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# DC Off-Board Vehicle to Grid/Building/Home: A Survey and Gap Analysis

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**ABSTRACT** In recent years, the research interest in bidirectional charging of electric vehicles has increased significantly, driven by improved accessibility to charging and payment information as well as the increasing emphasis on integrating variable renewable energy sources more effectively into the grid. Integrating bidirectional charging with the grid/building/home can also reduce grid congestion. Despite this, broader implementation of this technology has not yet been achieved. In this context, this article comprehensively surveys direct current (DC) off-board vehicle to grid/building/home chargers and analyses the gaps which prevent the technologies' wide implementation. These gaps are analysed by considering areas such as the development direction of bidirectional charging technology, battery cost and its degradation, V2G applicable standards, grid codes and charging protocols, deployment of V2G chargers (off-board versus on-board/wireless), market feasibility of V2G services, and the cost of bidirectional off-board chargers. The first survey of twenty-five commercial bidirectional chargers is presented and investigated in relation to the above-mentioned areas. Four key (technical, regulatory, financial, and behavioural) barriers are identified and discussed for the wide implementation of vehicle to grid/building/home charging.

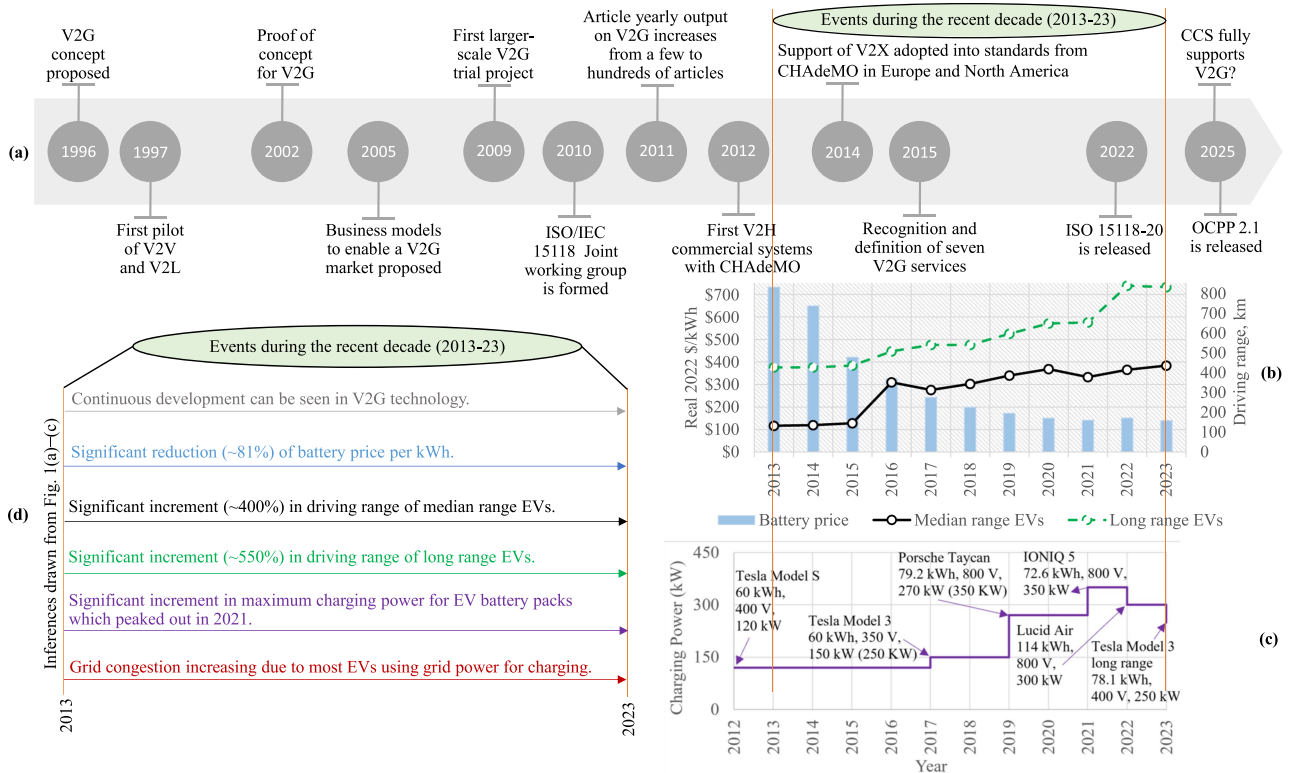
**INDEX TERMS** EV, battery degradation, bidirectional charging, fleet services, grid services, charging protocol, charger cost analysis, Vehicle to Grid (V2G), and Vehicle to everything (V2X).

