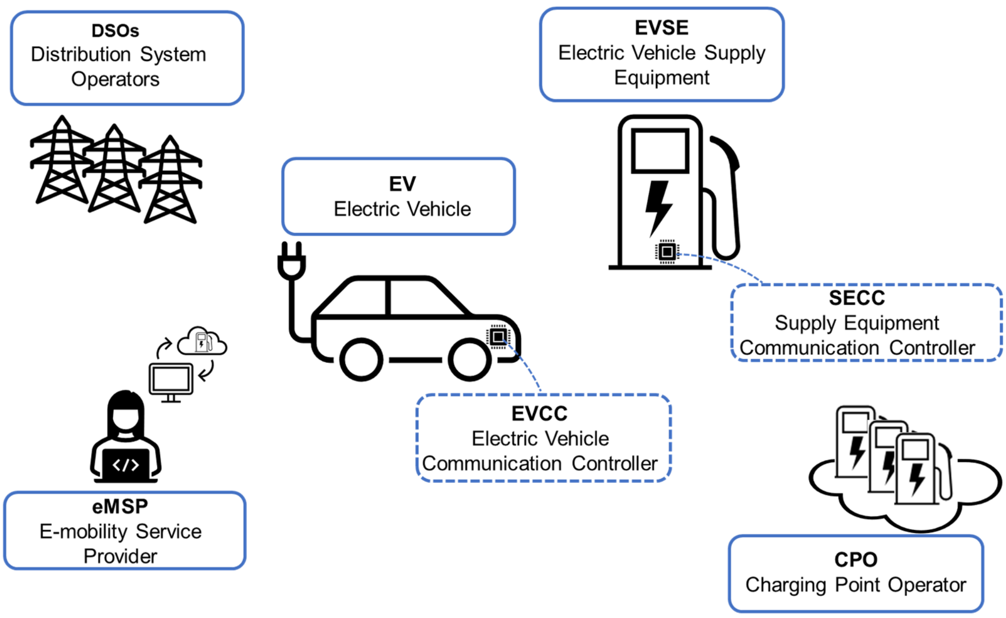

Figure 1. Main actors in EV charging ecosystem.

In the framework of V2G, EVs are connected to an EVSE, not only for charging but also for discharging their battery when necessary. In this process, different information interchange, such as the identification of the EV, the monitoring of the state of charge (SoC), the desired SoC at departure time, and the user charging/discharging preferences, among other criteria, is involved, as can be seen in Figure 2. The collected information from the EVs is forwarded from the EVSEs to the V2G operator, CPO, or eMSP for management and operation purposes. Then, the CPO or eMSP sends different instructions, such as confirmation of the plug-in process, charging, and regulation sequences, back to the EVSEs, where the corresponding control orders are sent back to the EVs. An overview of a V2G scheme is depicted in Figure 2. In this architecture, both the power flow and the data flow are sent bidirectionally.

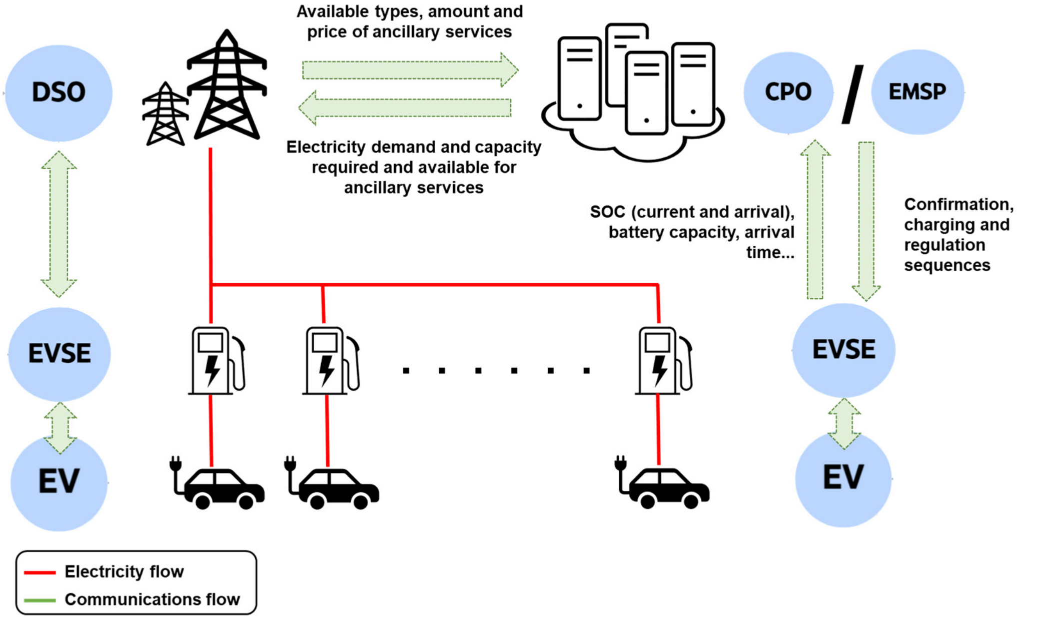

Figure 2. Overview of V2G system. Adapted from [10].

Beyond the classical conception of EV charging, V2G requires some technologies and features that must be implemented to be fully deployed [11,12]. These V2G capabilities must be available through three core elements: the EV itself, the EVSE, and the communication system.

- Adapted electric vehicles

In EVs, the management of energy is governed by an energy storage system (ESS), which is mainly formed by cells, modules, battery packs, a thermal management system, and a battery management system (BMS). Among them, the BMS is especially important to manage and safeguard the performance of the battery. It manages the current flow for both charging and discharging and is responsible for keeping track of the SoC. Its main functions are related to cell monitoring and balancing, state of health (SoH) and SoC estimations, battery protection, the charging and discharging power control, and communication to external devices and systems, among others. For V2G purposes, EVs must allow bidirectional systems to allow the flow of energy in both ways, hence increasing the complexity of the BMS. The recent technology advances around EVs involve batteries, ESS, and BMS systems, as well as their relationship with the EVSE and related disciplines, such as hard-core battery materials sciences, power electronics, and powertrain engineering [13–15].

- Electric Vehicle Supply Equipment

Most of the already installed CPs are conceived and designed for classical unidirectional charging. Hence, they must include additional features to upgrade to V2G services, such as a management system able to implement the smart functions related to V2G and bidirectional capabilities regarding the power flow. Bidirectional systems are required to deliver electricity from the grid to EVs' batteries and vice versa. To that end, it is possible to use two unidirectional converters or one single bidirectional converter. Recently, bidirectional converters have demonstrated better performance in contrast to unidirectional ones, in terms of efficiency, total cost, and weight [10].

Additionally, the EVSE required for V2G involves other disciplines and technologies, such as those related to microprocessors, energy measurement devices, transformers, conductors, connectors, and attachment plugs [16–18]. Due to the early stage of this technology, especially considering the advancements in recent years, design, modelling tools, and testing systems can play a key role [19,20].

- Communications system

Communication between the EV, EVSEs, and the external electric grid enables the exchange of data, setting of the charging mode decisions, and other possible instructions. It involves different agents, such as the eMSPs, the CPOs, the DSO, and also the EVSEs, as well as the EVs themselves, through their supply equipment communication controller (SECC) and electric vehicle communication controller (EVCC), respectively. The data exhibit variability in terms of quantity (the amount of connected EVs varies with time), type, and format, while also presenting diverse requirements (cybersecurity, data latency, and bandwidth, among others) and communication protocols and standards, contributing to a complex data structure. Several proposals aiming at addressing the V2G communication system can be found in the literature [21–24]. However, current initiatives are focused on standards that can help to pave the way towards V2G implementation [10]. In this sense, a comprehensive review of standards is addressed in Section 3.2., which can be further classified into functionality, interconnection/charging topology, and communications standards, respectively.

Depending on the location of the power converter and smart functions, two conventional types can be distinguished: onboard V2G (AC) versus off-board V2G (DC). Apart from them, a third smaller type can be also identified, known as V2G-split inverter. Within DC-V2G, the bidirectional V2G charging hardware and the smart functions are in the CP, meaning that despite EVs' need to be adaptable to this, the intervention is smaller in comparison to AC-V2G. In addition, this configuration allows for faster and more efficient charging with a low noise level [25]. However, the biggest disadvantage resides in the price, mainly due to the expensive DC cable and plug. Related experiences of this configuration implement the CHAdeMO protocol [26] and CCS [27]. In contrast, in AC-V2G, the charger is placed in the EV itself as well as the smart functions, increasing the complexity, presence of electronics, and, hence, cost of the EV, as well as the noise, since the electronics in the car are liquid-cooled, and this method of cooling causes noise due to the pump. As advantages, both car owners and local authorities benefit in terms of less expensive DC-V2G CPs and the required infrastructure in general. However, contrary to what can be expected, in AC-V2G systems, it is not possible to use any standard AC charger but a special version. Currently, although AC-V2G wallboxes are cheaper than DC-V2G chargers, they are more expensive than a normal AC charger [25]. Alternatively, in the V2G-split inverter, the EV charger includes smart functions. However, its corresponding power converter is located onboard the EV [28].

2.2. Summary of Benefits of V2G

The progressive introduction of V2G schemes into the grid could be highly beneficial. The most direct outcome may be the leverage of power grid congestion and the use of batteries when necessary (surplus of energy, back up for renewable resources, etc.). Battery storage has been traditionally considered as a very effective support system for balancing the grid, simply because in most cases it can be turned on and off very quickly and strategically. The disadvantage is the high cost a wide deployment of batteries would present, which cannot be afforded with batteries already placed in the power grid, as V2G proposes [29]. Beyond the obvious advantages in the electricity system, further improvements and different agents can also benefit from V2G and are described below [11,29].

2.2.1. Benefits of V2G to Electricity Systems

The electricity system could highly benefit from V2G, not only from the energy supply itself but also in terms of quality. Overall, V2G techniques provide the system with a high degree of flexibility, from several points of view.

Renewable Energy Load and Grid Integration

Managing an electricity system involves a balance between energy generation and demand, which is typically scheduled one day in advance. The daily schedule must ensure that there is enough generation to meet the forecasted load, where dispatchable generators are used to meet the operative goals (e.g., large forecast errors, load following, renewable integration, etc.). In this sense, V2G can be used to provide additional power when necessary and also to store surplus power when renewable electricity generation exceeds demand.

Considering storage capacity, it is expected that around 14 TWh of EV batteries would be available to provide grid services by 2050, compared to 9 TWh of stationary batteries [30]. Regarding availability, taking into consideration that cars in general, including EVs, are parked for about 95% of their lifetime and that the total time needed to charge the yearly required energy is about 10% of that time, if the EV remains connected to the charging infrastructure 100% of its parking time, this would mean that the yearly "flexibility window" for charging represents about 85% of the time [1,29]. In practice, this flexibility will vary due to parameters, such as the EVs' idle time and connection to the EVSE, the charging location, the charging technologies, and the battery capacity and desired SOC of EV owners, among others.

Examples of these balancing capacities and time-shift energy services can be seen in Figure 3, in which V2G can serve as (a) back-up power when there is a failure in the grid, and (b) peak-shaving service, preventing the need to turn on peaking and back-up plants during peak demand periods. In both cases, the surplus power from PV generation at midday can be used to recharge available EV batteries through coordinated EV charging schemes and to discharge when needed. These techniques should be promoted by incentivizing EV charging following solar and wind generation when they are mostly available, and night-time charging at valley times.

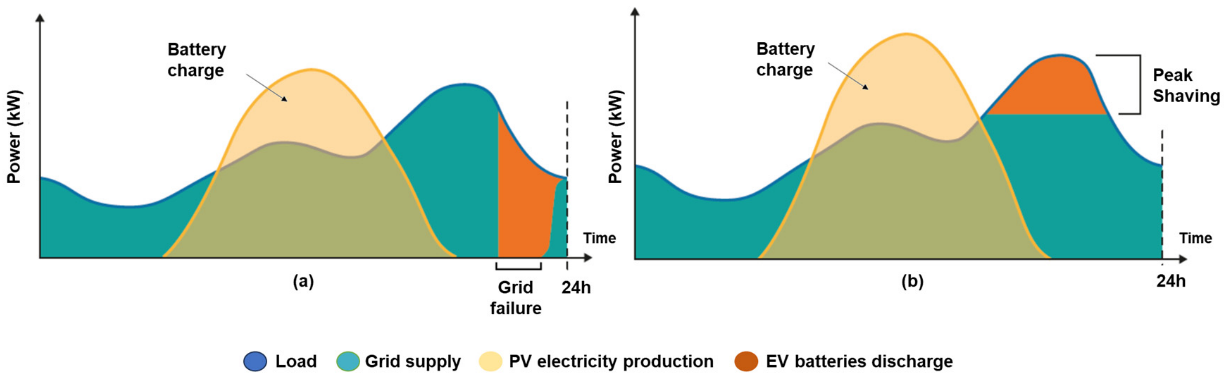

Figure 3. Examples of EV batteries used as (**a**) back-up for the grid and (**b**) peak shaving. Adapted from [29].

Frequency Management

The control of frequency in energy systems is fundamental to maintain the balance between generation and demand. When fast power mismatches and imbalances between supply and demand occur (due to forecast errors, renewable intermittency, and output power volatility), the frequency deviates from nominal (50 Hz or 60 Hz, depending on the region). If demand exceeds supply, the frequency declines, while if supply exceeds demand, the frequency increases.

For fast-frequency services, a quick response is necessary due to its relevance for the whole performance of the system; hence, local controls have been traditionally used. In this sense, V2G control, especially in an aggregated configuration, can respond suitably to frequency services, as indicated [31,32], even more quickly than traditional synchronous generators [33].

Power Quality

Power quality is a generic term used to refer to the undesired presence of disturbances in the power signal. In practice, it is represented by a deviation in the voltage and current waveform from the pure sinusoidal wave, which can be caused by voltage, current harmonics, imbalances, flickers, voltage sags, and swells, among others. Low power quality can affect the reliability of the power system by generating failures and interferences that can affect the performance and the lifetime of the connected devices as well as the power supply.

Improvements in the power quality have been traditionally achieved with capacitor banks and voltage regulators, which can be specifically purchased by DSOs to that end. In this sense, V2G represents an alternative to that investment, since aggregated EV batteries can be used to maintain power quality by controlling the reactive power, as proposed in related research [34,35].

2.2.2. Benefits of V2G to Service Providers

The benefits of V2G can also be extended to new players, such as service providers and aggregators, by combining many small resources (EV batteries) into a larger group able to provide market services. The role of aggregator can be played by a retailer, by an independent service provider, by a single large customer, or by the TSO itself.

Due to the complexity of the V2G ecosystem, aggregators must face technical and regulatory challenges. Among the technical challenges, service providers must utilize suitable hardware (V2G-adapted EVSEs and EVs, metering systems) and software (aggregation and optimization capabilities) as well as real-time communications and, especially, standardized protocols that guarantee communication among all involved parts. On the regulatory side, aggregators require adapted rules for V2G, which include clear price signals, encouragement of smart metering, security, clear definition of roles and responsibilities of different agents, dynamic pricing, data collection and sharing rules, among others [30].

2.2.3. Benefits of V2G to Users

Beyond the use of batteries to power users' homes, as the V2H concept comprises, EV users participating in V2G schemes are expected to be remunerated in some form for the use of their EV battery storage, as a new source of income [36]. Some examples of benefits for EV users from their participation in different V2G pilots are as follows:

- Two-year lease vehicle contract with charger and smart meter, 100% renewable energy, and cashback [37].
- Provision of charger and installation with fixed monthly subscription [38].
- Cheaper power through smart management, home automation, and data visibility [39].
- Cash rewards, free charger for the duration of the pilot, and possibility of purchasing charger at low cost at the end of the trial [40].

2.2.4. Benefits of V2G to Society

A global benefit for society would be a reduction in greenhouse gases (GHGs), since the success of V2G would lead to an increase in EVs, whose emissions are lower than traditional gas-powered vehicles. In addition, since V2G can help to increase the RES hosting capacity and renewable integration in the energy mix, that could help to reduce the amount of back-up power sources based on fossil fuels, which also contribute to GHG mitigation.

That could be particularly beneficial in island systems, often highly dependent on fossil fuels, with petroleum-derived fuels representing a major share of the total primary energy use. However, the introduction of RES in these systems is very challenging because the grid balance is more complex; the loss of a few power supply units has a bigger impact than in interconnected systems, and the effects of voltage drops are more significant. Hence, V2G could greatly contribute to a reduction in emissions and the promotion of RES [41,42].

While the primary objective of this study is to highlight the communication technologies and related aspects that can significantly enhance V2G as well as its benefits, it is essential to mention that there are limitations. Therefore, it is imperative to consider the potential drawbacks and challenges associated with V2G. In the subsequent discussion, we will briefly describe some of the key disadvantages identified, aiming to provide a balanced perspective on both the opportunities and limitations of V2G. Additionally, it is noteworthy that some of these disadvantages are correlated with the challenges outlined in Section 4, for which possible solutions are also discussed. One of the main disadvantages of V2G is the cost of the components and associated technology as well as its potential insufficient component supply [43]. As outlined in previous sections, V2G involves EVs, EVSEs, and related agents (DSO, eMVSP, etc.), so the required upgrades and improvements affect all of them. A wide deployment of V2G will require more advanced and improved power electronics, materials for batteries, communications systems, and related assets [16]. There are also concerns from society and utilities that still need to be addressed, which are often related to privacy issues and the need to upgrade their systems [18,44]. In this sense, improvements in the charging systems, the battery models, and grid integration schemes will play a key role. Furthermore, dissemination activities that emphasize the mutual benefits for all stakeholders can be highly effective. Lastly, the improvement and promotion of communication standards that ensure interoperability, robustness, and cybersecurity have traditionally proven to be instrumental in facilitating the adoption of a particular technology.

2.3. Future Roadmap for Electric Vehicles

The European Green Deal (EGD) stipulates that the European Union must reduce net greenhouse gas emissions by at least 55% by 2030 [45] and achieve climate neutrality by 2050. These objectives will be attained by implementing more ambitious policies to reduce reliance on fossil fuels in transportation, striving for zero-emission efforts [46]. The success of the EGD relies on the ability to make the entire transportation system sustainable. Despite the significant growth in the adoption of electric vehicles, road transportation is still not on track to achieve carbon neutrality by 2050 [47].

Therefore, the European Commission presented a strategy outlining a plan to steer European transportation toward a sustainable and intelligent future, "The Sustainable and Smart Mobility Strategy for European Transport" [46], together with an Action Plan of 82 initiatives. The EU's transport system plans a green and digital overhaul to enhance resilience and targets a 90% emission cut by 2050, aligning with the European Green Deal. The strategy outlines several future scenarios and goals for mobility, including the following [46]:

- By 2030, at least 30 million vehicles will be zero-emission vehicles, scheduled group travel covering distances less than 500 km should have a net-zero carbon footprint within the European Union, and automated mobility will be implemented on a large scale.
- By 2050, nearly all vehicle types will emit zero emissions, and the comprehensive Trans-European Transport Network (TEN-T), featuring various modes of transport and geared toward sustainable and intelligent transportation, will be fully operational, boasting high-speed connections across the network.

The European Commission sets out specifications for minimum quantities of charging stations within the core Trans-European Transport Network (TEN-T) of at least 300 kW every 60 km by 2025 and 600 kW by 2030 for charging stations and similarly for global TEN-T, but for 2030 and 2035, respectively. Concerning charging stations for heavy-duty vehicles, a minimum of 1400 kW is required every 60 km by 2025, escalating to 3500 kW by 2030 within the core TEN-T [45]. Additionally, the global TEN-T mandates a minimum frequency of charging stations every 100 km. It is estimated that by 2025, there will be around one million chargers, projected to increase to 3.5 million by 2030, 11.4 million by 2040, and 16.3 million by 2050 [45].

The literature identifies different scenarios when calculating the environmental impact of an EV system [48–51]; energy mix [48,50], region [48,50], types of charging technologies [50], ratio between the number of electric vehicles and the number of chargers [49,50], grid, charger and battery efficiencies [49,51], and the proximity of energy generation to the charging station [48,50].

3. Review of V2G Communications and Standards

V2G standards are still in the early stages of development and involve multiple organizations. However, they consist of a step forward in the deployment of V2G, since they establish a consistent and predictable framework. There are key factors that highlight the need for standardization [52]:

- Many different parties will access charging hardware (utilities, CPOs, eMSPs, EV users).
- A bad execution of V2G can affect the availability of EVs.
- Utilities that request the discharging of EVs can charge penalties if the V2G events are not executed.
- V2G often requires data from multiple sources, such as the EV itself, energy management system, and energy markets.
- CPs send sensitive data such as utility data and payment information.
- The aforementioned interactions require a high degree of flexibility and security.

While, sometimes, related reviews focus on the interface between the EV and the EVSE when speaking about V2G, the reality is that this communication interface alone does not enable a fully functional bidirectional charging process as V2G presents, and communication with the CPO and beyond is also required.

3.1. Role of Communications and Technologies

V2G requirements evidence that communications are essential. Indeed, without communications, even the simplest process, one-way charging without external inputs, could be affected. As the number of actors involved (EVs, infrastructure, users, and operators, among others) increases, the greater the reliance on communications and, by extension, their complexity, resilience, and cybersecurity requirements. Focusing on the technical requirements, the performance features to be fulfilled by the communication systems must address the following [53–55]:

- Latency: This is the elapsed time between sending and receiving data. V2G applications are sensitive to latency, since there is data-dependent decision making so that, for example, a delay in receiving availability information from a group of EVSEs can negatively affect the operation.
- Reliability: This is related to the guarantee that the data will reach the receiver correctly, which is crucial for V2G since charging decisions require robust, uninterrupted data exchange with ubiquitous coverage and quality-of-service (QoS) guarantees.
- Throughput: This is the rate of message delivery over a communication channel. While some applications such as EV charging systems can vary between 10 and 100 kbps, it is expected that novel applications such as V2G will demand a significantly higher data rate.
- Security and Privacy: Security prevents the unauthorized access of data, while privacy involves the handling of personal and sensitive information, which is protected with security. In this sense, the security and privacy of the information shared between EVs and the other agents are critical requirements, since they involve the IDs of EV users, payment data, location, consumption patterns, etc.

The first step towards a fully functional V2G system is suitable matching between EVs and the charging infrastructure or EVSE. This requires a communication system able to exchange information between each other, from the simplest to the most complex parameters, which can be differentiated as low-level and high-level communications, as depicted in Figure 4.

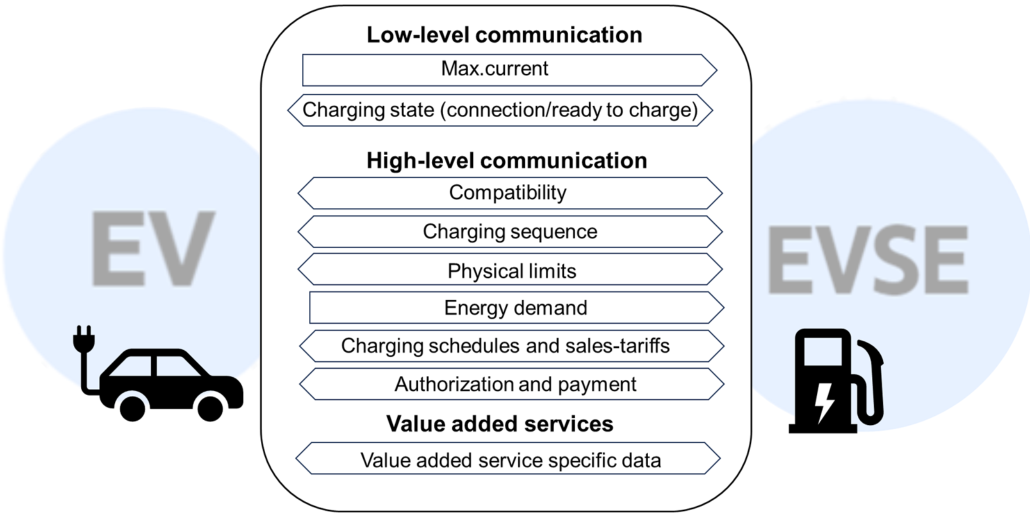

Figure 4. Overview of communication interchange between EV and EVSE. Adapted from Vector Informatik GmbH [56].

Firstly, low-level communication includes the exchange of information required for the charging process, such as the charging state and related electrical parameters. Traditionally, Pulse Width Modulation (PWM) has been used for this purpose, by alternating between +12 Volts and −12 Volts through different stages, as follows:

- State A (+12 V): no EV connected to the EVSE.
- State B (+9 V): EV connected to the EVSE but not ready for charging.
- State C (+6 V): EV connected and ready for charging; ventilation is not required.
- State D (+3 V): EV connected, ready for charging, and ventilation is required.
- State E (+0 V): electrical short to earth on the controller of the EVSE; no power supply.
- State F (−12 V): EVSE not available.

Through these states and via PWM, the EVSE can detect the presence of the EV and can mandate the maximum charge current an EV is allowed to consume.

Secondly, high-level communication includes the interchange of more complex information that exceeds the basic requirements of standard EV charging, such as schedules, tariffs, payment authorizations, input of charging preferences, and physical limits, among others.

Thirdly, a complementary level of communications corresponds to value-added services, which include specific further information required for other services, such as the remote control of an EV from the infrastructure during charging or V2G itself. In fact, for the full development of V2G, the interface between the EV and the EVSE alone does not enable a fully functional grid integration of EVs, so it is also necessary to exchange information between other key players, such as the eMSP, the CPO, and the DSO, to consider and coordinate the state of the power grid and the users' inputs, among others. Currently, no unique scheme is defined for V2G communications; instead, related research proposes different configurations depending on its focus: V2G operator or aggregator, system operation and optimization, etc. [21,22]. Aiming at paving the way towards the homogenization of V2G systems, specific standards are being developed, as will be addressed in Section 3.2.

In addition, it also necessary to guarantee interoperability between the implementations of communication inside the different agents involved in V2G, due to the different manufacturers/service providers, applying each part, for example, different interpretations of the same standards, or a CPO may have to handle EVSE from different manufacturers with several technologies. In this sense, interoperability techniques can be applied with specific recommendations as well as homogeneous data models, able to deal at least with the following requirements [57]:

- Different types of charging/discharging technologies as well as AC/DC power.

- Smart charging, ancillary and related services (frequency control, multiple identification and payment technologies, automatic connection devices, etc.).
- Support for local technical specification from the power grid (grid codes).
- Both wired and wireless communication.
- Coming paradigms such as autonomous driving and self-charging EVs.
- High cybersecurity requirements.

Regarding technologies, a variety can be found to address the different communication challenges faced in V2G. Given that V2G encompasses several agents, topologies, and distances, it is difficult to consider a single technology as the leading one but, rather, the ideal solution involves a combination of several of them. At the global level, two major distinctions can be made: wired technologies, dominated by PLCs in their different versions, widely known in the electricity sector due to their application in the AMI context, and wireless technologies, which are very popular nowadays due to the emergence of IoT and 5G, among others. The main characteristics of the related technologies are described hereafter and listed in Table 1.

- Wired communications

Among the wired alternatives, PLC communications are characterized using electrical wiring as the transmission medium. They stand out for their robustness and security, while their weaknesses include exposure to noise in the network and lower bandwidth compared to wireless alternatives. The simplest version, PWM, is used for sending low-level messages between the EV and EVSE, while more complex versions of the technology are used for sending high-level communications. For example, OFDM modulations or AMI proprietary standards such as PRIME and G3-PLC can be used to send upstream EVSE consumption data. In this sense, the bidirectionality of these standards, which are also intended for environments where electricity is not only consumed but also generated, can be useful for V2G applications. Those standards employ the narrow-band version of PLC, currently up to 500 KHz, whose data rates are up to 500 kbps, and the coverage can reach up to several kms [58]. Currently, high expectations are being placed on the broadband version of PLC, BPL, which, despite having a shorter range of hundreds of meters, has a high bit rate of up to several hundreds of Mbps, capable of handling large amounts of data in real time and meeting strict requirements, which can extend the capabilities of this technology beyond the EVSE.

- Wireless communications

The variety of wireless alternatives is wider than the wired option. Among their advantages are the possibility of communication without the need for complex infrastructure, low cost, and speed of deployment in general. In addition, depending on the technology, they can offer more coverage than traditional wired ones. Some common technologies in the IoT context stand out, such as Near-Field Communication (NFC), ZigBee, LoRaWAN, Bluetooth, and IEEE 802.16 (WiMAX). Due to their coverage and capacity, NFC, ZigBee, and Bluetooth are limited to use around the user, the EV, and EVSE, with applications related to EV-EVSE pairing, sending preferences by the user, communication between different entities, or sending measurement data [59]. WiMAX and LoRaWAN, on the other hand, cover communication between the CPO, the eMSP, and DSO and, therefore, represent a long-distance communication scenario [60]. It is also possible to find other widely known technologies in this group, such as the IEEE 802.11 family and, in particular, its IEEE 802.11p version, which is particularly suitable for the automotive sector and is the basis for dedicated short-range communications (DSRC), intended for wireless exchange in V2X and other intelligent transport systems. Finally, cellular technologies, nowadays on the rise, such as 4G/5G, are also a promising alternative, as, using their advantages in terms of bandwidth, delay, and reliability, it is possible to propose fast and efficient communications between the different actors in the V2G ecosystem [61]. Added to that, current initiatives such as the use of the index modulation concept can increase the utilization of information flow without requiring additional resources [62,63].

Table 1. Communication technologies for V2G applications.

Technology		Operating Frequency	Covered Distance
Wired			
PLC	NB-PLC	3–500 kHz	1–3 kms
	BPL	1–50 MHz	100–500 m
Wireless			
NFC		13.56 MHz	5–10 cm
ZigBee		868 MHz (Europe) 915 MHz (North America) 2.4 GHz (Worldwide)	10–100 m 300 m (LoS)
Bluetooth		2.4 GHz	1–100 m
IEEE 802.11p (DSRC)		5.85–5.925 GHz	300–500 m
LoRaWAN		433/868 MHz (Europe) 915 MHz (North America)	3 km
WiMAX		2–6 GHz	2–5 km
4G-LTE		600 MHz to 2.5 GHz	30 km
5G		600–900 MHz/1.7–4.7 GHz/ 24–47 GHz	1–2 km

Wireless communications in a highly mobile V2G environment do, however, also pose challenges, such as reliability and real-time communication. One such challenge involves smart metering capabilities and the issue of having the EV connected to a different aggregator, energy supplier, or visiting network when it is not connected to its HAN or LAN. Reliability over a large area of connection, thus, also becomes an issue [59].

3.2. Revision of Standards

Despite the fact that there is not a commonly agreed single classification for V2G standards, the revision of related research can be further derived in three different groups: vehicle and EVSE functionality interconnection and communications, meaning that no one single standard includes all the ways that V2G interacts with the grid [10,28]. In this sense, Table 2 lists the most relevant standards following the proposed classification, while Figure 5 shows the connection among them with the different key agents within the V2G ecosystem.

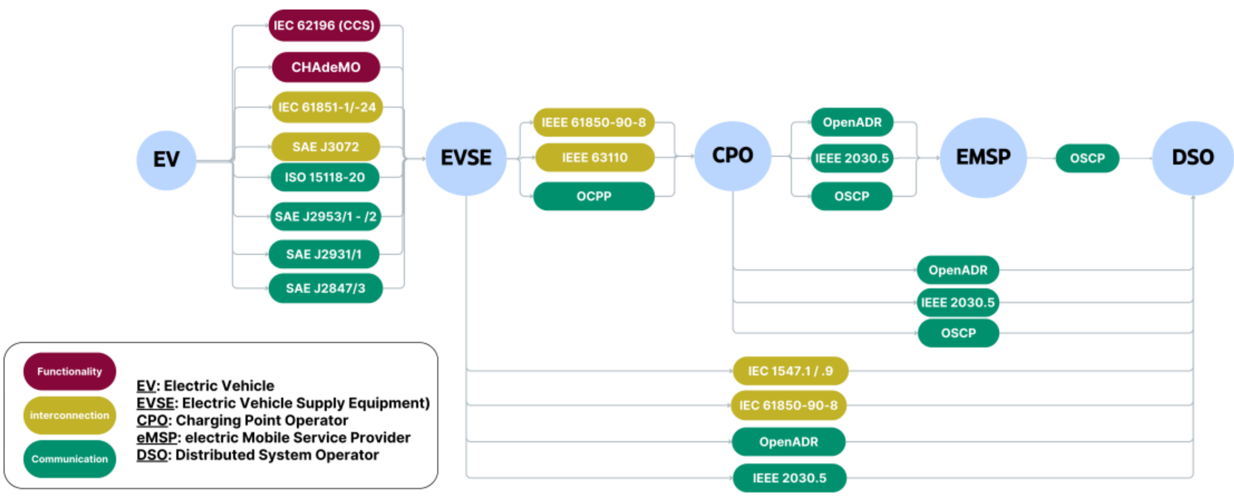

Figure 5. Connection map between standards and the agents of V2G. Adapted from [9].

Table 2. Summary of most relevant standards and related normative within V2G ecosystem. EV/EVSE functionality standards.

	Standard/Protocol and Version		Scope and Type	Description
EVs/EVSEs functionality	IEC-62196 or Combined Charging Systems (CCS) [64]		China and Europe	Standard for Plugs, socket-outlets, vehicle connectors and vehicle inlets—Conductive charging of electric vehicles.
	CHAdeMO [65]		North America and Japan	DC charging protocol with bidirectional charging functionality enabled.
Interconnection/ Charging topology	IEEE 1547	1547-2018 [66]	Worldwide standard	Standard for Interconnection and Interoperability of DER with Associated Electric Power Systems Interfaces
		1547.1-2020 [67]	Worldwide standard	Standard Conformance Test Procedures for Equipment Interconnecting DER with Electric Power Systems Interfaces and Associated Interfaces
		P1547.9-2022 [68]	Worldwide guide	Draft Guide to Using IEEE Std 1547for Interconnection of Energy Storage DER with Electric Power Systems
	IEC 61850	61850-90-8:2016 [69]	Worldwide technical report	Standard for Communication networks and systems for power utility automation—Part 90-8: Object model for E-mobility. Object model for E-mobility.
	IEC 61851	61851-1:2017 [70]	Worldwide standard	Standard for Electric vehicle conductive charging system—Part 1: General requirements.
	IEC 63110	63110-1:2022 [71]	Worldwide standard	Protocol for management of electric vehicles charging and discharging infrastructures—Part 1: Basic definitions, use cases and architectures.
	SAE J3072 [72]		Mainly USA and Canada standard	Standard for Interconnection Requirements for Onboard, Grid Support Inverter Systems.
Communication	IEEE 2030.5-2018 [73]		Worldwide report	Standard for Smart Energy Profile Application Protocol.
	SAE J2931/1-2023 [74]		Mainly USA and Canada report	Broadband PLC Communication for Plug-in Electric Vehicles.
	SAE J2847/3-2023 [75] and SAE J2836/3 [76]		Mainly USA and Canada standard and report	Standard for Communication for Plug-in Vehicles as a Distributed Energy Source. Information Report J2836—Instructions for Using Plug-In Electric Vehicle Communications, Interoperability and Security Documents
	SAE J2953/1 [77]		Mainly USA and Canada report	SAE Recommended Practice J2953/1 Plug-In Electric Vehicle Interoperability with Electric Vehicle Supply Equipment.
	SAE J2953/2 [78]		Mainly USA and Canada report	SAE Recommended Practice J2953/2 Test Procedures for the Plug-In Electric Vehicle Interoperability with Electric Vehicle Supply Equipment.
	OCPP 2.0.1 [52]		Worldwide open protocol	Open Charge Point Protocol—Protocol for the communication between charge point and central system.

Table 2. *Cont.*

	Standard/Protocol and Version		Scope and Type	Description
Communication	OSCP 2.0 [79]		Worldwide open protocol	Open Smart Charging Protocol—Protocol to communicate physical net capacity from the DSO (or site owner) to the back-office of the charge point operator.
	OpenADR 2.0a/b + OpenADR 3.0 [80]		Worldwide open protocol	Open Automated Demand Response OpenADR 2.0a and b Profile Specifications and OpenADR 3.0 Specification
	ISO 15118	15118-20:2022 [81]	Worldwide standard	Part 20: 2nd generation network layer and application layer requirements
		15118-21 [82]//Under development	Worldwide standard	Part 21: Common 2nd generation network layer and application layer requirements conformance test plan.
	IEC 61850-7-420:2021 [83]		Worldwide standard	Standard for Communication networks and systems for power utility automation—Part 7-420: Basic communication structure—Distributed energy resources and distribution automation logical nodes.
	IEC 61851-24:2014 [84]		Worldwide standard	Standard for Electric vehicle conductive charging system—Digital communication between a DC EV charging station and an electric vehicle for control of DC charging.

3.2.1. EV/EVSE Functionality Standards

The following subsections describe the main identified standards related to the functionality of EVs and EVSEs.

IEC-62196 or Combined Charging Systems (CCSs)

IEC 62196 series for *Plugs, socket-outlets, vehicle connectors, and vehicle inlets—Conductive charging of electric vehicles* cover the mechanical, electrical, and performance requirements for plugs, socket-outlets, vehicle connectors, and vehicle inlets for the connection between the CP and the EV. In this sense, the relevance of the standard for V2G is focused on the physical interoperability in terms of signaling pins and connector compatibility. Within the IEC 62196 series are EN 62196-2 for AC and EN 62196-3 for DC [64]. CCSs are the standard series promoted by the European Commission in this context.

CHAdeMO

CHAdeMO is a DC charging protocol with bidirectional charging functionality enabled. In this sense, it is a forerunner, since projects using V2G capacities of the CHAdeMO protocol have been going on since around 2012. CHAdeMO issues different versions of the protocol, offering several capabilities to car and charger manufacturers and their users: starting from the initial protocol edition, version 0.9, included by most CHAdeMO chargers deployed worldwide; version 1.0, which enhances vehicle protection, compatibility, and reliability; version 1.1, which includes dynamic changes in the current during charging, among others; version 1.2, allowing for 200 kW, with protection against over-temperature, overload/short-circuit current protection, and coordination; version 2.0, developed for high-power charging (up to 400 kW), enabling large commercial vehicles, compatible with plug-and-charge functionality; and version 3.0, defined for ultra-high-power charging, enabling over 500 kW of power and using the next-gen plug 'ChaoJi' [65].

3.2.2. Interconnection/Charging Topology Standards

Interconnection and Interoperability of DER (IEEE 1547-2018)

IEEE Standard 1547-2018 for *Interconnection and Interoperability of DER with Associated Electric Power Systems* is the base 1547 standard that supports the proliferation of DERs, as well as the added smart features, grid support capabilities, and interoperability requirements of those DERs. Since V2G involves an interface and a battery that can interact with the power grid, it can be considered within the scope of IEEE 1547. This standard is adopted by public utility regulators as part of the interconnection rulemaking process.