## I. INTRODUCTION

Bidirectional electric vehicle (EV) charging can mitigate the variability of renewable energy sources, like solar and wind, by acting as flexible energy storage. It facilitates greater integration of renewables into the grid, enables households to store energy during off-peak hours for use during higher-cost periods, and provides backup power during grid outages. This is often called vehicle to everything (V2X). The idea of "V2X" (X can be Grid (G), Building (B), Home (H), and Load (L) in this article, and their definitions are provided in the Supplementary Material) can be traced back to when the concept of vehicle to grid (V2G) was first described, as shown in Fig. 1(a). Given its almost 30-year-long history, the ideas for market implementation, communications,

standardisation for charging stations (led at first by Charge de Move (CHAdeMO) [1], but in recent years competing with and, in Europe and North America, being overcome by Combined Charging System (CCS) [2]), and the required power technology are well developed. Numerous trial projects have put these ideas to the test [3], [4].

In the recent decade, with increased driving range and reduction in battery price per kWh, EVs have enough power reserve for V2X, as depicted in Fig. 1(b). Moreover, during this time, the number of EVs has also increased rapidly, and with them the charging demand, as shown in Fig. 1(c). Relying on grid power to meet the rising charging demand adds significant pressure on the grid's ability to deliver power, and increased congestion, as summarised in Fig. 1(d).



**FIGURE 1.** (a) A timeline of milestones for the development of V2G compiled from [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15] paired with (b) the development of battery pricing and EV driving range and (c) EV charging power [16], [17], [18], [19]. (d) Inferences from Fig. 1(a)–(c) for the recent decade (2013–2023).

If EVs are charged more smartly—through smart charging (V1G) or bidirectional charging, as shown in Fig. 2, including V2G services, it could reduce grid congestion, provide virtual inertia and act as intermittent storage for renewable energy. This increased charging demand necessitates more efficient use of green energy, enabling V1G and V2G. Despite this, V2G has not been widely implemented, and this article aims to explain why.

### A. DESCRIPTION OF AVAILABLE HARDWARE CONFIGURATIONS IN BIDIRECTIONAL CHARGING

Bidirectional charging can be achieved through alternating current (AC)- and direct current (DC)-based systems, which are represented in red and blue, respectively, as shown in Fig. 2. These systems are either standalone or grid-connected. For the standalone or grid-connected AC-based (i.e., AC-V2G/B/H/L) bidirectional charging, an on-board charger (marked as 2 in Fig. 2), which can do bidirectional charging, is required. Whereas, an off-board charger (marked as 1 in Fig. 2) is needed for unidirectional fast charging as well as DC-based (i.e., DC-V2G/B/H/L) bidirectional charging in both standalone and grid-connected operations.

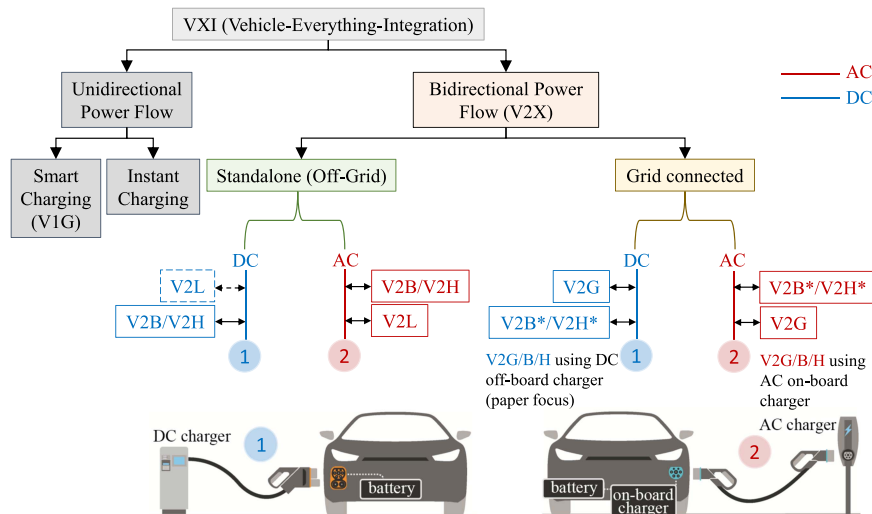
In standalone operation, when the EV battery supplies power to the appliances with a vehicle power inverter [20], which is usually the on-board charger, it is referred to as AC-V2L. The power draw is limited but typically has an upper

limit of 3.6 kW [21]. While DC-V2L is technically possible, practical use has not been seen, given that the appliances are designed to be connected to AC and would require an additional external inverter [20]. Besides that, AC-V2B/V2H or DC-V2B/V2H (standalone) is the local energy management with building loads and photovoltaic as one of the energy sources. The integration level in the home may vary, from using a switching unit to select either the EV or the power grid as the power source to using a power inverter which provides electricity to the internal wiring (sourced interchangeably from the EV, the grid, and optionally locally generated power) [20], [22], [23].

Whether bidirectional charging is performed via the on-board or an off-board charger, they can be designated as “V2G ready”. These chargers are identical in their hardware to V2G and V2B/V2H chargers, but the operational protocols and software provided with the chargers do not allow for V2G from the start (reasons are discussed in this article). Moreover, implementing high-power V2G/B/H on a large scale using DC off-board chargers can help prevent grid congestion. Therefore, DC off-board V2G/B/H is the paper’s primary focus, as depicted in Fig. 2.