IEEE 1547.1-2020

As a complement to IEEE 1547, IEEE 1547.1-2020 defines the type, production, commissioning, periodic tests, and evaluations that shall be performed to meet IEEE 1547 requirements [67]. Related research articles show the viability of achieving grid interconnection and performance testing procedures for V2G within the scope of IEEE 1547.1 [85].

IEEE 1547.9-2022

1547.9-2022—*IEEE Guide for Using IEEE Std 1547 for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems*—provides examples of ES-DER interconnection to the power system via a power electronic interface (the converter, inverter, or bidirectional inverter), capable of bidirectional active and reactive power flow, and capable of exporting active power to the power system. In addition, the guide provides guidance on prudent and technically sound approaches to these interconnections, and it also considers energy storage-related topics that are not currently addressed or fully covered in IEEE 1547-2018 and sets a basis for the future development of industry best practices for ES-DER-specific interconnection requirements [68].

The conception of the V2G concept under the scope of the IEEE 1547 standard can be seen in Figure 6. In the initialization phase, the EV connects to the EVSE and establishes point-to-point communication. The EVSE provides the configuration information to the EV, which the EV evaluates, and it provides its configuration information back to the EVSE. The EVSE, in turn, provides static management information to the EV. Then, when the active engagement is ready, the EVSE is the DER Managing Entity for IEEE 1547-defined functions and provides the EV with authorization to discharge. In turn, the EV provides its monitoring information prior to the discharge process [86].

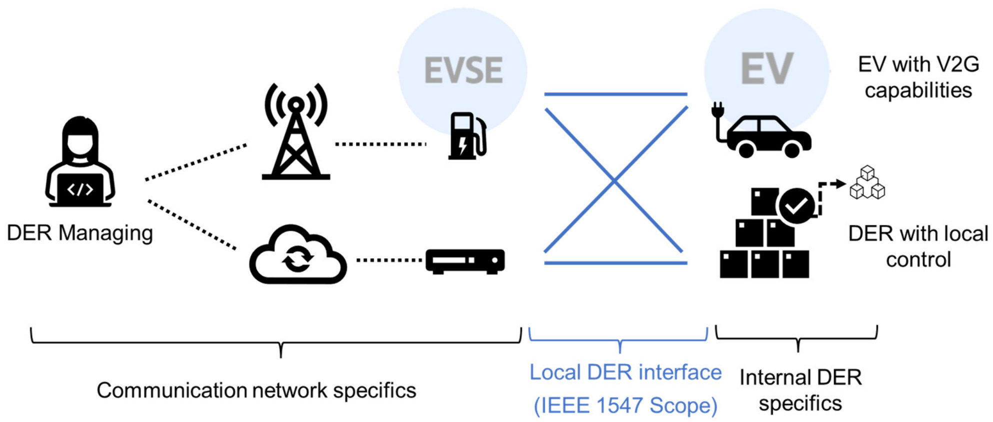

Figure 6. Communication and control scheme proposal for V2G communications following IEEE 1547 standards.

Design and Implementation of Substation Automation and Communication System (IEC 61850)

IEC 61850 is applicable to power utility automation systems and defines the communication between intelligent electronic devices and the related system requirements. The last version of the standard, from 2013, includes technical improvements regarding its scope, the power quality domain; statistical and historical data; distributed generation monitoring and automation purpose; communication between substations; smart grid considerations.

Communication Networks and Systems for Power Utility Automation (IEC 61850-90-8:2016)

The IEC 61850-90-8 technical report on *Communication networks and systems for power utility automation—Part 90-8: Object model for E-mobility* provides necessary background information and proposes an object model for EVs to establish an EV plugged into the power grid as DER according to the principles of IEC 61850-7-420. In addition, missing parts from the e-mobility domain that may not be fully covered in IEC 61850 and IEC 61850-7-420 can be modelled as new logical nodes and data objects with the definition included in this technical report.

Electric Vehicle Conductive Charging System (IEC 61851)

IEC 61851 applies to EV supply equipment for charging purposes, covering all road vehicles, including plug-in hybrid road vehicles (PHEVs), that derive all or part of their energy from onboard rechargeable energy storage systems (RESSs).

General Requirements Applied to EV Supply Equipment (IEC 61851-1:2017)

IEC 61851-1 standard *Electric vehicle conductive charging system—Part 1: General requirements* applies to EV supply equipment for charging electric road vehicles, with a rated supply voltage up to 1000 VAC or up to 1500 VDC and a rated output voltage up to 1000 VAC or up to 1500 VDC. The standard focuses on three aspects: characteristics and operating conditions of the EV supply equipment; specification of the connection between the EV supply equipment and the EV; and the requirements for electrical safety for the EV supply equipment [70]. The 61851 standards go hand in hand with the IEC 62196 series.

Protocol for Management of Electric Vehicle Infrastructure (IEC 63110)

The IEC 63110 set of standards defines protocols for the management of electric vehicle charging and discharging infrastructure. Specifically, it covers the protocols for EVs, EVSEs, and CPOs.

Basic Definitions, Use Cases, and Architectures (IEC 63110-1:2022)

IEC 63110-1 *Protocol for management of electric vehicles charging and discharging infrastructures—Part 1: Basic definitions, use cases and architectures*. This covers the definitions, use cases, and architecture for the management of EV charging and discharging infrastructure. To that end, the protocol describes the general requirements for the establishment of an e-mobility ecosystem, therefore covering the communication flows between different e-mobility actors as well as data flows with the electric power system. Specifically focusing on V2G, the protocol addresses the management of EVSEs (controlling, monitoring, maintaining, provisioning, firmware update, and configuration) as well as the management of energy transfer (including the charging session and the reporting, as well as the information exchange related to the required energy, grid usage, contractual data, and metering data, among others) [71]. As the information comes and goes to several secondary actors, IEC 63110 can be very relevant for utilities such as DSOs or eMSP. Considering its features, some experts consider IEC 63110 as an upgrade to OCPP [52].

Interconnection Requirements for Onboard, Grid Support Inverter Systems (SAE J3072)

SAE is a worldwide authority in mobility standards development, whose standards and technical recommendations are mainly applied in the USA and Canada [87].

An overview of SAE standards and documents related to e-mobility as well as their interaction can be seen in Figure 7. Among them, SAE Standard J3072 for *Interconnection Requirements for Onboard, Grid Support Inverter Systems* defines the communication between the EV and the charging infrastructure that configures and authorizes the discharging at a site. The requirements are intended to be used in conjunction with IEEE 1547 and IEEE 1547.1.

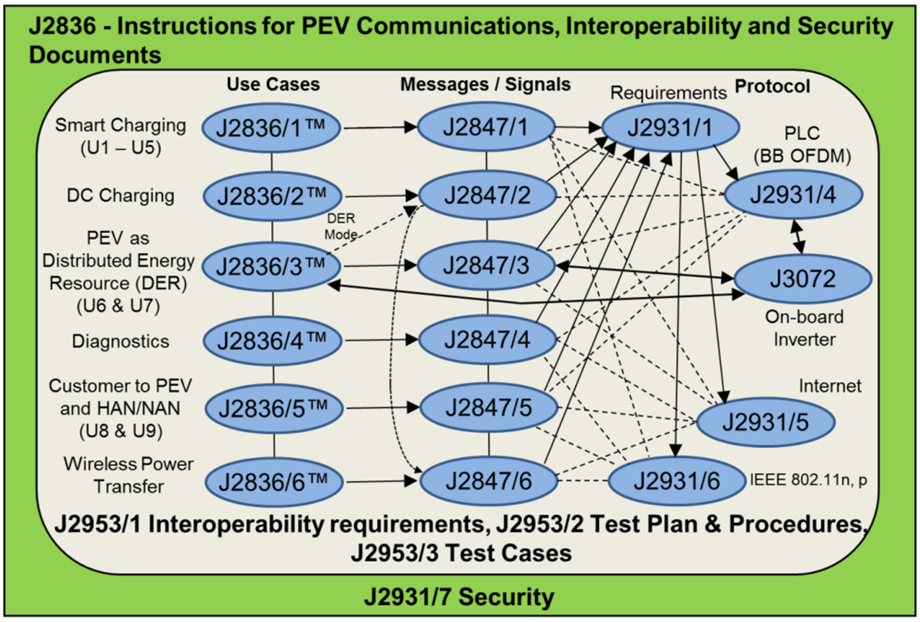

Figure 7. Interaction between the various documents including this document at the top. These start with Use Cases in the SAE J2836 slash sheets, and direct lines to the associated SAE J2847 document. [76].

3.2.3. Communication Standards

Standard for Smart Energy Profile Application Protocol (IEEE 2030.5-2018)

IEEE 2030.5-2018 Standard for Smart Energy Profile Application Protocol defines the application layer, with TCP/IP providing functions in the transport and Internet layers to enable the utility management of the end-user energy environment, including demand response, load control, time-of-day pricing, management of distributed generation, EV, etc. The standard also defines the mechanisms for exchanging application messages, the exact messages exchanged including error messages, and the security features used to protect the application messages [73].

An approach to the implementation of IEEE 2030.5 can be seen in Figure 8, in which the standard connects a V2G platform communication with the DER Management Systems (DERMS), hence converting EV batteries into dispatchable assets through V2G implementation [88].

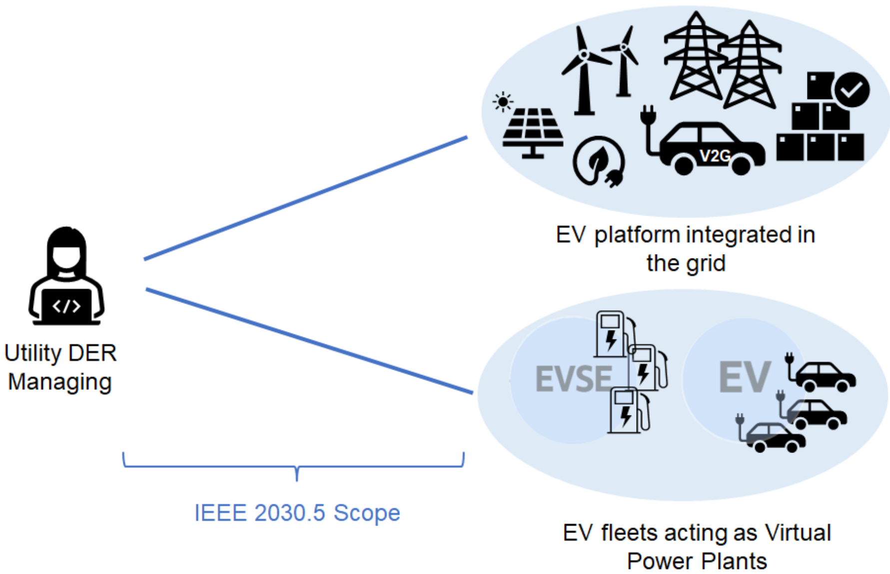

Figure 8. Overview of the implementation of IEEE 2030.5 standard.

Broadband PLC Communication for Plug-In Electric Vehicles (SAE J2931/2023)

This SAE Information Report establishes the requirements for the PLC digital communication between EVs and the EVSE by specifying the digital communication protocol stack between them. The document defines the architecture and general requirements, including association, registration, security, and HAN features, as well as mapping to other SAE documents [74].

Other Guidance Documents (SAE J2847/3-2023, SAE J2836/3, SAE J2953/1, SAE J2953/2)

As a complement to the previously described standards, SAE also defines related documents that provide guidance for using IEEE 2030.5, such as SAE J2847/3, a Recommended Practice that applies to EVs equipped with an onboard inverter and communicate using IEEE 2030.5-2018. In this sense, SAE J2836/3 defines a recommended set of practices that explains different approaches for using the energy of an EV battery to apply V2G. The primary purpose of SAE J2836/3 is to define use cases which must be supported by SAE J2847/3 [75].

SAE also defines documents that establish requirements by which EVs and the charging infrastructure can be considered interoperable (SAE J2953/1) and the test procedures that ensure the interoperability (SAE J2953/2), which can be seen in Figure 8.

Additionally, SAE J2931/4 Technical information establishes the specifications for physical and data-link layer communications using broadband PLC between the EV and the EVSE. Even though it is not included in the scope of this study, broadband PLC may also be used to connect directly to the utility smart meter or home area network (HAN).

Open Charge Point Protocol (OCPP 2.0.1)

The Open Charge Point Protocol (OCPP) is an open, patent- and royalty-free protocol, currently based in JSON and with no cost or licensing barriers. It was originally developed in 2009 by the E-Laad foundation (now ElaadNL), and it is now further developed and maintained by the Open Charge Alliance (OCA).

The objective of OCPP is to offer a uniform solution for the communication between CPs and the central system, regardless of the vendor of the CP. The current version of the protocol is v.2.0.1 and incorporates improvements for aspects found in the first implementations of OCPP 2.0, especially focusing on security, ISO 15118, smart charging, and the extensibility of OCPP. The general aspects that evolved from the previous versions can be consulted in OCA Alliance webpage [89].

Open Smart Charging Protocol (OSCP 2.0)

As a complement to OCCP, the OCA Alliance also developed the Open Smart Charging Protocol (OSCP). The objective of this protocol is to communicate physical net capacity from the DSO (or site owner) to the back-office of the CP operator. The protocol can be used to communicate a 24 h prediction of the local available capacity to the CP operator. The service provider will fit the charging profiles of the electrical vehicles within the boundaries of the available capacity.

The current version of the protocol is v.2.0 and describes use cases in which the messages are applied in more generic terms than the previous version, in order not to limit possibilities of the protocol to smart-charging EVs. This is driven by the integration of EVs in larger energy ecosystems, including PV, stationary batteries, heat pumps, and other devices. As occurred with OCPP, OSCP has switched to JSON and includes additional types of forecasts, such as generation, consumption, and fallback in comparison with the previous version [89].

Two-Way Information Exchange Model (OpenADR 2.0a/b + OpenADR 3.0)

Open ADR is an open and two-way information exchange model and global smart grid standard. It standardizes the message format used for DER management so that dynamic price and reliability signals can be exchanged in a uniform and interoperable fashion among utilities, ISOs, and energy management and control systems [90].

Recently, a new version of the standard was made available, OpenADR 3.0, which simplifies the way to add OpenADR functionalities in current, as well as different and new scenarios. However, it does not replace the previous OpenADR 2.0a/b Profile Specifications but complements them.

The OpenADR standard has been traditionally used, for more than a decade already, for demand-side management (DSM) programs by providing related information to customer-owned systems to trigger a response. The information contained can be related to variable prices or more specific energy requests, and the available capacity can be managed, always without disturbing the grid controls. Within the V2G concept, the energy requests would be oriented towards the use of the available storage resources—batteries from EVs. In this conception, general adjustment requests would be sent to the V2G control system and then executed via any available control standard, like IEEE 2030.5, Modbus, etc., and in accordance with other specifications such as IEEE 1547, as depicted in Figure 9. OpenADR services could address the registration of the EV in the control system, the reception of events from the utility/power grid, the continuous reporting of telemetry data to report on battery or site performance, and the allowance to users to opt out of specific events when desired and relaying that back to the utility, among others [91].

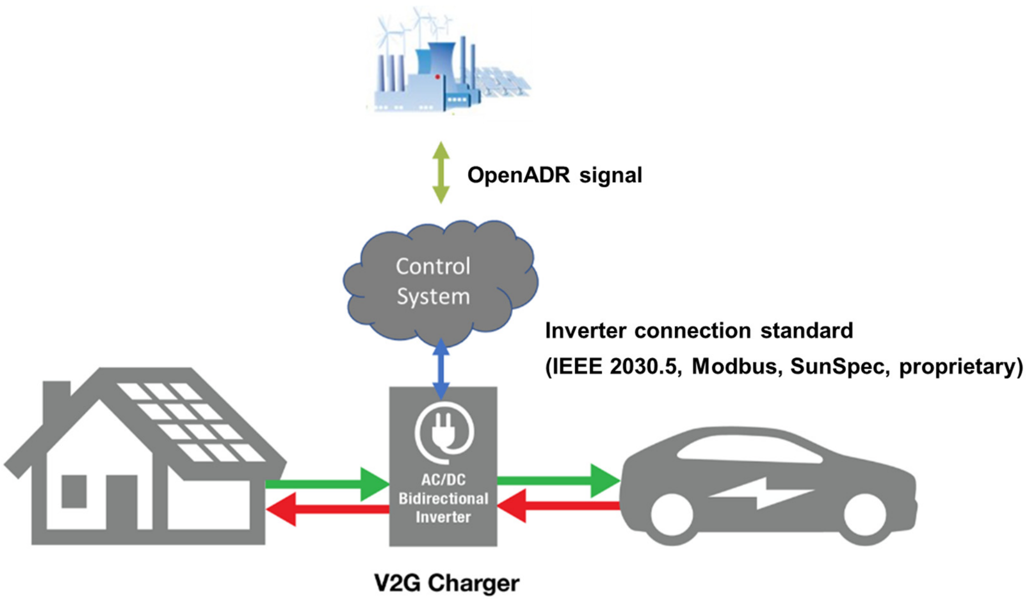

Figure 9. Implementation of OpenADR in V2G [91].

There exist other private organizations such as UL, which develop standards in the USA and Canada, that have defined standards related to V2G. Specifically, there are two UL standards: UL 1741, which applies to all types of generation equipment, and UL 9741, which applies only to vehicles and associated supply equipment [28].

Standard for Road Vehicles' Vehicle-to-Grid Communication Interface (ISO 15118)

ISO 15118 specifies terms and definitions, general requirements, and use cases for conductive and wireless HLC between the communication controllers of the EV and the EVSE.

Second-Generation Network Layer and Application Layer Requirements (15118-20:2022)

ISO 15118-20 *Standard for Road vehicles—Vehicle-to-grid communication interface, Part 20: 2nd-generation network layer and application layer requirements* specifies the communication between the EV and the EVSE by detailing the communication between the EV communication controller and the CP communication controller. The application layer messages defined in this document are designed to support the bidirectional power transfer between an EV and an EVSE, and aspects are specified to detect a vehicle in a communication network and enable IP-based communication between the EVCC and the SECC [81].

Conformance Test Plan (ISO 15118-21)/Under Development

ISO 15118-21 *Standard for Road vehicles—Vehicle-to-grid communication interface, Part 21: Common 2nd-generation network layer and application layer requirements conformance test plan* specifies all common test cases to be applied to and correctly handled by EVs and EVSEs implementing ISO 15118-20 that are independent of a particular charging type and considers the use cases defined in ISO 15118-1:2019 [82].

As can be seen in Figure 10, the ISO 15118 series cover the whole OSI stack for communication between the EV and the EVSE.