### B. LITERATURE SURVEY

Recent advancements in wide band gap (WBG) semiconductors have made chargers less cumbersome, enabling higher



**FIGURE 2.** Overview of more common operation modes of bidirectional charging, where V2G/B/H using DC off-board chargers is the main focus of the paper. V2B\* and V2H\* are behind-the-meter: From a metering perspective, they're separated from contributing to the grid energy, but can be switched to provide energy beyond the building as requested.

power densities, thereby defining suitable charging topologies [24], [25], [26], [27], [28], [29], [30], [31]. For charging levels 1 to 4, various topologies used in bidirectional on-board EV chargers are reviewed in [24], [25], and challenges for V2G operation are highlighted in [24]. The authors of [26] provided a comprehensive review and performance evaluation of bidirectional on-board EV charger topologies for V2G operations. A comprehensive review of different topologies compatible with V2G for integrated on-board charger-traction systems of commercially available EVs is presented in [27]. A detailed technical evaluation and review of V2G concepts alongside various power electronics converter topologies for light- and heavy-duty vehicles is provided in [28]. In [29], bidirectional converter topologies, charging methods, and communication standards are reviewed for V2G and V2H operations. The authors of [30] analyzed inductive and conductive, i.e., on-board (two-stage and integrated) and off-board chargers for plug-in EVs. Despite these advancements in charging topologies and WBG semiconductors, the price of chargers is still high for many users [32], [33], [34], [35].

On the contrary, the price of Li-Ion batteries has been decreasing over the past 10 years [36], as shown in Fig. 1(b). Even if Li-Ion battery prices are dropping, battery degradation through increased cycling in V2X is a major concern [37], [38], [39], [40], [41], [42]. The authors of [37] reviewed the impact of V2G services on EV battery degradation. A survey on different V2B applications, a review of energy management methods, and battery degradation in smart buildings with V2B integration are presented in [38]. For V2X services, the economic implications of Li-ion battery degradation are reviewed in [39]. The authors of [40] presented a method to quantify EV battery degradation from driving versus multiple V2G services, and an increase in battery degradation is reported when EVs are involved in V2G

services frequently. Further, the impact of V2X service on EV batteries for garage storage versus outdoor parking is studied under Canada's local climatic conditions [41], and a minimal impact on battery life is reported for 50% V2X.

Grid integration and grid code are other factors limiting V2G implementation [43], [44], [45], [46], [47], [48], [49], [50], [51]. In [43], policy recommendations for integrating grid-vehicle charging are provided for policymakers, emphasizing power electronics and the grid perspective. EV grid integration working group from the Australian Distributed Energy Integration Program (DEIP) presented gaps in Vehicle-Grid Integration (VGI) standards, which could lead to inefficiencies and increased costs in transitioning to electrified transportation [44]. In [45], the California Energy Commission has recommended AC chargers for International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) standard 15118, emphasizing grid integration and reliability. Besides that, open communication protocols for VGI, including their advantage and challenges, are reviewed in [46]. The authors of [47] analysed that adapting the latest protocol versions of Open Charge Point Protocol (OCPP) and Open Charge Point Interface Protocol (OCPI) can achieve desired outcomes for V2X ecosystems, though uptake is slow. In [48], the status of V2G standards and any gaps that need to be addressed to unlock the capabilities of V2G-enabled equipment are reviewed.

Furthermore, the V2G market study in [49] identified ISO/IEC 15118 and OCPP 2.0 as key standards with robust business models needed to understand V2G economics and revenue streams. The authors of [50] reported a comparative analysis of standardized protocols for EV roaming, which revealed governance structure and supported business models as key differences between protocols.

### C. CONTRIBUTIONS

The above-mentioned literature shows that previously published V2G/B/H review article primarily focused on bidirectional charging topologies, communication standards, integrated on-board charging systems, charging strategies, battery degradation, grid code, and grid integration, either in isolation or combining a few of the topics. However, none of the literature synthesized all of these areas within a unified framework and investigated the critical influences and dependencies between each other, or examined the landscape of commercial bidirectional chargers, which reflects their combined influence on the implementation of V2G technology. Economic constraints, the lack of representative charging profiles for charging and discharging, advancements in DC off-board charging technology, and its compatibility with V2X are existing but overlooked issues in the preceding literature. Therefore, this article presents a survey and gap analysis for V2G/B/H implementation, primarily focusing on DC off-board chargers. The main contributions are:

- The first survey of 25 commercially available bidirectional chargers is presented and evaluated based on several criteria such as power density, to highlight current technology trends, and a comparison of off-board implementations with on-board and wireless charging approaches is provided.
- A complete overview of grid services, which was partly presented in [52], adding categorisation of the service with respect to scheduling time horizon, if bidirectional charging is required, and if the service has been evaluated in a trial project.
- A feasibility study to implement V2G on a large scale when compared to selected grid services related to trial projects.
- V2G-specific battery degradation and how this discourages user participation in V2G is discussed in detail.
- A cost overview of the manufacture of chargers, providing insight into the costs of off-board DC chargers and why they remain comparatively high.

### D. ARTICLE ORGANIZATION

The rest of this article is organised as follows: Section II presents the properties of bidirectional chargers found through the datasheet survey. Section III provides details on the economic trend of Li-Ion batteries in EVs and the known degrading effects of bidirectional charging. Section IV considers communication protocols and grid codes which have a direct effect on V2G implementation. In Section V, we compare how the implementation type (on-board, off-board, and wireless) influences near-time V2G usage. Section VI discusses different grid services, how they were tested in various trial projects, and the most relevant conclusions from the trial projects. The manufacturing costs of a charger are explained in Section VII. Finally, Section VIII concludes with the four key themes which prevent global V2G implementation and

provides direction for future research, as well as recommendations to the industry and market actors.

## II. TECHNOLOGY TRENDS IN BIDIRECTIONAL CHARGERS

### A. BIDIRECTIONAL CHARGERS SURVEY

This section presents a survey including datasheets of off-board chargers, representative of current bidirectional charging technology. The survey primarily includes DC chargers at power levels achievable in a home installation, with inclusion of select AC chargers to support the discussion on ISO 15118's role in enabling bidirectional charging. Off-board chargers were prioritized as they are already aligned with existing grid codes for distributed generation, as further discussed in Section V-A. Inclusion of chargers supporting at least one out of three plug types for Mode 3 or Mode 4 charging was another criteria, as well as inclusion of early models with bidirectional capabilities (e.g., models from EVTEC, Honda, Tsubaki, and Nichicon). The data was compiled using: (i) a preliminary list of chargers from the DriVe2X research initiative, (ii) cross-referencing with listings on CHAdeMO's V2G product page, and (iii) targeted web and press release searches for CCS-compatible chargers. All datasheets of these chargers are given in the Supplementary Material.

Table 1 presents most of the currently available bidirectional chargers offering V2G services. Based on these 25 chargers, the authors have attempted to find the technology trends of the current market. Moreover, these chargers are also used to understand the factors important for V2G implementation, which are discussed in the upcoming sections.

According to the surveyed charger datasheets, V2G is the most popular bidirectional function to implement, as summarized in Table 2. It should be noted that in many cases, the charger can support V2G only with a future software update specified or with a remark that V2G functionality is only available in certain regions, often described as "V2G-ready". V2H and V2B chargers have been grouped together because they are similar from the charger's perspective. For charger 1, the bidirectional flow was specifically for photovoltaics (PV) peak shaving purposes, and for charger 25, the type of bidirectional charging was not specified.

### B. DECREASING SIZE OF OFF-BOARD CHARGERS

When comparing which year the charger was released on the market to its power density, it can be noted that earlier charging technologies were less power-dense. The year, rated power, weight, and dimensions from Table 1 are used to calculate both specific power density and volumetric power density, as shown in Fig. 3(a) and (b), respectively, together with a trend line modelled by best fit (in a least-squares sense) for the data. These trends for off-board charger power density may be compared to those of on-board charger power density studied in [25], [27], where similar conclusions about power density increase are drawn. Before Wide BandGap devices (WBGs) became cheaper to produce, power electronics design made

**TABLE 1. Bidirectional Chargers Included in this Survey. Column 2 Indicates the Release Year Or, for Chargers 23–25 Under Development, the Announcement Year. Column 7 Reports Efficiency At Rated Power. The Last Column Specifies Installation Type: Wall, Ground (Required for Heavy Units), or Module (Power Electronics Only, Without Enclosure or EV Interface)**

Sr. no.	Year	Name	Manufacturer	P <sub>rated</sub> (kW)	V <sub>rated</sub> (V)	Efficiency % *	Weight (kg)	H×W×D (m)	Installation
1	2015	Coffee& Charge	EVTEC AG	10/12	170 - 500 VDC	93	50	0.59×1.12×0.35	Ground
2	2018	Power Manager	Honda	5.5	200 VAC	-	101	0.9×0.6×0.3	Wall
3	2018	V2G500 V15A	PRE	6	50-500 VDC	95	12	0.4×0.3×0.15	Module
4	2018	FE-15	Fermata Energy	15	380 VDC	96	-	0.58×0.88×0.25	Wall
5	2018	Single	Venema B.V.	10	150-500 VDC	95	-	-	-
6	2019	Sospeso& Charge	EVTEC AG	10	170-500 VDC	98	38	0.82×0.55×0.28	Wall
7	2019	VCG-666CN7	Nichicon	<6	150-450 VDC	-	91	0.81×0.85×0.34	Ground
8	2019	V2G 4.0	Magnum Cap	10	0-500 VDC	>90 chr., 93 dis.	55	1.02×0.5×0.22	Wall
9	2019	eLINK TPS10-A	Tsubaki	5	150-450 VDC	-	114	1.5×0.4×0.3	Ground
10	2020	Quasar	Wallbox	7.4/7.2	150-500 VDC	-	20	0.35×0.35×0.31	Wall
11	2020	V2G500 V30A	PRE	10	50-500 VDC	95	15	0.5×0.3×0.11	Module
12	2020	Highbury DC Bi-directional	Rectifier Technologies	11	50-500 VDC	>96 chr., 95 dis.	32	0.82×0.35×0.12	Wall
13	2020	Double	Venema B.V.	10	150-500 VDC	95	-	-	-
14	2021	r16	debel	15.2	150-500 VDC	96.3	28	0.8×0.5×0.23	Wall
15	2021	Casio	Venema B.V.	10	150-500 VDC	95	-	-	-
16	2022	Quasar 2	Wallbox	11.5	-(DC)	97	20	0.7×0.3×0.13	Wall
17	2022	RES-HD60-V2G	Nuvve	60	270-870 VDC	95	816	0.8×2.08×0.62	Ground
18	2022	HYC50	Alpitronic	50	150-1000 VDC	97	95-145	1.3×0.52×0.25	Wall
19	2023	EQ 200	Blink Charging	22	400 or 230 VAC	-	5	0.42×0.3×0.16	Wall
20	2023	FE-20 (Heliox)	Fermata Energy	20	150-500 VDC	-	89	0.94×0.76×0.279	Wall
21	2023	BDL	Kostal	11	400 VAC	-	25	0.56×0.41×0.23	Wall
22	2024	-	SolarEdge	12/24	-	99, if DC/DC	22	0.62×0.34×0.2	Wall
23	Future (2021)	Latinki 11	InterControl	11	120-500 VDC	-	-	-	Wall
24	Future (2022)	-	Delta	-	-(DC)	97.5	-	-	-
25	Future (2023)	240kW DCFC	Blink Charging	-	-(DC)	-	-	-	Wall