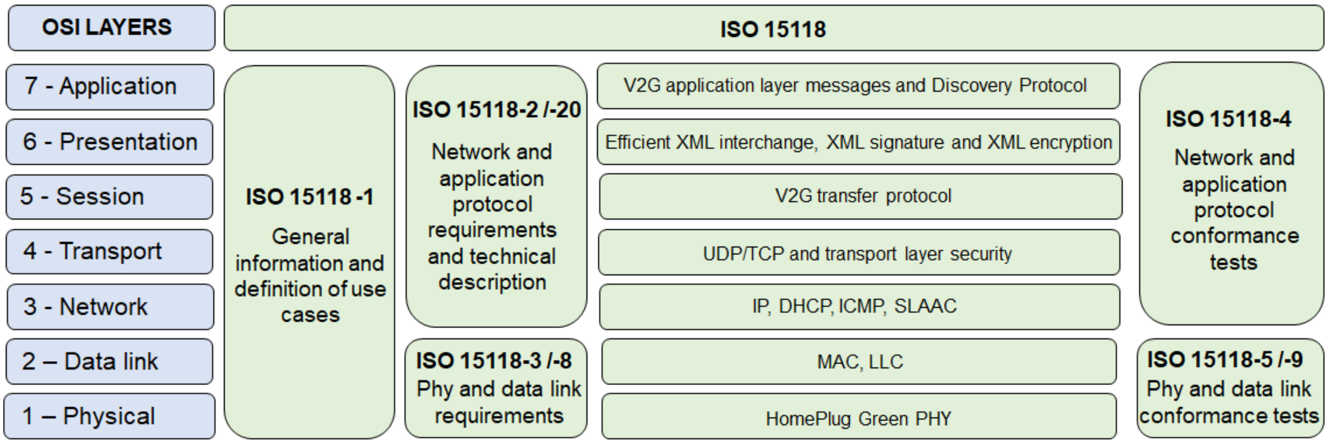

Figure 10. ISO 15118 document parts and their relation to the OSI layers.

Communication Networks and Systems for Power Utility Automation (IEC 61850-7-420:2021)

IEC 61850-7-420 standard Communication networks and systems for power utility automation—Part 7-420: Basic communication structure—Distributed energy resources and distribution automation logical nodes. This standard defines the information models to be used in the exchange of information with DERs and distribution automation (DA) by utilizing existing IEC 61850-7-4 logical nodes where possible, while defining DER and DA-specific logical nodes to provide the necessary data objects for DER and DA functions, including for the DER interconnection grid codes specified by various countries and regions. Hence, the V2G communication interface, which is necessary for the two-way flow of energy, can be derived partly from the specifications in this standard [5,83]. This standard was developed by the working group IEC TC 57, as further described in this study.

Digital Communication between a DC EV Charging Station and an EV (IEC 61851-24:2014)

IEC 61851-24 standard Electric vehicle conductive charging system—Part 24: Digital communication between a DC EV charging station and an electric vehicle for control of DC charging applies to digital communication between DC EV supply equipment and the EV for control of the conductive DC power transfer, with a rated supply voltage up to 1000 VAC or up to 1500 VDC and a rated output voltage up to 1500 VDC. Specifically focusing on V2G, the standard also applies to digital communication between the DC EV CP and the EV, considering the CP as a charging/discharging station [84].

4. Challenges to Be Addressed and Supporting Role of Communications

Despite the fact that V2G shows great promise, there are still some challenges to be addressed in order to achieve a safe and successful deployment in the coming years. The implementation of communication systems and standards can address issues, such as data exchange between different agents, the management of hundreds or thousands of assets, interoperability, and cybersecurity, among others. However, as described above, the V2G concept encompasses a variety of actors, technologies, and domains. Therefore, this section describes the challenges that still need to be addressed and offers some useful solutions and guidelines based on data science. These challenges are categorized as technological, environmental, and regulatory.

4.1. Technological and Regulatory Challenges

4.1.1. Battery Models

Battery models, especially those for lithium-ion batteries (LIBs), play a key role, not only in the design and development of this technology but also in the effective management of the systems incorporating them. In this context, the acquisition of reliable, robust, accurate, and computationally cost-effective models not only eases the progression towards the next generation of advanced batteries, such as lithium-air, flow batteries, or solid-state batteries, but also enables the optimal management of existing technologies. Proper management, in this sense, implies an extension of the battery lifespan, cost reduction, and a reduced environmental footprint, promoting their utilization [92]. Within the field of EVs, these models are indispensable when developing optimal charging strategies, V2G approaches, and estimating the remaining battery lifespan. They also assist in the selection of suitable applications for a second life and in the design of hybrid systems that require efficient management of both electric and thermal power flows. Conventionally, there are three main types of battery models:

- Electrochemical models are based on partial differential equations that can accurately describe the physicochemical phenomena occurring in cells, such as mass transport, charge transport, temperature changes, etc. These models are often used in battery design. However, they are computationally intensive and slow, making them impractical for real-time management of systems in applications requiring fast execution, such as optimization applications. The most common ones are pseudo two-dimensional models, which still need further improvements to accurately adjust coefficients [93], and simplified electrochemical models, which are not yet highly precise [94].
- Mathematical models consist of mathematical functions based on experimental data that relate and estimate various variables, such as current, SoC, voltage, temperature, aging, etc. They are commonly used for predicting cell or battery degradation, remaining useful capacity, SoH, expected lifetime, etc. However, due to their architecture, they are incapable of predicting cell dynamics [95].
- Models based on equivalent electrical circuits determine the behavior and properties of LIBs based on the parameters of the circuit components. More accurate models can be obtained by increasing the number of equivalent circuit components. They are commonly used to quickly emulate cell behavior under specific conditions [96]. They are reasonably precise and do not demand high computational load. However, they require a substantial amount of experimental data to adjust the parameters [97].

When constructing battery models, either a model-based approach, which involves adjusting parameters of formulas that reflect the behavior of LIBs [98], or a data-driven approach can be utilized. Examples of algorithms for the first approach include Kalman filters [99] and Recursive Least Squares algorithms [100]. Within the second approach, models based on regressions and interpolations can be found [101]. These data-driven-based models perform well in handling the inherent noise in experimental data while maintaining high precision. However, they are not suitable for use in applications close to real time, due to the computational effort involved in interpolation operations.

To address this issue, models based on Machine Learning (ML) [102–104] are gaining increasing importance. These models are constructed through supervised learning by mapping input data to output data. They allow for abstraction from the physicochemical mechanisms that occur in cells during charge, discharge, and rest, as long as highly correlated data with the results are available. Examples of such algorithms include Gaussian processes, neural networks, or support vector machines [105]. However, a substantial amount of experimental data is required, which come with the associated time and cost.

Moreover, experimental data often contain significant noise, making it challenging to train ML algorithms [106]. Additionally, it should be noted that despite these algorithms providing good responses on their training datasets, they may not always be extrapolated to the real world, where working conditions are unknown to these algorithms [92].

Therefore, the scientific community is dedicating efforts to develop a methodology for obtaining equivalent models of LIBs that are accurate, insensitive to experimental data noise, fast to execute, require fewer experimental tests, as these consume time and resources, are extrapolatable to new usage conditions, and are generalizable to different materials used in LIBs. In this context, semi-supervised learning algorithms [107] and self-learning algorithms based on Deep Learning (DL) [108–111] are emerging as the ideal solution to this challenge. However, this research area is still underdeveloped, and further investigation is needed in this field.

Figure 11 depicts the methodologies for acquiring a Machine Learning (ML)-based model (a) and a Deep Learning (DL)-based model (b). It also provides an example of SoH, Remaining-Useful-Life (RUL) estimation, (c) and the use of a trained battery model in an optimization algorithm (d).

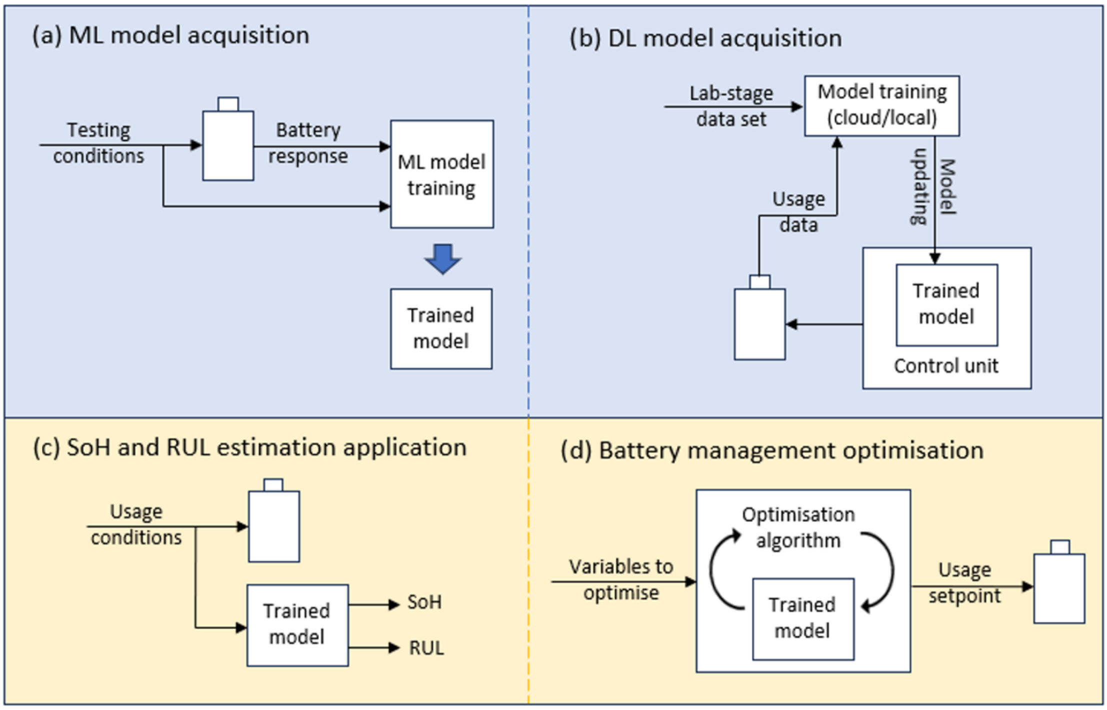

Figure 11. (**a**) ML model acquisition, (**b**) DL model acquisition, (**c**) SoH and RUL estimation based on a trained battery model, (**d**) optimization algorithm considering the model of the battery.

Several challenges regarding data acquisition and communication can be identified:

- One of the main challenges for the proper development of battery models is the lack of data availability. The integration of specific hardware and sensors becomes necessary to acquire the most relevant data used in self-learning processes, such as temperature, current, voltage, SoC, and Depth of Discharge (DOD), among others. Hardware devices could be integrated into the BMS currently used in electric mobility applications.
- Another challenge is related to the high energy consumption and computational resource requirements of self-learning algorithms. In this regard, self-learning processes should preferably be conducted remotely, optimizing the use of hardware resources and reducing locally consumed energy. In this way, the data acquisition hardware integrated into the vehicles should allow for storing and transmitting the acquired data, preferably when the vehicles are connected to an electric charger. This approach would

also reduce connectivity needs and energy consumption during vehicle operation, resulting in increased autonomy.

- A possible solution would be for next-generation electric chargers to incorporate specific hardware for collecting and transmitting acquired data, as well as for reading and updating the battery model on the vehicle's hardware. This could be achieved through wireless communication between the vehicle and the electric charger. Furthermore, to ensure interoperability between different vehicles, battery types, and electric chargers, the definition of specific standards and protocols is necessary to guarantee interoperability among all involved systems.

The collaboration and joint efforts of all relevant industries, including the automotive industry, battery manufacturers, electric charger manufacturers, and others, will be required.

4.1.2. Smart V2G Control and Grid Integration

Smart V2G charging strategies can reduce electricity costs for consumers, maximize the use of renewable energy sources, increase the EV hosting capacity, and minimize their impact on the electrical grid. V2G may even support the grid during peak demand through peak shaving, during grid congestion or overloads, and be oriented to other grid support services. However, a sophisticated communication infrastructure may be required for real-time information between EV customers, the aggregator or electro-mobility service provider, the charging point operator, and distribution system operator so that charging activities can be monitored and controlled.

In the near future, DSOs will face technical challenges and increased complexity in the operation of electrical grids due to the widespread adoption of EVs. Smart control strategies often require the coordination of large EV fleets, which can be carried out in a centralized or decentralized manner, involving more collaboration among new EV actors and stakeholders. Thus, advanced communication technologies are crucial for ensuring effective and stable smart operation.

Centralized decision making for EV charging is led by a central operator or aggregator, who receives the data from EVs and the electrical grid and decides the optimal scheduling [112]. These central coordination methods can reach globally optimal solutions due to higher computing resources but at higher communication and data exchange requirements [113], centralized data repository, and adequate synchronization. For example, [114] proposes a central V2G aggregation framework to mitigate voltage and frequency deviations of the grid. Ref. [115] present profit maximization from the EV aggregator perspective, including the provision of ancillary services, the optimal V2G dispatch, and the design of TOU prices for EV clusters. Ref. [116] implement a genetic algorithm for a valley-filling EV-charging scheme, solving grid congestion and overloading. Ref. [117] propose microgrid dispatch optimization.

In contrast, decentralized or distributed charging scheduling is developed in such a way that EV owners can communicate upstream by sending and receiving signals [112]. The data exchange between agents is reduced, and the decision-making process is carried out locally. For example, ref. [118] propose decentralized cooperative EV-charging management among charging stations, through an urgency priority factor, user satisfaction, and trafo overloads. Another distributed charging schedule is presented by [119], in which each EV can contribute to overload mitigation, reached iteratively in a distributed way.

Apart from decentralized or distributed optimization problems, price-based and market-based approaches can be also categorized as decentralized or distributed charging strategies.

Time-of-use pricing is the most common price-based approach, which involves predefined rate schedules or fixed time periods and encourages them to charge the EV, normally during off-peak prices [120], paying attention to bill optimization [121]. Other dynamic pricing schemes [122] are conceived to influence the EV-charging schedule based on current grid conditions, toward the network power loss and electricity cost minimization, peak load reduction, voltage regulation, and overload minimization. [123] make use of dynamic tariffs to schedule EVs and provide up- and downregulation. Ref. [124] propose a real-time pricing control of EV parking stations under DSO control for cost reductions and grid stability. Indeed, real-time pricing methods mainly require real-time data, bidirectional communication flow, low latency, and quick response times.

Market-based programs rely on the effective exchange of information between EV owners, charging points, EV aggregators, and grid operators to coordinate and manage the response of EVs to grid signals and market conditions. EVs should be able to communicate their available capacity for grid services and respond to grid signals to provide support when needed. For example, frequency regulation services require high-resolution frequency measurements and low-latency communication to be able to react according to frequency dynamics [113]. Thus, automated control and algorithms are essential for scheduling and controlling EV charging. Ref. [125] optimize pool combinations of commercial EVs in frequency and auction spot markets. Similarly, ref. [126] present EVs participating in the energy and regulation market through V2G managed by a central aggregator. V2G control is experimentally demonstrated for primary frequency regulation in [127]. Ref. [128] minimize the load variance in the grid via a blockchain-based V2G trading system.

Nowadays, transactive energy and local energy markets are emerging in contrast to traditional centralized energy models to offer potential benefits, such as grid flexibility, increased renewable energy integration, cost savings for EV users, and greater consumer engagement. Ref. [129] propose the optimal matching of virtual communities, including V2G flexibility.

Several limitations regarding communication are identified in the context of smart EV charging:

- Ideal communication networks are usually modelled in the literature. The impact of realistic communication systems in the data exchange between EVs and the charging station located in multiple nodes of the distribution system was studied in [130].
- There is a lack of application of related standards in communication protocols nowadays. Apart from the existing ISO 15118 and OCPP, other standard two-way communication protocols are required upstream, with the eMSPs and with grid operators and EV owners.

Therefore, several technical challenges should be addressed for effective and smart EV charging:

- Real-time advanced metering and communications infrastructure is required for system operation to integrate EV flexibility. One suggestion moves in the direction of incorporating grid communications into the charging infrastructure or service provider premises to enable future bidirectional charging and other power system services.
- More advanced control and communication functionalities in the vehicle. The effective compatibility of electrical communications with vehicles, charge point operators, electric mobility service providers, and the power system is required to go forward [131].
- Smart V2G strategies should rely on highly reliable and scalable two-way communication networks, with low latency and an affordable cost to be deployed on a large scale.
- Smart EV charging involves the exchange of sensitive data, such as user information or payment details. Ensuring data security and privacy should be essential.
- The communication infrastructure and data exchange needs vary depending on which control approach will be selected and deployed:
    - ○ Centralized decision-making approaches require high communication, data exchange requirements, synchronization, and a centralized data repository. They are less scalable, so there is a need to monitor and control all EVs and stations.
    - ○ Decentralized or distributed charging scheduling requires reduced data exchange, but EVs should be able to send and receive signals upstream, from the charging operators, aggregators, grid operators, and/or EV users. In most cases, the EV is dynamically controlled based on price, market, or grid conditions. Thus, real-time data, bidirectional communication flow, low latency, and quick response times are needed to coordinate efficiently decentralized systems.

- Increasingly, reliable communication with the grid operator will be a must. Price-based and market-based programs rely on the effective exchange of information between all EV stakeholders, being able to communicate local decisions (e.g., price, flexibility) at a given time and manage the EV response based on price signals, the grid, and/or market conditions.

4.1.3. Power Electronics

The growing decommissioning of conventional synchronous generation based on fossil fuels to install new decentralized renewable generation or storage systems, which are connected to the grid using electronic power converters, has increased the stability problems in the electric system [132]. In this way, grid-forming (GF) control techniques that endow these converters with the ability to regulate the grid voltage amplitude and frequency and provide inertia to the system are very interesting to apply in these new generation and storage systems, with the aim of mitigating these instabilities [132,133].

On the other hand, the growing number of EVs integrated in the grid may also create stability and overload problems. Hence, V2G services may help to mitigate these problems since the EV would operate as a flexible storage system, providing frequency regulation, peak shaving, or grid balancing [134].

In this way, the combination of V2G with GF control techniques is being explored to improve the ancillary services provided by the EVs connected to the grid [132]. This combination can be given by a bidirectional AC/DC charger [135] for every EV [136,137]. For this type of charger, a control technique to adjust the inertia of a V2G virtual synchronous machine (V2G-VSM) is proposed in [136], limiting the frequency change rate of the converter. In [138], a bidirectional charger topology, without electrolytic capacitors, is also proposed to provide grid-forming capabilities.

The combination of V2G and GF can also be implemented through a hybrid AC/DC grid, which contains an AC/DC converter and several DC/DC converters associated with every EV connected to a DC grid (see Figure 12) [139]. Therefore, it is possible to benefit from the DC distribution grid advantages, such as lower cable costs and losses than AC networks, asynchronous grid connection, or no proximity and skin effects, among others. For this kind of solution, in [139], a V2G-VSM is proposed, based on synchronverter technology, to regulate the AC grid voltage amplitude and frequency, also considering the SOC of every EV battery. However, the effect of inertia and damping is not studied in detail [136], and communications between the VSM and the EV are required to determine the VSM power reference and droop coefficient.

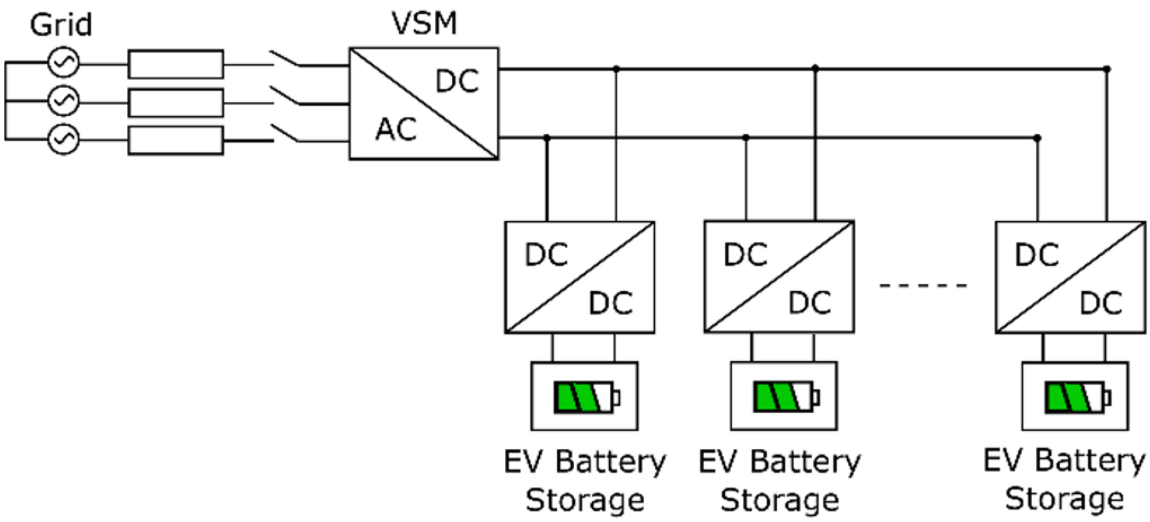

Figure 12. DC grid for distributed EV connection where AC auxiliary services are provided by virtual synchronous machine (VSM).

As has been commented, a DC distribution grid for EV connection provides several advantages. However, several main challenges must be met to provide robust ancillary services based on V2G-GF, with distributed EV connection:

- Reliable communication system to modify the VSM dynamic response depending on the SOC of EV batteries. In this sense, features such as inertia or droop control should be reconfigured in real time under different SOCs, battery failures, or unplanned EV connections/disconnections.
- Grid-forming control techniques that are able to regulate the DC bus voltage and, simultaneously, the AC voltage frequency, providing, additionally, inertia to the electric system, are required. These control methods could be designed with or without communication requirements [140].
- Novel tuning methods should be researched for this kind of V2G-GF control technique, since the regulation of the DC bus voltage will affect the dynamic response of the associated VSM, even under SOC stable conditions. In this way, tuning methods [141] that approximate the V2G-GF performance to the ideal GF behavior (that does not regard the DC side) represent a relevant challenge.

4.1.4. Non-Intentional Emissions

Due to the switching operation of the inverters included in electric vehicle (EV) chargers, EV-charging processes (EVCPs) generate conducted non-intentional emissions (NIEs) at the switching frequency of these inverters (above 10 kHz) and their multiples [142]. These high-amplitude and time-variant NIEs may lead to audible noise, malfunction of equipment, or voltage drops, in addition to degrading the proper performance of power line communication (PLC) technologies operating in this frequency range [143–146].

In recent years, several works have addressed the characterization of these conducted emissions, especially covering the supraharmonic frequency band (2–150 kHz). For instance, in [147], the conducted emissions generated by electric bus inductive charging are studied, with the conclusion that the emissions do not decrease with frequency and that they can be as high as the Compatibility Levels (CLs) at specific frequencies. In [148], the long-term variations in the conducted NIEs were measured at three different EV-charging infrastructures in the frequency and time domains. This study concludes that the higher the number of EVs connected to the grid, the higher the amplitude of the NIEs. In [142], the emissions generated by two different EVs are presented in the frequency domain, pointing out that the conducted emissions depend on both the characteristics of the charger and the EV under study. Other authors [149–151] also study the spectral characteristics of NIEs, where the magnitude and dominant frequencies of the emissions generated by twelve, ten, and eight EVCPs, respectively, are determined. [152] show a comparison of the emissions generated by EVCPs in the 2–150 kHz frequency range in a laboratory test stand and in the LV grid, concluding that the grid parameters may affect the amplitude of these emissions. Other authors, in turn, have conducted investigations in laboratory scenarios under controlled conditions, in order to avoid external and variable grid effects. In [153], the conducted emissions generated by two EV models considering different charging currents are characterized in the frequency and time domains using a Line Impedance Stabilization Network (LISN) for frequencies up to 500 kHz.

By contrast, the emissions generated by V2G processes have not yet been widely addressed by the scientific community. Authors in [154,155] analyze the conducted emissions generated by a V2G system at a reconstructed LV grid in Vienna, highlighting the existence of both narrowband and broadband emissions in the 9–150 kHz frequency band, as well as identifying their main cause of occurrence. The waveforms recorded in different conditions of this V2G process have also been used to perform a statistical comparison of CISPR 16-1-1 and LightQP methods [156], CISPR 16-1-1, IEC 61000-4-7, and IEC 61000-4-30 methods [157]. Therefore, the NIE generated by novel V2G technologies is still a phenomenon to be addressed by laboratory and field measurements.

According to the literature, the spectral and time characteristics of the emissions generated by EVs during their charging process depend on the EV model, SoC, charging current, and EVCS under study [150,153,158]. Some EVCPs, as depicted in Figure 13a, show narrowband emissions occurring at certain frequencies, corresponding to the switching frequency of the inverter (16 kHz) and its multiples. For other charging processes, in turn, the spectral pattern of the NIEs is in the form of colored noise, decreasing with frequency (amplitudes from 79 dBμV to 48 dBμV), as observed in Figure 13b in the 70–500 kHz frequency range.

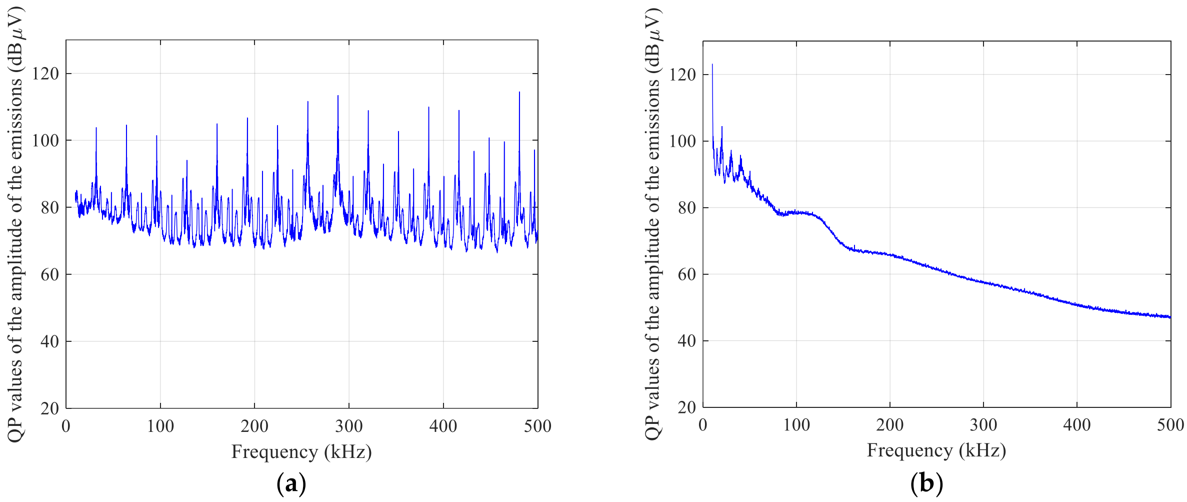

Figure 13. Emissions generated by two different EVCPs (**a**) QP values of the amplitude for an EVCP, (**b**) QP values of the amplitude for a EVCP [158].

Regarding the time-dependent behavior of the NIEs, the procedure for the time characterization presented in [158] based on a Fast Fourier-Transform (FFT) analysis, leads to the conclusion that the emissions generated by EVCPs vary within the fundamental period of the mains (20 ms). In Figure 14, as an example, the emissions generated by a certain EVCP with respect to time (vertical axis) and frequency (horizontal axis) are represented by means of a spectrogram. Figure 14 shows tonal emissions (around 47 kHz and 94 kHz), whose central frequency oscillates periodically with time [153].

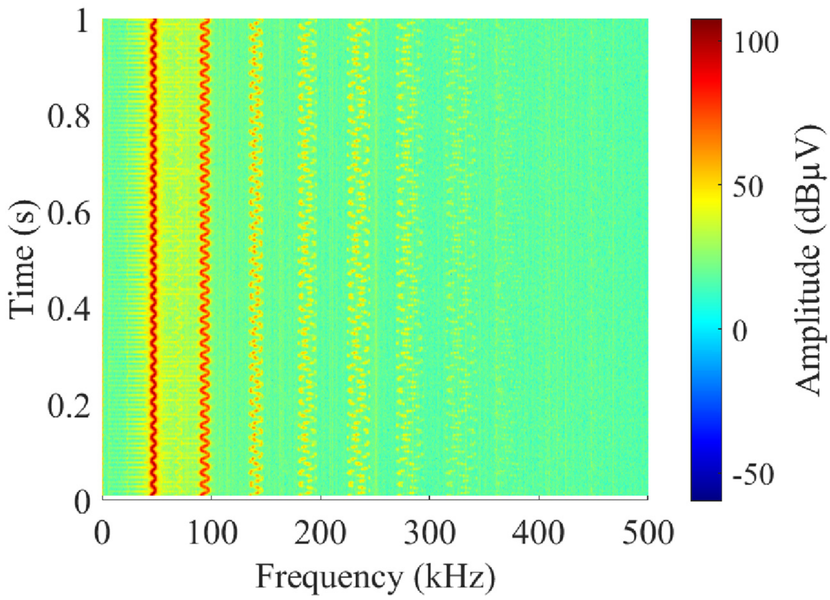

Figure 14. Spectrogram of the conducted emissions generated by a certain EVCP [153].

The time-dependent behavior of this type of emission was specifically studied in [159], where a periodic pattern with a repetition rate of 41 Hz (24.4 ms) was reported. A similar time-dependent behavior (25 ms) of these tonal emissions was also observed in [151]. These fast time variations may have detrimental effects on the quality of PLC technologies by jeopardizing the operation of the channel estimation and equalization processes.

Finally, it should be noted that the conducted emissions generated by electronic equipment have been proven to propagate from the LV grid through the medium-voltage (MV) grid [158,160–162]. Although, in [158], it was concluded that the amplitude of the emissions generated by EVCPs generally decreases with the distance, resonance effects in the grid impedance may cause a noticeably higher amplitude at specific frequencies [158,163]. For this reason, several authors have characterized the grid impedance in the presence of EVCPs [154,164,165], in order to obtain knowledge about how changes in the impedance during the EVCPs affect the amplitude and propagation of NIEs.

Regarding V2G processes, the influence of the power electronic components comprising the charging station is studied in [166] based on simulations, while [154] analyzes the effect of this technology on the grid impedance by means of empirical trials for frequencies up to 150 kHz.

4.1.5. Electromagnetic Interference (EMI)

The measurement framework for the characterization of the conducted emissions in the distribution grid is not fully defined. For frequencies below 9 kHz, the power quality (PQ) regulation is well established, since the issues related to waveform distortions have been studied for decades. The regulatory challenges related to electromagnetic interferences still to be solved can be found in frequencies above 9 kHz. That is the reason why this section focuses on this frequency range.

Measurement Methods for EMI above 9 kHz

The phenomena of conducted disturbances in the distribution grid were not addressed by standardization bodies related to the power quality up to the development of the power line communications. The first standards defining measurement methods and limits were published in the last few decades. Nevertheless, EMC coordination is needed to define a consistent measurement framework.

The IEC 61000-4-30:2015 [167] standard defines the PQ methods for measurements in the low-voltage (LV) grid. The Annex C of this standard proposes three measurement approaches (none of them normative for grid measurements) for the characterization of the conducted emission in the 9–150 kHz range: CISPR 16 receivers [168], an extension IEC 61000-4-7 Annex B method [169], and an alternative method described in the same standard [167].

The CISPR 16 receivers [168] were defined several decades ago to quantify the radio interferences. This instrument is based on a heterodyne receiver followed by a quasi-peak detector, which subsequently scans the desired frequency band to assess the worst-case scenario. Studies have concluded that this method presents several drawbacks when it is applied to grid measurements, such as reproducibility issues, the lack of a reliable technique to measure the energy (RMS values) of the emissions, and the high complexity of implementing the method in existing PQ platforms [170–172].

The IEC 61000-4-7 [169] method was originally defined for the 2–9 kHz band. The Annex C of IEC 61000-4-30 suggests its extension to the 9–150 kHz range, but there is no guidance on how to extend this technique to upper frequencies. The original method implements a short-time Fourier Transform (STFT), using non-overlapped rectangular windows of 200 ms, followed by a spectral grouping to compute the spectra of the measurements with a resolution bandwidth of 200 Hz. The third technique is the alternative method described in Annex C of the IEC 61000-4-30 standard [167]. This method relies on an STFT, based on rectangular windows of 0.5 ms, in which measurement gaps are allowed to analyze only in 1 out of 16 measurement intervals. This method presents two main issues. Firstly, the resolution bandwidth is 2 kHz, which impedes comparisons of the outputs with respect to those of the previous two methods. Secondly, 92% of the spectral information is lost due to the measurement gaps.

Annex C of IEC 61000-4-30 [167], where the three methods are described, is an 'informative' annex. Therefore, its implementation and usage are not mandatory for PQ instrument manufacturers and grid operators, respectively. Moreover, this standard only suggests methods to quantify the disturbance up to 150 kHz; however, the same type of emissions measured below 150 kHz can be found up to 500 kHz. In the 150–500 kHz range, a unique measurement technique is defined in standards, the CISPR 16 receiver. Nonetheless, it presents the same drawbacks as for frequencies below 150 kHz. Furthermore, there is a lack of a normative methods for the characterization of grid emissions in the whole 9–500 kHz range, since all the proposed techniques, or application to grid measurements, are suggested in 'informative' sections of PQ standards.

Apart from regulatory inconsistencies, the described standardized methods only provide information of the emissions in the frequency domain. These outputs are obtained by weighting the spectral information over fixed observation periods. Nevertheless, in the results of these analyses, the impulsive disturbances are hidden, which have been proved to interfere with power line communications (PLCs) and to provoke malfunctions on the rest of the devices connected to the grid [173–176]. Therefore, the next-generation measurement methods must analyze the emissions, not only in the time or frequency domain but also in the joint time-frequency domain, to be able to provide information about the evolution over the time of the emissions in different frequency ranges and, in particular, to characterize the impulsive disturbances separately from the rest of the emissions.

Certain standardization bodies are addressing the inconsistencies in the measurement framework for conducted emissions in the grid above 9 kHz. The CENELEC TC219 WG11 is working on the compilation of the state of the art of the conducted emissions in the grid up to 500 kHz to show the need of defining a proper EMI measurement framework. In the same spirit, the IEC SC77A WG9, which is in charge of the maintenance of IEC 61000-4-30, has been working during the last 4 years on defining and selecting the most suitable method for the 9–150 kHz band. As a result of this work, the chosen method(s) will be included in Ed.4 of IEC 61000-4-30, which is scheduled to come into force in 2025.

Several studies have been published addressing the challenge of defining measurement methods for conducted emissions in the distribution grid. The Wavelet Approach [177] relies on 'wavelet package decomposition' to compute the spectral components of the measurements. In this technique, the signal is subsequently filtered and downsampled to obtain 740 frequency bins of 200 Hz in the 2–150 kHz frequency range. The Subsampling Approach [178] aims to reduce the complexity of the calculation process using an analogue filter bank. These filters divide the whole 2–150 kHz range into the 10 bans of 15 kHz, demanding fewer computational resources. The spectral components are then computed using an STFT with a rectangular window of 0.5 ms. The RM-A [179] method is an adaptation of the IEC 61000-4-7 Annex B method to obtain RMS values in the 9–150 kHz band. This technique implements an STFT, with non-overlapped rectangular windows of 20 ms length, and a spectral grouping to obtain spectral outputs with 200 Hz resolution bandwidth. The Light-QP [180] is an alternative technique to CISPR 16 to compute the quasi-peak (QP) spectra in the 9–150 kHz band. The Light-QP relies on the RM-A method to compute the spectral components and implements a digital QP detector to provide the QP values of the measurements. Finally, the Statistical-QP [181], which also relies on the RM-A method, applies a statistical conversion to the RMS spectra in order to estimate the QP values in the distribution grid.

EMI Emission Limits

In parallel to the work on the measurement techniques, the limits for conducted emissions have been defined by standardization committees. The IEC 61000-2-2:2002 + A1:2017 + A2:2018 [182] defines the maximum amplitude for the intentional and non-intentional emissions in the distribution grid up to 150 kHz. These reference levels defined as the combination of the emissions generated by all the equipment connected to the grid, also known as compatibility levels (CLs), were established to avoid interferences on PLCs and are intended to be met in 95% of the locations and time, since it is assumed that it is impossible to have the whole distribution grid under control continuously.

As a complementary reference to the CL, several standards define the emission limits generated by particular equipment. In this line, EN 50065-1 [183] defines the amplitude limits for the PLC transmissions, not only for the intentional emissions injected into the corresponding transmission channel but also for the spurious out-of-band emissions. Additionally, standards CISPR 14-1:2020 [184] and CISPR 15:2018 [185] define the emission limits for household 'appliances, electric tools and similar apparatus' and emission limits for 'electrical lighting and similar equipment', respectively.

Nonetheless, there are families of devices that are not covered by any standard, and, therefore, there are no emission limits that have been stated for them. In the meantime, a coherent proposal for these types of devices without specific regulations would be to use the CL as an upper reference for the emission limits of any specific instrument not covered by any standard, together with a reasonable margin. Accordingly, a tentative proposal is to consider emission limits of an amplitude 9 dB below to the corresponding CL at that frequency.

EMC Challenges Related to EVs

EVCSs are known for injecting non-intentional high-amplitude disturbances. Nonetheless, there is a lack of limits for the disturbances generated by these specific devices. Following the criteria explained before, one of the most relevant challenges that should be addressed in the near future is the definition of the emission limits for the EVCS or alternatively to use the reference of the CL with a safety margin of 9 dB below the corresponding CL.

The propagation of the conducted emissions generated during the charging process, together with the phenomena related to the aggregation of emissions from several EVCSs in a small area, needs to be characterized, in order that EMC measurement procedures can be completed.

In addition, the maximum total supraharmonic value (TSHV), which is the summation of the energy of the emissions in a specific band, should be defined for EVCS emissions in order to limit the impact on the thermal stress produced by these disturbances in the rest of the equipment connected to the distribution grid.

4.2. Sustainability Challenges

V2G represents an innovative interaction between electric vehicles and the power grid, holding the potential to transform mobility and energy sustainability [186]. This section scrutinizes the challenges and opportunities concerning EV batteries, charging infrastructure, end users, and the environmental impact assessment associated with V2G.

4.2.1. EV Batteries

Batteries pose three primary sustainability challenges in V2G [187–189]: battery degradation due to V2G, battery capacity, and battery durability. Several authors like [187–190] emphasize that frequent V2G charging and discharging could expedite battery degradation, potentially leading to increased electronic waste and additional consumption of natural resources used in battery production and disposal. Conversely, studies [190,191] suggest that the impact of this degradation due to V2G might be minimal compared to daily battery wear. Moreover, certain battery chemistries exhibit heightened sensitivity to premature aging when subjected to frequent charging and discharging in V2G scenarios [192]. This finding underscores the importance of understanding different battery chemistry behaviors when assessing charging strategies and V2G applications [192].

Enhanced battery capacity can reduce emissions and displace electric load, positively impacting the environment by reducing the carbon footprint [189]. However, inadequate capacity might shorten the battery lifespan, leading to increased electronic waste and natural resource demand for production and disposal [186]. This debate emphasizes the need to balance energy efficiency with sustainability in V2G environments.