**TABLE 2. Stated Type of Bidirectional Functionality in the Surveyed Chargers. “V2G-Ready” (Capable of Supporting V2G With a Future Software Update) Chargers are Included in V2G**

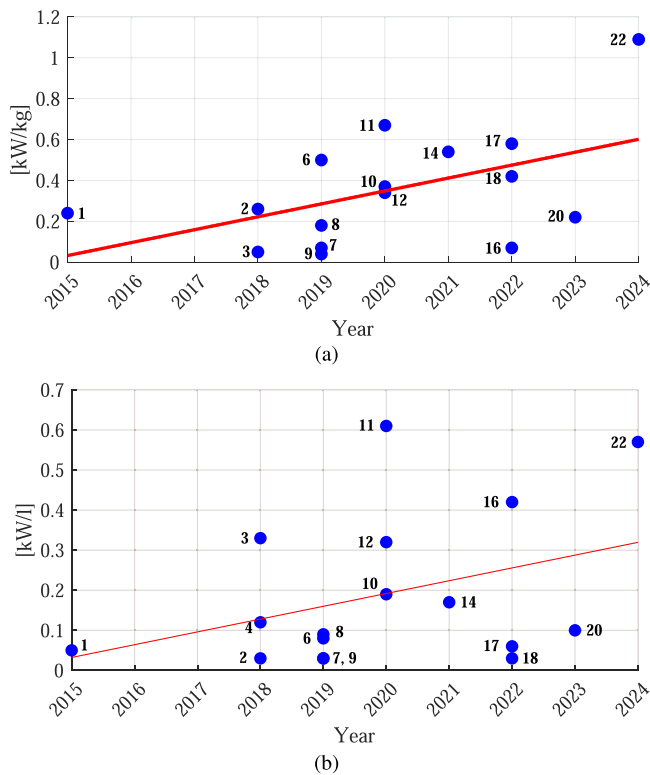
Bidirectional functionality type	Total chargers out of 25 (from Table 1)	Sr. no.
V2H/V2B	13	2, 6, 7, 8, 9, 12, 14, 16, 17, 21, 22, 23, 24
V2G	21	2, 3, 4, 5, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24
EV + PV peak shaving only or Unspecified	2	1, 25

use of primarily silicon-based switches, which, in comparison to WBG Silicon Carbide (SiC), have lower thermal conductivity and a lower critical field value [53]. As WBGs became more accessible, DC/DC converters could be equipped with downsized magnetic components due to the ability to increase switching frequency without overheating, while AC/DC converters could operate at higher DC-link voltages for higher efficiency over a variable voltage range [25]. This is because the critical field value determines the SiC devices’ ability to tolerate higher voltages [53]. Higher switching frequencies also reduce ripple in voltage and current, enabling smaller transformers thanks to increased flux change [24], [27], [31]. Compared to Si MOSFETs, SiC MOSFETs withstand higher voltages and achieve higher switching frequencies, improving two power density-related factors: DC/DC conversion benefits from very high frequency, reducing magnetic component size, and AC/DC conversion benefits from voltage tolerance, specifically in the 800 V range. The inverter’s DC link can be varied to adjust to the state of DC-connected devices (e.g., PV generation, EV battery), offering high efficiency and a

mostly flat curve across the entire voltage range [25], [31]. Gallium Nitride (GaN) based switches are, alongside SiC, also WBGs. Still, due to SiC’s better performance compared to GaN (e.g., lower on-state resistance) and better-known data on reliability, SiC is one step ahead for EV charging technology implementation [31]. The isolating transformer is situated at either the first stage before the input filter of the converter if it is a low-frequency transformer, or it is embedded in the converter DC/DC conversion stage, which is after the inverter stage and before the output filter if it is a high-frequency transformer [30], [31], [54]. The topologies of power electronics enabling bidirectional charging have been reviewed in more detail in [26], [28], [29], [30], [31], and a few topologies are emerging as the more commonly applied ones, such as the three-level boost DC/DC converter and the dual active bridge (DAB) converter [26].