The relationship between battery durability and DOD holds significant environmental implications [192,193]. It has been observed that higher DOD, depending on battery chemistry, can accelerate aging and degradation [188]. Instead, ref. [193] indicate that the effects might be less severe. This discrepancy highlights the importance of understanding the interplay between V2G operation, battery lifespan, and environmental impact, considering diverse battery chemistries and their specific behaviors in V2G operations.

4.2.2. Grid and Charging Systems

One of the most promising opportunities presented by V2G is its potential to provide grid reliability, avoiding the need for activating unsustainable power plants [190,194–196]. Thus, V2G could contribute to grid stability and emission reductions during periods of higher environmental impact energy demand [190,195]. However, integrating electric vehicles into the energy infrastructure for V2G also presents challenges concerning VE setup for V2G support, power electronics, grid stability, and energy mix uncertainty.

Regarding VE setup, the geographical dispersion and limited capacity of individual EV batteries hinder providing reliable and consistent energy at a large scale [197]. A solution proposed in the literature for more efficient V2G involves heavy-duty EV fleets (buses, trucks, etc.) [190,193]. The aggregated capacity and centralized deployment of these fleets [196], along with the predictability of EV deployment to support the grid [192], allow for a more reliable, consistent, and planned energy supply, minimizing fluctuations that could arise with dispersed individual EVs and enabling more precise estimates of EV availability to support the grid. However, sudden charging and discharging of a large EV fleet during V2G technology application could cause voltage fluctuations that might impact grid stability [188].

Other issues concerning V2G are the harmonic distortions and voltage anomalies that charging controllers of EV batteries might generate [188]. Thus, synchronous compensators or active power filters are necessary, potentially increasing the environmental impact due to new natural resource utilization [196]. The same applies to power electronics, such as additional converters and wiring [188], required to enable V2G. Hence, careful assessment is needed to determine if the potential environmental benefits outweigh the technology's environmental costs [188,192,193].

V2G allows one to offset renewable source intermittency, maintaining grid stability and balancing energy supply and demand through controlled energy storage and release [190,191,196,197]. Furthermore, V2G enables the establishment of more sustainable microgrids, where local renewable energy sources combine with storage via electric vehicles to meet local demands [190,191,196,197].

Moreover, regional influences (energy mix, number of EVs, EV and energy hourly profile, etc.) and variability between the supply and demand of the electrical supply have been shown to significantly impact the V2G equation [186,189,191].

Finally, there is a recognized need to establish a standard for the environmental impact assessment of V2G systems, such as Product Category Rules (PCRs) [198], to enable accurate environmental comparisons and make decisions aligned with sustainable development.

4.2.3. Challenges from Users

The successful implementation of V2G for individual electric vehicles faces multiple challenges, such as battery degradation concerns [187,194], sensitivity to V2G contract constraints [187,197], and uncertainty about vehicle availability for V2G operations [187,197]. The lack of sustainable business models and specific regulatory incentives limits its adoption [188,195] while concerns about cybersecurity [188,197] and the lack of accurate models for predicting energy consumption pose technical challenges [197]. Socioeconomic and political aspects influence user understanding of benefits [189,192] and profitability [190].

The adoption of V2G by individual users is affected by distrust [191], high inconvenient costs [186], and uncertainty about the economic benefits [189,197]. All these challenges hinder the successful implementation of V2G systems for individual electric vehicles [193].

4.2.4. Challenges in Environmental Impact Assessment

V2G systems help reduce the environmental impact of electric vehicle systems [186,189, 191,193,194,197]. However, studies like [186,189,191,193,194,197] suggest that accurately assessing V2G's environmental impact requires a comprehensive approach, considering not only the vehicle's direct emissions but also grid management, battery durability and lifespan, charging patterns, vehicle battery management, and the accuracy of simulation models. Similarly, ref. [195] highlight that one of the major challenges in assessing V2G's environmental impact is the considerable variation in GHG emissions from electricity among different regions due to the uncertainty present in each, affecting the accuracy of the results [191,195].

This emphasizes the importance of further research and technology development to fully understand and quantify V2G's environmental impact, indicating complexities and considerations that need to be addressed when assessing the environmental implications of this technology [188]. Additionally, ref. [190] emphasize the importance of the life cycle assessment (LCA) to analyze the environmental impact of V2G technology implementation, as it allows for the assessment of environmental impacts before and after technology implementation.

Ultimately, the primary challenge remains in the scarcity of essential information necessary to calculate the environmental impact of V2G.

5. Conclusions

In this study, a comprehensive review of the current state, benefits, and challenges of V2G is provided. Firstly, a detailed description of V2G and its main benefits is provided. Then, the role of communications is introduced as well as an in-depth revision of the main technologies and standards and their role within the V2G framework. In this sense, the importance of reliable and efficient communication protocols for enabling seamless interaction between EVs and the grid is highlighted. Finally, the main challenges of V2G are described, following different technological, regulatory, and sustainable criteria.

V2G is a very promising technique that can contribute to boosting the introduction of EVs within the electricity system, beyond classical unileteral charging, and serves as mobile DER when required, helping to smooth demand curves and small power shortages. In addition, it can contribute to the achievement of the environmental goals established in the European Green Deal, primarily contributing to sustainable mobility and climate action. However, V2G faces several challenges, such as the degradation of batteries, the grid integration, the power electronics as well as the non-intentional emissions and their effect over other assets and related EMI issues. In this sense, this work proposes some useful insights to tackle them and highlight the key role of strong, reliable, and efficient communications as well as advanced control systems. As an overall conclusion, the future success of V2G requires interdisciplinary collaboration and stakeholder engagement in overcoming those challenges, and there are opportunities for addressing some of them through communication as well as regulatory and environmental solutions. In this sense, this study provides useful information for regulators, utilities, manufacturers, and researchers in their respective work and initiatives within V2G.

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References

1. Letendre, S.; Denholm, P.; Lilienthal, P. Electric & hybrid cars: New load, or new resource. *Public Util. Fortn.* **2006**, *144*, 28–37.
2. Precedence Research. *Electric Vehicle Charging Station Market Size $344.61 Bn by 2032*; Electric Vehicle Charging Station Market; Precedence Research: Ottawa, ON, Canada, 2023.
3. Conzade, J.; Nägele, F.; Ramanathan, S.; Schaufuss, P. *Europes-EV-Opportunity-and-the-Charging-Infrastructure-Needed-to-Meet-It-VF*; McKinsey & Company: Chicago, IL, USA, 2022.
4. Habib, S.; Kamran, M.; Rashid, U. Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks–a review. *J. Power Sources* **2015**, *277*, 205–214. [CrossRef]
5. IEC. *The New Age of Mobility*; IEC: Geneva, Switzerland, 2023.
6. Precedence Research. *Vehicle-to-Grid Technology Market Size, Share, Report 2022–2027*; Vehicle-to-Grid Technology Market; Precedence Research: Ottawa, ON, Canada, 2020.
7. Kempton, W.; Letendre, S.E. Electric vehicles as a new power source for electric utilities. *Transp. Res. Part D Transp. Environ.* **1997**, *2*, 157–175. [CrossRef]
8. Eisler, M. False Starts—The Story of Vehicle-to-Grid Power—IEEE Spectrum. Available online: https://spectrum.ieee.org/v2g (accessed on 11 March 2023).
9. Paul, K.; Lonneke, D.; EV Related Protocol Study. Research Gate. 2021. Available online: https://www.researchgate.net/publication/317265159_EV_Related_Protocol_Study?enrichId=rgreq-3d1c7a942f100139c989a57c85a7f6b5-XXX&enrichSource=Y292ZXJQYWdlOzMxNzI2NTE1OTtBUzo5ODEzODE4MzY0NjAwMzRAMTYxMDk5MTA3MTI0MA==&el=1_x_3&_esc=publicationCoverPdf (accessed on 10 December 2023).
10. Ravi, S.S.; Aziz, M. Utilization of Electric Vehicles for Vehicle-to-Grid Services: Progress and Perspectives. *Energies* **2022**, *15*, 589. [CrossRef]
11. Jones, L.; Lucas-Healey, K.; Sturmberg, B.; Temby, H.; Islam, M. *The A–Z of V2G a Comprehensive Analysis of Vehicle-to-Grid Technology Worldwide*; Australian Renewable Energy Agency: Canberra, Australia, 2021.
12. Briones, A.; Francfort, J.; Heitmann, P.; Schey, M.; Schey, S.; Smart, J. *Vehicle-to-Grid (V2G) Power Flow Regulations and Building Codes Review by the AVTA*; INL: Idaho Falls, ID, USA, 2012. Available online: http://www.inl.gov (accessed on 11 November 2023).
13. Van Mierlo, J.; Berecibar, M.; El Baghdadi, M.; De Cauwer, C.; Messagie, M.; Coosemans, T.; Jacobs, V.A.; Hegazy, O. Beyond the state of the art of electric vehicles: A fact-based paper of the current and prospective electric vehicle technologies. *World Electr. Veh. J.* **2021**, *12*, 20. [CrossRef]
14. Skouras, T.A.; Gkonis, P.K.; Ilias, C.N.; Trakadas, P.T.; Tsampasis, E.G.; Zahariadis, T.V. Electrical Vehicles: Current State of the Art, Future Challenges, and Perspectives. *Clean Technol.* **2019**, *2*, 1–16. [CrossRef]
15. Jaman, S.; Chakraborty, S.; Tran, D.D.; Geury, T.; El Baghdadi, M.; Hegazy, O. Review on Integrated On-Board Charger-Traction Systems: V2G Topologies, Control Approaches, Standards and Power Density State-of-the-Art for Electric Vehicle. *Energies* **2022**, *15*, 5376. [CrossRef]
16. Kisacikoglu, M.C.; Bedir, A.; Ozpineci, B.; Tolbert, L.M. PHEV-EV Charger Technology Assessment with an Emphasis on V2G Operation. 2012. Available online: http://www.osti.gov/contact.html (accessed on 10 December 2023).
17. Sovacool, B.K.; Kester, J.; Noel, L.; Zarazua de Rubens, G. Actors, business models, and innovation activity systems for vehicle-to-grid (V2G) technology: A comprehensive review. *Renew. Sustain. Energy Rev.* **2020**, *131*, 109963. [CrossRef]
18. Hannan, M.A.; Mollik, M.S.; Al-Shetwi, A.Q.; Rahman, S.A.; Mansor, M.; Begum, R.A.; Muttaqi, K.M.; Dong, Z.Y. Vehicle to grid connected technologies and charging strategies: Operation, control, issues and recommendations. *J. Clean. Prod.* **2022**, *339*, 130587. [CrossRef]
19. García-Martínez, E.; Muñoz-Cruzado-alba, J.; Sanz-Osorio, J.F.; Perié, J.M. Design and experimental validation of power electric vehicle emulator for testing electric vehicle supply equipment (EVSE) with vehicle-to-grid (V2G) capability. *Appl. Sci.* **2021**, *11*, 11496. [CrossRef]

20. Jaman, S.; Verbrugge, B.; Garcia, O.H.; Abdel-Monem, M.; Oliver, B.; Geury, T.; Hegazy, O. Development and Validation of V2G Technology for Electric Vehicle Chargers Using Combo CCS Type 2 Connector Standards. *Energies* **2022**, *15*, 7364. [CrossRef]
21. Saltanovs, R.; Krivchenkov, A.; Krainyukov, A. Analysis of effective wireless communications for V2G applications and mobile objects. In Proceedings of the 2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 12–13 October 2017; pp. 1–5.
22. Mahmud, K.; Town, G.E.; Morsalin, S.; Hossain, M.J. Integration of electric vehicles and management in the internet of energy. *Renew. Sustain. Energy Rev.* **2018**, *82*, 4179–4203. [CrossRef]
23. Du, Y.; Lukic, S.; Jacobson, B.; Huang, A. Review of high power isolated bi-directional DC-DC converters for PHEV/EV DC charging infrastructure. In Proceedings of the 2011 IEEE Energy Conversion Congress and Exposition, Phoenix, AZ, USA, 17–22 September 2011; pp. 553–560.
24. Wei, Z.; Li, Y.; Zhang, Y.; Cai, L. Intelligent parking garage EV charging scheduling considering battery charging characteristic. *IEEE Trans. Ind. Electron.* **2017**, *65*, 2806–2816. [CrossRef]
25. Kardolus, M.; van Beusekom, E. On-Board V2G vs. Off-Board V2G (AC vs. DC)—News—Pr-Electronics.nl. 2023. Available online: http://www.pr-electronics.nl/en/news/88/on-board-v2g-versus-off-board-v2g-ac-versus-dc/ (accessed on 10 September 2023).
26. Steitz, C. *Nissan Leaf Gets Approval for Vehicle-to-Grid Use in Germany*; Reuters: London, UK, 2018; Available online: https://www.reuters.com/article/us-autos-electricity-germany/nissan-leaf-approved-for-vehicle-to-grid-use-in-germany-idUSKCN1MX1AH/ (accessed on 23 October 2018).
27. De Zon, D. *Car Sharing System Powered by Sun Funtions as Neighborhood Battery in the Netherlands and Belgium*; DeeldeZon: Brussels, Belgium, 2022; Available online: https://www.deeldezon.eu/english/ (accessed on 23 November 2023).
28. Mafazy, M. Vehicle-to-Grid (V2G) Standards for Electric Vehicles. 2022. Available online: www.irecusa.org (accessed on 10 September 2023).
29. International Renewable Energy Agency. *Innovation Outlook: Smart Charging for Electric Vehicles*; International Renewable Energy Agency: Masdar City, United Arab Emirates, 2019.
30. International Renewable Energy Agency. *Business Models: Aggregators—Innovation Landscape*; International Renewable Energy Agency: Masdar City, United Arab Emirates, 2019.
31. Izadkhast, S.; Garcia-Gonzalez, P.; Frias, P. An aggregate model of plug-in electric vehicles for primary frequency control. *IEEE Trans. Power Syst.* **2014**, *30*, 1475–1482. [CrossRef]
32. Hashemi, S.; Arias, N.B.; Andersen, P.B.; Christensen, B.; Træholt, C. Frequency regulation provision using cross-brand bidirectional V2G-enabled electric vehicles. In Proceedings of the 2018 IEEE International Conference on Smart Energy Grid Engineering (SEGE), Oshawa, ON, Canada, 12–15 August 2018; pp. 249–254.
33. Kempton, W.; Udo, V.; Huber, K.; Komara, K.; Letendre, S.; Baker, S.; Brunner, D.; Pearre, N. A test of vehicle-to-grid (V2G) for energy storage and frequency regulation in the PJM system. *Results Ind.-Univ. Res. Partnersh.* **2008**, *32*, 1–32.
34. Li, Y.; Li, L.; Peng, C.; Zou, J. An MPC based optimized control approach for EV-based voltage regulation in distribution grid. *Electr. Power Syst. Res.* **2019**, *172*, 152–160. [CrossRef]
35. Brinkel NB, G.; Gerritsma, M.K.; AlSkaif, T.A.; Lampropoulos, I.; van Voorden, A.M.; Fidder, H.A.; van Sark, W. Impact of rapid PV fluctuations on power quality in the low-voltage grid and mitigation strategies using electric vehicles. *Int. J. Electr. Power Energy Syst.* **2020**, *118*, 105741. [CrossRef]
36. Noel, L.; Zarazua, G.; Rubens, D.E.; Kester, J.; Sovacool, B.K. Vehicle-to-Grid a Sociotechnical Transition Beyond Electric Mobility. 2019. Available online: http://www.palgrave.com/gp/series/14966 (accessed on 8 October 2023).
37. Octopus Electric Vehicles. *Powerloop–V2G*; Octopus Electric Vehicles: London, UK, 2022; Available online: https://octopusev.com/powerloop (accessed on 12 October 2023).
38. Enel, X. JuicePass App for Charging Electric Cars. 2020. Available online: https://www.enelx.com/ro/en/juicepass (accessed on 11 September 2023).
39. Reposit Power. Guaranteed no Electricity Bills for 7 Years—Reposit Power. 2023. Available online: https://repositpower.com/ (accessed on 10 December 2023).
40. Dudek, E.; Platt, K.; Storer, N.; Barnfather, P.; Duke, R. *Electric Nation Customer Trial Final Report Report*; Western Power Distribution: Bristol, UK, 2019.
41. Ramirez Diaz, A.; Ramos-Real, F.J.; Marrero, G.A.; Perez, Y. Impact of electric vehicles as distributed energy storage in isolated systems: The case of Tenerife. *Sustainability* **2015**, *7*, 15152–15178. [CrossRef]
42. Taibi, E.; Fernández, C. The impact of electric vehicles deployment on production cost in a Caribbean Island Country. In Proceedings of the Mobility Integration Symposium, Berlin, Germany, 23 October 2017; Volume 23.
43. Emadi, A. Transportation 2.0. *IEEE Power Energy Mag.* **2011**, *9*, 18–29. [CrossRef]
44. Sovacool, B.K.; Hirsh, R.F. Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition. *Energy Policy* **2009**, *37*, 1095–1103. [CrossRef]
45. European Commission. *A European Green Deal. Striving to Be the First Climate-Neutral Continent*; European Commission: Luxembourg, 2021.
46. EC. *Sustainable & Smart Mobility Strategy: Putting European Transport on Track for the Future*; European Commission: Luxembourg, 2020.