**C. STANDALONE FEATURES AND EXPANDED V2G INCLUSION**

Another noticeable trend among the surveyed chargers is the coupling of standalone features with bidirectional EV chargers. This can be local PV or battery storage, which was a feature for chargers 1, 3, 6, 11, 13, 15 and 22. Two chargers, 14 and 16, market their ability to operate a typical home during a blackout from the EV battery via the charging modules, also called standalone mode. Not only DC but also AC chargers are marketed (i.e., 19, 21, 23), which is possible after the final approval of bidirectional functionalities in the ISO 15118 protocol [2], [12], and one charger (i.e., 17) includes an EV fleet charging management app. Both expand the opportunities for V2G.



**FIGURE 3.** (a) Specific power density (kW/kg) and (b) volumetric power density (kW/L) of chargers released on the market between 2015 and 2024 (as indexed in Table 1) with their power density trend line.

### D. EVS WITH V2G - ON-BOARD BIDIRECTIONAL CHARGING

The functionality of bidirectional charging can be realized only when the vehicle is equipped with bidirectional capability. At the time of writing, there is a limited number of vehicles known to the authors that are V2G-compatible, as listed in Table 3 [16], [55], [56], [57]. Despite their much lower battery capacity, plug-in hybrid EVs (PHEVs) may prove useful within a V2H context, where less flexibility is required compared to V2B or V2G contexts, in which Battery EVs (BEVs) are better. Although more and more EVs reaching the market are promoted to include V2X functionality with V2G services, it must be considered that a suitable implementation of V2G functionality on the charger side is equally fundamental for widespread implementation. The number of commercially available chargers (with varying levels of V2G compatibility) is limited to the author’s knowledge (Table 1).

## III. BATTERY COST, PACK SIZE, AND DEGRADATION IN RELATION TO BIDIRECTIONAL CHARGING

### A. RANGE AND PRICE TREND

Vehicles with larger battery sizes and capacity are becoming more common to increase EVs’ driving range. The median driving range has increased from 109 km in 2013 to 414 km in 2022, as shown in Fig. 1(b) [17], [19]. The driving range is based on Environmental Protection Agency estimates using the battery sizes of available models [58]. This trend is

**TABLE 3.** List of V2G-Compatible cars [16], [55], [56], [57]. The Tesla, BYD, Volvo EX30, Hyundai Ioniq 5, Polestar, and Ford Models Have Only Been Unofficially Confirmed Via Ambibox and Intercontrol Charging pilot [57]

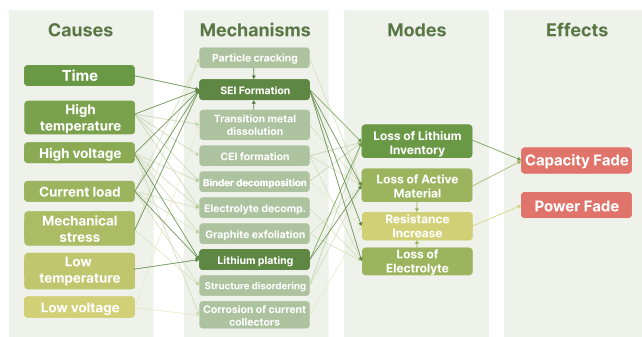
Make and Model	Powertrain type	Charging Standard	Battery Capacity [kWh]
Build Your Dreams Atto 3	BEV	CCS	60.5
Cupra Born	BEV	CCS	58
Ford Mustang Mach-E	BEV	CCS	72.6 / 91
Honda e Advance	BEV	CCS	28.5
Hyundai Ioniq 5	BEV	CCS	63 / 84
Hyundai Ioniq 9	BEV	CCS	-
Kia EV9	BEV	CCS	95
Mitsubishi iMiEV	BEV	CHAdeMO	14.5
Mitsubishi Outlander	PHEV	CHAdeMO	13.8
Mitsubishi Eclipse Cross	PHEV	CHAdeMO	13.8
Nissan E-NV200	BEV	CHAdeMO	37
Nissan LEAF	BEV	CHAdeMO	39 / 62
Polestar 2	BEV	CCS	82
Skoda Enyaq	BEV	CCS	58
Tesla Model 3	BEV	NACS	60 / 78.1
Tesla Model Y	BEV	NACS	60 / 78.1
Volkswagen ID.3	BEV	CCS	58
Volkswagen ID.4, ID.5, ID.Buzz and ID.Buzz cargo	BEV	CCS	77
Volvo EX30	BEV	CCS	51 / 69
Volvo EX90	BEV	CCS	101

observed for both average and long-range vehicles. Battery technology improvements, such as higher energy capacity, improved thermal performance, improved cell chemistry, and better battery management, allowing higher charging and discharging currents and support of an increased number of charge cycles, are the main reasons for the increased compactness and efficiency of the battery packs [31].

The price of battery packs has simultaneously been decreasing [17], [36], by extension decreasing the cost of additional wear that comes with providing V2G or V2B/H services from EV batteries. The increased available total volume of EV batteries is inadvertently beneficial for V2G/B/H applications when they are energy-intensive. More room is left to charge and discharge the battery without impacting the used driving range, and the influence on the battery’s state of health (SoH) is reduced. Even if the cost of batteries is decreasing, battery degradation is an important limiting factor for bidirectional charging [37], [38]. High battery degradation can occur through increased cycling if bidirectional charging is performed without considering degradation [39]. In the field of battery degradation due to V2G/B/H, two main obstacles can be identified: Degradation and user acceptance.

### B. BATTERY TYPE AND OPTIMISATION

The first obstacle to be considered is the optimisation of the battery degradation. Battery degradation is a complex process that depends on many operating conditions like temperature, charging current, State of Charge (SoC), and Depth of Discharge (DoD). When the V2G/B/H charging algorithm does



**FIGURE 4.** Cause and effects in battery degradation of the Li-ion cell. Adapted from [59] and [60] under CC BY 4.0 license.

not consider the battery degradation, battery lifetime will decrease due to the added cycles [39].

However, in the right conditions, V2G/B/H charging can increase battery lifetime too, when the charging pattern is optimised for minimal degradation [61], [62], [63].

Li-ion batteries currently dominate the EV battery market with the most popular types consisting of a graphite anode and a nickel manganese cobalt (NMC), lithium iron phosphate (LFP), or nickel cobalt aluminium (NCA) cathode, with a market share of 60%, 30%, and 8%, respectively, in 2022 [36]. Battery degradation of a Li-ion cell is influenced by external causes, like temperature, current load, voltage, and mechanical stress, eventually leading to capacity loss and power loss. An overview of degradation mechanisms and the effects is given in Fig. 4. The two most important mechanisms are SEI formation and Lithium plating [64]. The ageing mechanisms can be grouped in calendar ageing and cyclic ageing. The effect of calendar ageing is always present regardless of whether the battery is used. Cyclic ageing is caused by the charging and discharging cycles of the battery. Calendar ageing is mainly driven by SEI formation. High temperature and high SoC increase the speed of calendar ageing. Cyclic ageing is driven by lithium plating, and affected by low temperature, DoD, charging current, and average SoC. The dependency on these parameters differs per battery chemistry [62], [64], [65], [66]. Both NMC and NCA cathodes are sensitive to high DoD, while the LFP cathode is not [64], [65]. The differences in battery degradation can also be traced back to V2G/B/H studies, e.g., in [42], the authors derive a semi-empirical degradation model for LFP/Gr cells in V2G/B/H where they state that DoD has minor influence. In [66], the authors find a 2.1% decrease in yearly normalised battery degradation when applying light V2X profiles on LFP/Gr batteries, while the same conditions for an NCA/Gr battery result in a 0.3% increase in battery degradation, showing that NCA/Gr is more sensitive to cyclic ageing than LFP. Battery chemistry greatly influences the degradation of V2G/B/H and should be considered when providing V2G/B/H. [64] provides a full review of battery degradation in V2X, including a quantitative comparison.

### C. V2G SERVICES AND OPTIMISATION

The provided V2G service has a large influence on the battery degradation. The required power, energy throughput, and the frequency of service are important factors. A service like Load shifting requires high energy, causing higher degradation due to deep discharge cycles, [40] measures 2.18% added yearly degradation when applying daily Load shifting. In comparison, frequency containment reserve (FCR) and Peak shaving (PS) require lower energy and thus have a smaller impact, with 0.38% and 0.68% of added yearly degradation for FCR and PS, respectively. A similar conclusion was drawn by [67].

Lastly, although charging and discharging currents are not considered to be a degradation driver itself [68], higher currents have been shown to increase the degradation when applying V2G [40], [41]. All the factors mentioned above should be considered when optimising the charging pattern for V2G. With the right conditions and optimisation, the degradation can be reduced using V2G [61], [63], [66]. Since calendar ageing is accelerated at higher SoC, battery ageing can be improved by lowering the SoC through V2G. At lower SoC the calendar ageing will improve but the cyclic ageing will increase due to the added cycle. The optimal resting SoC is where the calendar and added cyclic ageing combined are minimal. [61] used degradation models of NCA/Gr cells to verify the method and reduce capacity fade by 9.1%; the method is also verified by [63] for NMC/Gr cells, resulting in a reduction of 8.6%. Until now, the method has only been proven for a few operating conditions. Models and experimental results are based on battery cell models [62] and not on EV battery packs.