47. MaKerracher, C.; O'Donovan, A.; Soulopoulos, N.; Grant, A.; Mi, S.; Doherty, D.; Fisher, R.; Cantor, C.; Lyu, J.; Ampofo, K.; et al. *Electric Vehicle Outlook 2022*; BloombergNEF: New York, NY, USA, 2022; Available online: https://about.bnef.com/electric-vehicle-outlook/ (accessed on 10 November 2023).
48. Zhao, E.; May, E.; Walker, P.D.; Surawski, N.C. Emissions life cycle assessment of charging infrastructures for electric buses. *Sustain. Energy Technol. Assess.* **2021**, *48*, 101605. [CrossRef]
49. Kabus, M.; Nolting, L.; Mortimer, B.J.; Koj, J.C.; Kuckshinrichs, W.; De Doncker, R.W.; Praktiknjo, A. Environmental impacts of charging concepts for battery electric vehicles: A comparison of on-board and off-board charging systems based on a life cycle assessment. *Energies* **2020**, *13*, 6508. [CrossRef]
50. Zhang, Z.; Sun, X.; Ding, N.; Yang, J. Life cycle environmental assessment of charging infrastructure for electric vehicles in China. *J. Clean. Prod.* **2019**, *227*, 932–941. [CrossRef]
51. Zhang, Z.; Messagie, M.; Hegazy, O.; Van Mierlo, J. The Environmental Performance of Different Power Rate's Charging Infrastructure for Electric Vehicles, a Life Cycle Perspective. In Proceedings of the 2017 IEEE Vehicle Power and Propulsion Conference, VPPC 2017, Belfort, France, 11–14 October 2017. [CrossRef]
52. Lohse, J. What Are OCPP, IEC 63110 & ISO 15118 and How Do They Relate to V2G. Available online: https://smartcharging-electricvehicles.medium.com/what-are-ocpp-iec-63110-iso-15118-and-how-do-they-relate-to-v2g-de928153f49 (accessed on 14 January 2022).
53. ElGhanam, E.; Hassan, M.; Osman, A.; Ahmed, I. Review of communication technologies for electric vehicle charging management and coordination. *World Electr. Veh. J.* **2021**, *12*, 92. [CrossRef]
54. Department of Energy. *Communications Requirements for of Smart Grid Technologies*; Department of Energy: New York, NY, USA, 2010.
55. Singh, P.K.; Singh, R.; Nandi, S.K.; Ghafoor, K.Z.; Nandi, S. Seamless V2I communication in hetnet: State-of-the-art and future research directions. In *Connected Vehicles in the Internet of Things: Concepts, Technologies and Frameworks for the IoV*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 37–83.
56. Vector. *Smart Charging Know-How*; Vector: San Mateo, CA, USA, 2022; Available online: https://www.vector.com/int/en/know-how/smart-charging/# (accessed on 12 September 2023).
57. *IEC 63110*; Standardising the Management of EV (Dis-)Charging Infrastructures. IEC: Geneva, Switzerland, 2017. Available online: https://www.switch-ev.com/blog/iec-63110-standardizing-management-of-ev-charging-infrastructures (accessed on 27 April 2017).
58. Uribe-Pérez, N.; Hernández, L.; la Vega, D.; Angulo, I. State of the art and trends review of smart metering in electricity grids. *Appl. Sci.* **2016**, *6*, 68. [CrossRef]
59. Sarp, M.; Altin, N. Review on vehicle-to-grid systems: The most recent trends and smart grid interaction technologies. *Gazi Univ. J. Sci.* **2020**, *33*, 394–411. [CrossRef]
60. Klaina, H.; Guembe, I.P.; Lopez-Iturri, P.; Astrain, J.J.; Azpilicueta, L.; Aghzout, O.; Alejos, A.V.; Falcone, F. Aggregator to Electric Vehicle LoRaWAN Based Communication Analysis in Vehicle-to-Grid Systems in Smart Cities. *IEEE Access* **2020**, *8*, 124688–124701. [CrossRef]
61. Li, Y.; Yu, G.; Liu, J.; Deng, F. Design of V2G auxiliary service system based on 5G technology. In Proceedings of the 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China, 26–28 November 2017; pp. 1–6.
62. Li, J.; Dang, S.; Wen, M.; Li, Q.; Chen, Y.; Huang, Y.; Shang, W. Index Modulation Multiple Access for 6G Communications: Principles, Applications, and Challenges. *IEEE Netw.* **2023**, *37*, 52–60. [CrossRef]
63. Wen, M.; Zheng, B.; Kim, K.J.; Di Renzo, M.; Tsiftsis, T.A.; Chen, K.-C.; Al-Dhahir, N. A Survey on Spatial Modulation in Emerging Wireless Systems: Research Progresses and Applications. *IEEE J. Sel. Areas Commun.* **2019**, *37*, 1949–1972. [CrossRef]
64. *IEC 62196-1-2022*; Plugs, Socket-Outlets, Vehicle Connectors and Vehicle Inlets—Conductive Charging of Electric Vehicles—Part 1: General Requirements. IEC: Geneva, Switzerland, 2022. Available online: https://webstore.iec.ch/publication/59922 (accessed on 13 January 2024).
65. CHAdeMO. Protocol Development—CHAdeMO. 2022. Available online: https://www.chademo.com/technology/protocol-development (accessed on 1 November 2023).
66. *IEEE SA—IEEE 1547-2018*; IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. IEEE: New York, NY, USA, 2018. Available online: https://standards.ieee.org/ieee/1547/5915/ (accessed on 12 January 2024).
67. *IEEE SA—IEEE 1547.1-2020*; IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces. IEEE: New York, NY, USA, 2020. Available online: https://standards.ieee.org/ieee/1547.1/6039/ (accessed on 2 December 2023).
68. *IEEE SA—IEEE 1547.9-2022*; IEEE Guide for Using IEEE Std 1547 for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems. IEEE: New York, NY, USA, 2022. Available online: https://standards.ieee.org/ieee/1547.9/10875/ (accessed on 18 January 2024).
69. *IEC TR 61850-90-8-2016*; Communication Networks and Systems for Power Utility Automation—Part 90-8: Object Model for E-Mobility. IEC: Geneva, Switzerland, 2016. Available online: https://webstore.iec.ch/publication/24475 (accessed on 16 January 2024).
70. *IEC 61851-1-2017*; Electric Vehicle Conductive Charging System—Part 1: General Requirements. IEC: Geneva, Switzerland, 2017. Available online: https://webstore.iec.ch/publication/33644 (accessed on 3 December 2023).

71. *IEC 63110-1-2022*; Protocol for Management of Electric Vehicles Charging and Discharging Infrastructures—Part 1: Basic Definitions, Use Cases and Architectures. IEC: Geneva, Switzerland, 2022. Available online: https://webstore.iec.ch/publication/60000 (accessed on 13 January 2024).
72. *SAE J3072*; Interconnection Requirements for Onboard, Grid Support Inverter Systems. SAE: New York, NY, USA, 2021. Available online: https://www.sae.org/standards/content/j3072_202103/ (accessed on 13 January 2024).
73. *IEEE 2030.5-2023*; IEEE Approved Draft Standard for Smart Energy Profile Application Protocol. IEEE: New York, NY, USA, 2023. Available online: https://standards.ieee.org/ieee/2030.5/11216/ (accessed on 10 January 2024).
74. *SAE J2931-1*; Digital Communications for Plug-in Electric Vehicles. SAE: New York, NY, USA, 2023. Available online: https://global.ihs.com/doc_detail.cfm?document_name=SAE%20J2931/1&item_s_key=00581338 (accessed on 12 January 2024).
75. *SAE J2847*; Communication Between Plug-in Vehicles and Off-Board DC Chargers. SAE: New York, NY, USA, 2023. Available online: https://www.sae.org/standards/content/j2847/2_202309/ (accessed on 12 January 2024).
76. *SAE J2836_201807TM*; Instructions for Using Plug-In Electric Vehicle (PEV) Communications, Interoperability and Security Documents. SAE: New York, NY, USA, 2018. Available online: https://www.sae.org/standards/content/j2836_201807/ (accessed on 12 January 2024).
77. *SAE J2953/1*; Plug-In Electric Vehicle (PEV) Interoperability with Electric Vehicle Supply Equipment (EVSE). SAE: New York, NY, USA, 2023. Available online: https://www.sae.org/standards/content/j2953/1_202305/ (accessed on 12 January 2024).
78. *SAE J2953*; Test Procedures for the Plug-In Electric Vehicle (PEV) Interoperability with Electric Vehicle Supply Equipment (EVSE). SAE: New York, NY, USA, 2023. Available online: https://www.sae.org/standards/content/j2953/2_202305/ (accessed on 12 January 2024).
79. Open Charge Alliance. Open Smart Charging Protocol. Available online: https://openchargealliance.org/download-oscp/ (accessed on 13 January 2024).
80. Open ADR Alliance. OpenADR 2.0 and 3.0 Specification. Available online: https://www.openadr.org/specification (accessed on 13 January 2024).
81. *ISO 15118-20-2022*; Road Vehicles—Vehicle to Grid Communication Interface—Part 20—2nd Generation Network Layer and Appli. ISO: Geneva, Switzerland, 2022. Available online: https://www.iso.org/standard/77845.html (accessed on 13 January 2024).
82. *ISO/DIS 15118-21*; Road Vehicles—Vehicle to Grid Communication Interface—Part 21: Common 2nd Generation Network Layer and Application Layer Requirements Conformance Test Plan. 2024. Available online: https://www.iso.org/standard/84170.html (accessed on 13 January 2024).
83. *IEC 61850-7-420-2021*; IEC Webstore—LVDC. IEC: Geneva, Switzerland, 2024. Available online: https://webstore.iec.ch/publication/34384 (accessed on 13 January 2024).
84. *IEC 61851-24-2014*; Electric Vehicle Conductive Charging System—Part 24: Digital Communication between a d.c. EV Charging Station and an Electric Vehicle for Control of d.c. Charging. IEC: Geneva, Switzerland, 2023. Available online: https://webstore.iec.ch/publication/6033 (accessed on 13 January 2024).
85. Kramer, W.; Chakraborty, S.; Kroposki, B.; Hoke, A.; Martin, G.; Markel, T. Grid Interconnection and Performance Testing Procedures for Vehicle-To-Grid (V2G) Power Electronics: Preprint. 2012. Available online: http://www.osti.gov/bridge (accessed on 8 December 2023).
86. Asgeirsson, H. *Electric Vehicle V2G AC Standards SAE, IEEE, UL*; Pacific Northwest National Laboratory: Richland, WA, USA, 2021.
87. SAE. SAE Standards for Mobility Knowledge and Solutions. 2023. Available online: https://www.sae.org/standards (accessed on 12 January 2024).
88. North American Clean Energy. Nuvve Vehicle-to-Grid Tech Receives IEEE Certification for Utility-Scale Communications. 2022. Available online: https://www.nacleanenergy.com/energy-efficiency/nuvve-vehicle-to-grid-tech-receives-ieee-certification-for-utility-scale-communications (accessed on 12 October 2023).
89. OCA Alliance. *Protocols*; Open Charge Alliance: Arnhem, The Netherlands, 2023; Available online: https://openchargealliance.org/protocols/ (accessed on 12 October 2023).
90. Open ADR. About OpenADR. 2023. Available online: https://www.openadr.org/about-us (accessed on 12 October 2023).
91. Open ADR Alliance. DER_V2G. *Purpose of Vehicle-to-Grid (V2G) Integration.* 2021. Available online: https://www.openadr.org/openadr-v2g-and-der (accessed on 12 October 2023).
92. Li, A.G.; West, A.C.; Preindl, M. Towards unified machine learning characterization of lithium-ion battery degradation across multiple levels: A critical review. *Appl. Energy* **2022**, *316*, 119030. [CrossRef]
93. Jokar, A.; Rajabloo, B.; Désilets, M.; Lacroix, M. Review of simplified Pseudo-two-Dimensional models of lithium-ion batteries. *J. Power Sources* **2016**, *327*, 44–55. [CrossRef]
94. Petit, M.; Calas, E.; Bernard, J. A simplified electrochemical model for modelling Li-ion batteries comprising blend and bidispersed electrodes for high power applications. *J. Power Sources* **2020**, *479*, 228766. [CrossRef]
95. Peng, J.; Meng, J.; Wu, J.; Deng, Z.; Lin, M.; Mao, S.; Stroe, D.I. A comprehensive overview and comparison of parameter benchmark methods for lithium-ion battery application. *J. Energy Storage* **2023**, *71*, 108197. [CrossRef]
96. Saldaña, G.; Martín JI, S.; Zamora, I.; Asensio, F.J.; Oñederra, O. Analysis of the current electric battery models for electric vehicle simulation. *Energies* **2019**, *12*, 2750. [CrossRef]
97. Cheng, Y.S. Identification of parameters for equivalent circuit model of Li-ion battery cell with population based optimization algorithms. *Ain Shams Eng. J.* **2024**, *15*, 102481. [CrossRef]

98. Prasad, G.K.; Rahn, C.D. Model based identification of aging parameters in lithium ion batteries. *J. Power Sources* **2013**, *232*, 79–85. [CrossRef]
99. Andre, D.; Appel, C.; Soczka-Guth, T.; Sauer, D.U. Advanced mathematical methods of SOC and SOH estimation for lithium-ion batteries. *J. Power Sources* **2013**, *224*, 20–27. [CrossRef]
100. Zhang, C.; Allafi, W.; Dinh, Q.; Ascencio, P.; Marco, J. Online estimation of battery equivalent circuit model parameters and state of charge using decoupled least squares technique. *Energy* **2018**, *142*, 678–688. [CrossRef]
101. Saldana, G.; Martin JI, S.; Zamora, I.; Asensio, F.J.; Onederra, O.; Gonzalez, M. Empirical Electrical and Degradation Model for Electric Vehicle Batteries. *IEEE Access* **2020**, *8*, 155576–155589. [CrossRef]
102. Rauf, H.; Khalid, M.; Arshad, N. A novel smart feature selection strategy of lithium-ion battery degradation modelling for electric vehicles based on modern machine learning algorithms. *J. Energy Storage* **2023**, *68*, 107577. [CrossRef]
103. Zhang, Y.; Zhao, M. Cloud-based in-situ battery life prediction and classification using machine learning. *Energy Storage Mater.* **2023**, *57*, 346–359. [CrossRef]
104. Zhao, J.; Feng, X.; Pang, Q.; Wang, J.; Lian, Y.; Ouyang, M.; Burke, A.F. Battery prognostics and health management from a machine learning perspective. *J. Power Sources* **2023**, *581*, 233474. [CrossRef]
105. Li, W.; Chen, J.; Quade, K.; Luder, D.; Gong, J.; Sauer, D.U. Battery degradation diagnosis with field data, impedance-based modeling and artificial intelligence. *Energy Storage Mater.* **2022**, *53*, 391–403. [CrossRef]
106. Zhang, M.; Yang, D.; Du, J.; Sun, H.; Li, L.; Wang, L.; Wang, K. A Review of SOH Prediction of Li-Ion Batteries Based on Data-Driven Algorithms. *Energies* **2023**, *16*, 3167. [CrossRef]
107. Xiong, R.; Tian, J.; Shen, W.; Lu, J.; Sun, F. Semi-supervised estimation of capacity degradation for lithium ion batteries with electrochemical impedance spectroscopy. *J. Energy Chem.* **2023**, *76*, 404–413. [CrossRef]
108. Wang, Q.; Ye, M.; Cai, X.; Sauer, D.U.; Li, W. Transferable data-driven capacity estimation for lithium-ion batteries with deep learning: A case study from laboratory to field applications. *Appl. Energy* **2023**, *350*, 121747. [CrossRef]
109. Tian, J.; Chen, C.; Shen, W.; Sun, F.; Xiong, R. Deep Learning Framework for Lithium-ion Battery State of Charge Estimation: Recent Advances and Future Perspectives. *Energy Storage Mater.* **2023**, *61*, 102883. [CrossRef]
110. Deng, Z.; Xu, L.; Liu, H.; Hu, X.; Duan, Z.; Xu, Y. Prognostics of battery capacity based on charging data and data-driven methods for on-road vehicles. *Appl. Energy* **2023**, *339*, 120954. [CrossRef]
111. Zou, B.; Xiong, M.; Wang, H.; Ding, W.; Jiang, P.; Hua, W.; Zhang, Y.; Zhang, L.; Wang, W.; Tan, R. A Deep Learning Approach for State-of-Health Estimation of Lithium-Ion Batteries Based on a Multi-Feature and Attention Mechanism Collaboration. *Batteries* **2023**, *9*, 329. [CrossRef]
112. Alaee, P.; Bems, J.; Anvari-Moghaddam, A. A Review of the Latest Trends in Technical and Economic Aspects of EV Charging Management. *Energies* **2023**, *16*, 3669. [CrossRef]
113. Gonzalez Venegas, F.; Petit, M.; Perez, Y. Active integration of electric vehicles into distribution grids: Barriers and frameworks for flexibility services. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111060. [CrossRef]
114. Ur Rehman, U. A robust vehicle to grid aggregation framework for electric vehicles charging cost minimization and for smart grid regulation. *Int. J. Electr. Power Energy Syst.* **2022**, *140*, 108090. [CrossRef]
115. Sharma, S.; Jain, P. Risk-averse integrated DR and dynamic V2G scheduling of parking lot operator for enhanced market efficiency. *Energy* **2023**, *275*, 127428. [CrossRef]
116. Abdullah-Al-Nahid, S.; Khan, T.A.; Taseen, M.A.; Jamal, T.; Aziz, T. A novel consumer-friendly electric vehicle charging scheme with vehicle to grid provision supported by genetic algorithm based optimization. *J. Energy Storage* **2022**, *50*, 104655. [CrossRef]
117. Zhang, X.; Wang, Z.; Lu, Z. Multi-objective load dispatch for microgrid with electric vehicles using modified gravitational search and particle swarm optimization algorithm. *Appl. Energy* **2022**, *306*, 118018. [CrossRef]
118. Paudel, A.; Hussain, S.A.; Sadiq, R.; Zareipour, H.; Hewage, K. Decentralized cooperative approach for electric vehicle charging. *J. Clean. Prod.* **2022**, *364*, 132590. [CrossRef]
119. Alsabbagh, A.; Yin, H.; Ma, C. Distributed Electric Vehicles Charging Management with Social Contribution Concept. *IEEE Trans. Ind. Inform.* **2020**, *16*, 3483–3492. [CrossRef]
120. Gnann, T.; Klingler, A.L.; Kühnbach, M. The load shift potential of plug-in electric vehicles with different amounts of charging infrastructure. *J. Power Sources* **2018**, *390*, 20–29. [CrossRef]
121. González-Garrido, A.; Thingvad, A.; Gaztañaga, H.; Marinelli, M. Full-scale electric vehicles penetration in the Danish Island of Bornholm—Optimal scheduling and battery degradation under driving constraints. *J. Energy Storage* **2019**, *23*, 381–391. [CrossRef]
122. Amin, A.; Tareen WU, K.; Usman, M.; Ali, H.; Bari, I.; Horan, B.; Mekhilef, S.; Asif, M.; Ahmed, S.; Mahmood, A. A review of optimal charging strategy for electric vehicles under dynamic pricing schemes in the distribution charging network. *Sustainability* **2020**, *12*, 10160. [CrossRef]
123. Chandra Mouli, G.R.; Kefayati, M.; Baldick, R.; Bauer, P. Integrated PV charging of EV fleet based on energy prices, V2G, and offer of reserves. *IEEE Trans. Smart Grid* **2019**, *10*, 1313–1325. [CrossRef]
124. Rasheed, M.B.; Awais, M.; Alquthami, T.; Khan, I. An Optimal Scheduling and Distributed Pricing Mechanism for Multi-Region Electric Vehicle Charging in Smart Grid. *IEEE Access* **2020**, *8*, 40298–40312. [CrossRef]

125. Tepe, B.; Figgener, J.; Englberger, S.; Sauer, D.U.; Jossen, A.; Hesse, H. Optimal pool composition of commercial electric vehicles in V2G fleet operation of various electricity markets. *Appl. Energy* **2022**, *308*, 118351. [CrossRef]
126. Zheng, Y.; Shao, Z.; Lei, X.; Shi, Y.; Jian, L. The economic analysis of electric vehicle aggregators participating in energy and regulation markets considering battery degradation. *J. Energy Storage* **2022**, *45*, 103770. [CrossRef]
127. Meesenburg, W.; Thingvad, A.; Elmegaard, B.; Marinelli, M. Combined provision of primary frequency regulation from Vehicle-to-Grid (V2G) capable electric vehicles and community-scale heat pump. *Sustain. Energy Grids Netw.* **2020**, *23*, 100382. [CrossRef]
128. Luo, Q.; Zhou, Y.; Hou, W.; Peng, L. A hierarchical blockchain architecture based V2G market trading system. *Appl. Energy* **2022**, *307*, 118167. [CrossRef]
129. Hashemipour, N.; Crespo del Granado, P.; Aghaei, J. Dynamic allocation of peer-to-peer clusters in virtual local electricity markets: A marketplace for EV flexibility. *Energy* **2021**, *236*, 121428. [CrossRef]
130. Inala, K.P.; Sah, B.; Kumar, P.; Bose, S.K. Impact of V2G Communication on Grid Node Voltage at Charging Station in a Smart Grid Scenario. *IEEE Syst. J.* **2020**, *15*, 3749–3758. [CrossRef]
131. IEA. Grid Integration of Electric Vehicles—A Manual for Policy Makers. 2022. Available online: www.iea.org (accessed on 10 August 2023).
132. Yusuf, S.; Abubakar, A. A Comprehensive Review on Grid-forming Inverter: Potential and Future Trends. *Majlesi J. Electr. Eng.* **2023**, *17*, 1–27.
133. Mo, O.; D'Arco, S.; Suul, J.A. Evaluation of virtual synchronous machines with dynamic or quasi-stationary machine models. *IEEE Trans. Ind. Electron.* **2016**, *64*, 5952–5962. [CrossRef]
134. Ben Sassi, H.; Alaoui, C.; Errahimi, F.; Es-Sbai, N. Vehicle-to-grid technology and its suitability for the Moroccan national grid. *J. Energy Storage* **2021**, *33*, 102023. [CrossRef]
135. Wouters, H.; Martinez, W. Bidirectional On-Board Chargers for Electric Vehicles: State-of-the-Art and Future Trends. *IEEE Trans. Power Electron.* **2023**, *39*, 693–716. [CrossRef]
136. Li, H.; Han, J.; Yu, C.; Yin, Z.; Wang, Y.; Chen, M.; Jiang, F.; Zhang, Y. An Inertia Adjustment Control Strategy of Grid-Forming Electric Vehicle for V2G Application. In Proceedings of the 2022 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific), Haining, China, 28–31 October 2022; pp. 1–5.
137. Luh, M.; Blank, T. Design and experimental verification of advanced control strategies to provide ancillary services with a bidirectional Vehicle-to-Grid (V2G) inverter. In Proceedings of the 2023 25th European Conference on Power Electronics and Applications (EPE'23 ECCE Europe), Aalborg, Dänemark, 4–8 September 2023; pp. 1–9.
138. Rosas, D.; Zarate, A. Single-Phase Grid-Forming Strategy with Power Decoupling Implementation for Electrolytic-Capacitor-Free EV Smart Battery Charger. *Energies* **2023**, *16*, 894. [CrossRef]
139. Liu, D.; Zhong, Q.; Wang, Y.; Liu, G. Modeling and control of a V2G charging station based on synchronverter technology. *CSEE J. Power Energy Syst.* **2018**, *4*, 326–338. [CrossRef]
140. Narula, A. *Grid-Forming Wind Power Plants*; Chalmers Tekniska Hogskola: Göteborg, Sweden, 2023.
141. Dong, S.; Chen, Y.C. A method to directly compute synchronverter parameters for desired dynamic response. *IEEE Trans. Energy Convers.* **2017**, *33*, 814–825. [CrossRef]
142. Darmawardana, D.; David, J.; Perera, S.; Robinson, D.; Meyer, J.; Jayatunga, U. Analysis of high frequency (supraharmonics) emissions caused by electric vehicle charging. In Proceedings of the 2020 19th International Conference on Harmonics and Quality of Power (ICHQP), Dubai, United Arab Emirates, 6–7 July 2020; pp. 1–6.
143. Llano, A.; De La Vega, D.; Angulo, I.; Marron, L. Impact of channel disturbances on current narrowband power line communications and lessons to be learnt for the future technologies. *IEEE Access* **2019**, *7*, 83797–83811. [CrossRef]
144. Wasowski, M.; Habrych, M.; Sikorski, T.; Kostyła, P.; Jurczyk, M.; Gornicki, L.; Sokol, J.; Golemo, M. Sources of non-intentional Supraharmonics in LV network and its impact on OSGP PLC communication–experimental study. *IEEE Trans. Power Deliv.* **2022**, *37*, 5244–5254. [CrossRef]
145. Ronnberg, S.K.; Bollen MH, J.; Wahlberg, M. Interaction between narrowband power-line communication and end-user equipment. *IEEE Trans. Power Deliv.* **2011**, *26*, 2034–2039. [CrossRef]
146. Wang, L.; Qin, Z.; Slangen, T.; Bauer, P.; Van Wijk, T. Grid impact of electric vehicle fast charging stations: Trends, standards, issues and mitigation measures-an overview. *IEEE Open J. Power Electron.* **2021**, *2*, 56–74. [CrossRef]
147. Lodetti, S.; Bruna, J.; Sanz, J.F.; Melero, J.J. Characterization of the Emission of an Electric Bus Inductive Charging in the 2 kHz to 150 kHz Range. In Proceedings of the 2019 AEIT International Conference of Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE), Turin, Italy, 2–4 July 2019; pp. 1–6.
148. Streubel, T.; Kattmann, C.; Eisenmann, A.; Rudion, K. Characterization of Supraharmonic Emission from Three Different Electric Vehicle Charging Infrastructures in Time and Frequency Domain. *Energies* **2022**, *15*, 394. [CrossRef]
149. Chen, F.; Zhong, Q.; Zhang, H.; Zhu, M.; Müller, S.; Meyer, J.; Huang, W. Survey of Harmonic and Supraharmonic Emission of Fast Charging Stations for Electric Vehicles in China and Germany. In Proceedings of the CIRED 2021—The 26th International Conference and Exhibition on Electricity Distribution, Online, 20–23 September 2021.
150. Meyer, J.; Mueller, S.; Ungethuem, S.; Xiao, X.; Collin, A.; Djokic, S. Harmonic and supraharmonic emission of on-board electric vehicle chargers. In Proceedings of the 2016 IEEE Pes Transmission & Distribution Conference and Exposition-Latin America (Pes T&D-La), Dallas, TX, USA, 3–5 May 2016; pp. 1–7.

151. Slangen, T.; van Wijk, T.; Ćuk, V.; Cobben, S. The propagation and interaction of supraharmonics from electric vehicle chargers in a low-voltage grid. *Energies* **2020**, *13*, 3865. [CrossRef]
152. Schöttke, S.; Meyer, J.; Schegner, P.; Bachmann, S. Emission in the frequency range of 2 kHz to 150 kHz caused by electrical vehicle charging. In Proceedings of the 2014 International Symposium on Electromagnetic Compatibility, Gothenburg, Sweden, 1–4 September 2014; pp. 620–625.
153. González-Ramos, J.; Fernández, I.; Angulo, I.; Gallarreta, A.; De La Vega, D.; Arrinda, A. Empirical characterization of the conducted disturbances generated by the electric vehicles during the charging process. *CIRED Porto Workshop 2022 E-Mobil. Power Distrib. Syst.* **2022**, *2022*, 319–323.
154. Grasel, B.; Baptista, J.; Tragner, M. Supraharmonic and harmonic emissions of a bi-directional V2G electric vehicle charging station and their impact to the grid impedance. *Energies* **2022**, *15*, 2920. [CrossRef]
155. Grasel, B.; Baptista, J.; Tragner, M.; Leonhartsberger, K.; Keusch, G. Supraharmonic Emissions of a bidirectional electric vehicle charging station-a research methodology based on tests at reconstructed distribution grid. In Proceedings of the 2021 IEEE 4th International Conference on Power and Energy Applications (ICPEA), Busan, Republic of Korea, 9–11 October 2021; pp. 51–59.
156. Gallarreta, A.; Grasel, B.; González-Ramos, J.; Fernández, I.; Angulo, I.; Arrinda, A.; De La Vega, D.; Baptista, J.; Tragner, M. On the Feasibility of the Light-QP Method for the Assessment of V2G Supraharmonic Disturbances. In Proceedings of the 2023 International Conference on Smart Energy Systems and Technologies (SEST), Muğla, Turkey, 4–6 September 2023; pp. 1–6.
157. Grasel, B.; Reis MJ, C.S.; Baptista, J.; Tragner, M. Comparison of Supraharmonic emission measurement methods using real signals of a V2G charging station and a PV power plant. In Proceedings of the 2022 International Conference on Smart Energy Systems and Technologies (SEST), Eindhoven, The Netherlands, 5–7 September 2022; pp. 1–6.
158. González-Ramos, J.; Gallarreta, A.; Fernández, I.; Angulo, I.; de la Vega, D.; Arrinda, A. Emissions Generated by Electric Vehicles in the 9–500 kHz Band: Characterization, Propagation, and Interaction. *Electr. Power Syst. Res.* **2024**, *231*, 110289. [CrossRef]
159. González-Ramos, J.; Gallarreta, A.; Fernández, I.; Angulo, I.; de la Vega, D.; Arrinda, A. Comparison of Conducted Emissions Due to Electric Vehicle Charging Processes under Isolated and On-Line Conditions in the 9–500 kHz Frequency Range. *Sustain. Energy Grids Netw.* **2024**, *38*, 101333. [CrossRef]
160. Novitskiy, A.; Schlegel, S.; Westermann, D. Analysis of supraharmonic propagation in a MV electrical network. In Proceedings of the 2018 19th International Scientific Conference on Electric Power Engineering (EPE), Brno, Czech Republic, 16–18 May 2018; pp. 1–6.
161. Novitskiy, A.; Schlegel, S.; Westermann, D. Measurements and analysis of supraharmonic influences in a MV/LV network containing renewable energy sources. In Proceedings of the 2019 Electric Power Quality and Supply Reliability Conference (PQ) & 2019 Symposium on Electrical Engineering and Mechatronics (SEEM), Kärdla, Estonia, 12–15 June 2019; pp. 1–6.
162. Espin-Delgado, Á.; Busatto, T.; Ravindran, V.; Rönnberg, S.K.; Meyer, J. Evaluation of supraharmonic propagation in LV networks based on the impedance changes created by household devices. In Proceedings of the 2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), Hague, The Netherlands, 26–28 October 2020; pp. 754–758.
163. Rönnberg, S.; Bollen, M.; Larsson, A.; Lundmark, M. An overview of the origin and propagation of Supraharmonics (2–150 kHz). In Proceedings of the Nordic Conference on Electricity Distribution System Management and Development, Stockholm, Sweden, 8–9 September 2014.
164. González-Ramos, J.; Angulo, I.; Fernández, I.; Gallarreta, A.; Arrinda, A.; de la Vega, D. Influence of Electric Vehicle Charging on the Grid Access Impedance from 20 kHz to 500 kHz. In Proceedings of the 2023 International Conference on Smart Energy Systems and Technologies (SEST), Muğla, Turkey, 4–6 September 2023; pp. 1–6.
165. Erhan, V.; Slangen TM, H.; Ćuk, V.; Cobben JF, G.; Van Wijk, T. Measurement and Analysis of the Low Voltage Network Impedance in the Supraharmonic Range. In Proceedings of the 20th International Conference on Harmonics & Quality of Power (ICHQP), Naples, Italy, 29 May–1 June 2022; pp. 1–6.
166. Grasel, B.; Baptista, J.; Tragner, M.; Puthenkalam, S. The impact of a bi-directional V2G charging station to the frequency dependent grid impedance up to 500 KHZ. In Proceedings of the 27th International Conference on Electricity Distribution (CIRED 2023), Rome, Italy, 12–15 June 2023.
167. *IEC 61000-4-30-2015+AMD1-2021 CSV*; Electromagnetic Compatibility (EMC)—Part 4-30: Testing and Measurement Techniques—Power Quality Measurement Methods. IEC: Geneva, Switzerland, 2021. Available online: https://webstore.iec.ch/publication/68642 (accessed on 12 January 2024).
168. *CISPR 16-1-1-2019*; Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods—Part 1-1: Radio Disturbance and Immunity Measuring Apparatus—Measuring Apparatus. IEC: Geneva, Switzerland, 2019. Available online: https://webstore.iec.ch/publication/60774 (accessed on 12 January 2024).
169. *IEC 61000-4-7-2002*; IEC Webstore—Electromagnetic Compatibility, EMC, Smart City. IEC: Geneva, Switzerland, 2002. Available online: https://webstore.iec.ch/publication/4226 (accessed on 5 September 2023).
170. Lodetti, S.; Gallarreta, A.; Ritzmann, D.; Khokhlov, V.; Wright, P.; Meyer, J.; Fernández, I.; de la Vega, D. On the suitability of the CISPR 16 method for measuring conducted emissions in the 2–150 kHz range in low voltage grids. *Electr. Power Syst. Res.* **2023**, *216*, 109011. [CrossRef]

171. Hudlička, M.; Azpúrua, M.A.; Wojciechowski, M. Metrological Characterization of EMI Receivers. In Proceedings of the 2023 International Symposium on Electromagnetic Compatibility–EMC Europe, Kraków, Poland, 4–8 September 2023; pp. 1–6.
172. Ritzmann, D.; Lodetti, S.; de la Vega, D.; Khokhlov, V.; Gallarreta, A.; Wright, P.; Meyer, J.; Fernández, I.; Klingbeil, D. Comparison of measurement methods for 2–150-kHz conducted emissions in power networks. *IEEE Trans. Instrum. Meas.* **2020**, *70*, 1–10. [CrossRef]
173. Yigit, M.; Gungor, V.C.; Tuna, G.; Rangoussi, M.; Fadel, E. Power line communication technologies for smart grid applications: A review of advances and challenges. *Comput. Netw.* **2014**, *70*, 366–383. [CrossRef]
174. Shrestha, D.; Mestre, X.; Payaró, M. On channel estimation for power line communication systems in the presence of impulsive noise. *Comput. Electr. Eng.* **2018**, *72*, 406–419. [CrossRef]
175. Espin-Delgado, Á.; Rönnberg, S.; Letha, S.S.; Bollen, M. Diagnosis of supraharmonics-related problems based on the effects on electrical equipment. *Electr. Power Syst. Res.* **2021**, *195*, 107179. [CrossRef]
176. Khokhlov, V.; Meyer, J.; Schegner, P.; Agudelo-Mart'inez, D.; Pavas, A. Immunity Assessment of Household Appliances in the Frequency Range from 2 to 150 kHz. In Proceedings of the 25th International Conference on Electricity Distribution (CIRED), Madrid, Spain, 3–6 June 2019.
177. Lodetti, S.; Bruna, J.; Melero, J.J.; Khokhlov, V.; Meyer, J. A robust wavelet-based hybrid method for the simultaneous measurement of harmonic and supraharmonic distortion. *IEEE Trans. Instrum. Meas.* **2020**, *69*, 6704–6712. [CrossRef]
178. Mendes, T.M.; Duque, C.A.; Silva LR, M.; Ferreira, D.D.; Meyer, J. Supraharmonic analysis by filter bank and compressive sensing. *Electr. Power Syst. Res.* **2019**, *169*, 105–114. [CrossRef]
179. Gallarreta, A.; Fernández, I.; Ritzmann, D.; Lodetti, S.; Khokhlov, V.; Wright, P.; Meyer, J.; De La Vega, D. Adaptation of the IEC 61000-4-7 Measurement Method to CISPR Band A (9–150 kHz). In Proceedings of the 2022 IEEE 12th International Workshop on Applied Measurements for Power Systems (AMPS), Cagliari, Italy, 28–30 September 2022; pp. 1–6.
180. Gallarreta, A.; Fernández, I.; Ritzmann, D.; Lodetti, S.; Khokhlov, V.; Wright, P.; Meyer, J.; de la Vega, D. A Light Measurement Method for 9–150 KHz Disturbances in Power Grids Comparable to CISPR Quasi-Peak. *IEEE Trans. Instrum. Meas.* **2022**, *71*, 3195255. [CrossRef]
181. Gallarreta, A.; Fernández, I.; Ritzmann, D.; Lodetti, S.; Khokhlov, V.; de la Vega, D.; Wright, P.; Meyer, J. Statistical relationship between RMS and QP spectra of voltage measurements in the 9–150 kHz range. *Electr. Power Syst. Res.* **2023**, *218*, 109213. [CrossRef]
182. *IEC 61000-2-2-2002+AMD1-2017+AMD2-2018 CSV*; IEC Webstore—Electromagnetic Compatibility, EMC, Smart City, Rural Electrifica. IEC: Geneva, Switzerland, 2018. Available online: https://webstore.iec.ch/publication/63116 (accessed on 12 January 2024).
183. UNE. UNE-EN 50065-1-2012 Transmisión de Señales por la Red Eléctric. 2012. Available online: https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0048827 (accessed on 12 January 2024).
184. *CISPR 14-1-2020*; IEC Webstore—Electromagnetic Compatibility, EMC, Smart City. IEC: Geneva, Switzerland, 2020. Available online: https://webstore.iec.ch/publication/60734 (accessed on 12 January 2024).
185. *CISPR 15-2018*; IEC Webstore—Electromagnetic Compatibility, EMC, Smart City. IEC: Geneva, Switzerland, 2018. Available online: https://webstore.iec.ch/publication/29646 (accessed on 19 September 2023).
186. Zhao, Y.; Tatari, O. A hybrid life cycle assessment of the vehicle-to-grid application in light duty commercial fleet. *Energy* **2015**, *93*, 1277–1286. [CrossRef]
187. Daramola, A.S.; Ahmadi, S.E.; Marzband, M.; Ikpehai, A. A cost-effective and ecological stochastic optimization for integration of distributed energy resources in energy networks considering vehicle-to-grid and combined heat and power technologies. *J. Energy Storage* **2023**, *57*, 106203. [CrossRef]
188. Mojumder MR, H.; Ahmed Antara, F.; Hasanuzzaman, M.; Alamri, B.; Alsharef, M. Electric Vehicle-to-Grid (V2G) Technologies: Impact on the Power Grid and Battery. *Sustainability* **2022**, *14*, 3856. [CrossRef]
189. Regett, A.; Kranner, C.; Fischhaber, S.; Böing, F. Using Energy System Modelling Results for Assessing the Emission Effect of Vehicle-to-Grid for Peak Shaving. In *Sustainable Production, Life Cycle Engineering and Management*; Springer: Berlin/Heidelberg, Germany, 2019. [CrossRef]
190. Ercan, T.; Noori, M.; Zhao, Y.; Tatari, O. On the front lines of a sustainable transportation fleet: Applications of vehicle-to-grid technology for transit and school buses. *Energies* **2016**, *9*, 230. [CrossRef]
191. Zhao, Y.; Noori, M.; Tatari, O. Vehicle to Grid regulation services of electric delivery trucks: Economic and environmental benefit analysis. *Appl. Energy* **2016**, *170*, 161–175. [CrossRef]
192. Petit, M.; Prada, E.; Sauvant-Moynot, V. Development of an empirical aging model for Li-ion batteries and application to assess the impact of Vehicle-to-Grid strategies on battery lifetime. *Appl. Energy* **2016**, *172*, 398–407. [CrossRef]
193. Parsons, G.R.; Hidrue, M.K.; Kempton, W.; Gardner, M.P. Willingness to pay for vehicle-to-grid (V2G) electric vehicles and their contract terms. *Energy Econ.* **2014**, *42*, 313–324. [CrossRef]
194. Wang, Z.; Jochem, P.; Yilmaz, H.Ü.; Xu, L. Integrating vehicle-to-grid technology into energy system models: Novel methods and their impact on greenhouse gas emissions. *J. Ind. Ecol.* **2022**, *26*, 392–405. [CrossRef]
195. Liao, Z.; Taiebat, M.; Xu, M. Shared autonomous electric vehicle fleets with vehicle-to-grid capability: Economic viability and environmental co-benefits. *Appl. Energy* **2021**, *302*, 117500. [CrossRef]
196. Onishi, V.C.; Antunes, C.H.; Fernandes Trovão, J.P. Optimal energy and reserve market management in renewable microgrid-PEVs parking lot systems: V2G, demand response and sustainability costs. *Energies* **2020**, *13*, 1884. [CrossRef]

197. Borge-Diez, D.; Ortega-Cabezas, P.M.; Colmenar-Santos, A.; Blanes-Peiró, J.J. Contribution of driving efficiency and vehicle-to-grid to eco-design. *Energies* **2020**, *13*, 3997. [CrossRef]
198. European Commission. *Commission Recommendation (EU) 2021/2279*; European Commission: Luxembourg, 2021; Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021H2279#:~:text=This%20Recommendation%20promotes%20the%20use,and%20services,%20and%20of%20organisations (accessed on 7 September 2023).