### D. BATTERY WARRANTIES AND USER ACCEPTANCE

The second obstacle is user acceptance of V2G/B/H. Even though the impact of battery degradation can be limited [69], the perception of battery degradation and insufficient warranties for their EV batteries can cause users to avoid V2G/B/H participation. Therefore, it is one of EV users' highest concerns related to V2G/B/H charging [70]. Warranties are being updated to reflect this. For example, Renault offers an extended warranty of eight years on their traction battery, compared to the base warranty for the car itself, which communicates that V2G/B/H operations are safe or compensated by Renault [71]. Besides updated battery warranties, an EU directive was also issued to ensure improved user insight on different EV batteries health over time. The battery health data must be made available to the user and third parties authorized by the user both when in a charging session and when driving [72]. This shows that clear communication from trusted sources and real-world degradation analysis are being recognized as crucial to overcome this obstacle. The car original equipment manufacturer (OEM) and the grid operators obtain high levels of trust from EV users, but the most trusted party differs per country [73].

Until now, battery degradation is considered as a shortcoming of V2G/B/H; however, with increased efforts

to comprehend and control battery degradation, it has the potential to become a strength of V2G/B/H. More research on optimisation for avoiding battery degradation with V2G/B/H is needed. By lowering the effect of calendar ageing, where battery chemistry and temperature are crucial factors that cannot be overlooked, bidirectional charging of the battery becomes a strong argument for V2G/B/H implementation, and increases the likelihood of OEM's including satisfactory traction battery warranties.

## IV. V2G APPLICABLE STANDARDS, GRID CODES, AND PROTOCOLS

### A. V2G-RELEVANT STANDARDS

The large-scale rollout of V2G technology faces several challenges, including the need for coherent standardisation, grid code compatibility issues, and communication protocol limitations. Table 4 provides an overview of the standards and their relation to the V2G charging environment. Grid codes are being adapted to account for V2G, e.g., by reducing or eliminating taxation on two-way energy storage [43] or by changing requirements in the standards which are non-applicable for automotive standards [48]. While grid codes have variations across countries, they are not dissimilar: Connected units must adhere to the grid frequency and required voltage. In case of an emergency, a stop signal from the grid operator needs to be acknowledged but not all units stop simultaneously since operation of the grid must continue despite grid disturbances. And in case of a black-out, it must not feed back to the grid as long as it is down, which is why anti-islanding detection is necessary [74].

### B. LAGGING IMPLEMENTATION

The overview provided in Table 4 shows that standards relevant to V2G integration exist or are under development. The issue is standardisation harmonisation – no single set of standards has become dominant worldwide, contrasting with the conclusion of [29]. In [29], ISO/IEC 15118, together with IEC 61850, are pointed out as the leading standards enabling communication from EV to charging station to the grid, respectively. While the protocols are bidirectional, globally they have not yet been fully implemented and tend to be regionalised or even country-specific. This, in turn, leads to varying implementations of products required by manufacturers to adhere to the different standards per region, leading to extra costs [44], [46]. One example of country-specific requirements is in Australia where an Electric Vehicle Supply Equipment (EVSE) in 2021 needed an AS/NZS 4755.1-compliant demand response enabling device, even though EVSEs' capable of V2G operation already have built-in communication capability [44]. Many manufacturers, therefore, opted for developing their proprietary protocols for communications between EVSE and Charging Station Management System (CSMS) instead to speed up the release of their product [44], [46] and market adaption of the latest developed standards is slow [45], [47]. For the enabling of V2G high-level charging control, this is not necessarily an

obstacle as many APIs belonging to the OEMs are publicly exposed and available for integration by third-party charging control developers. Task 53 was initiated to coordinate this interoperability on a global scale between different brands of EVs and EVSEs with a consortium based on a simplified de facto protocol derived from the international standard ISO-15118-20 [75].

### C. FEATURES OF ISO 15118-20

ISO-15118-20 includes message headers like EVSEPresentVoltage and EVPresentVoltage that facilitate communication between the EV and the EVSE. These messages help manage the charging and discharging processes by providing real-time data on voltage and current. The standard further defines various parameters such as EVMinimumChargeCurrent, EVMinimumDischargeCurrent, EVMinimumChargePower and EVMinimumVoltage, along with Maximum parameters for the same, which are crucial for maintaining the desired power levels [76]. It also includes rules for asymmetric polyphase values to ensure balanced power distribution across phases, while allowing unbalanced loading in each respective phase. The TargetSOC and MinimumSOC parameters allow for precise battery status communication, aiding in efficient energy management. Additionally, the standard supports dynamic control modes and scheduling, making it adaptable to various grid requirements. The inclusion of PowerTolerance and BatteryEnergyCapacity parameters further enhances its capability to support aggregated V2G services. The extent to which the parameters allow flexible V2G integration is especially apparent in Table 94 of the standard [76]. This table lists all the physical value parameters which may be used to communicate the status of the EV and the measurements of the EV as made by the EVSE. There are 14 parameters for current, including MaximumChargeCurrent, MinimumCurrent (defined for Charge as well as discharge) and with respect to both EV and EVSE. There are also 14 parameters for power, which largely mirrors the parameters and messages for current. These (14 + 14) parameters are important, considering that when both are known, the energy profile is known, too. Five parameters for energy are defined, including EVEnergyRequest and EVMinimumEnergyRequest, which allows to charge based on scheduling in terms of energy need. Likewise, five parameters for voltage, including EVTargetVoltage and EVSEPresentvoltage, are defined. Two parameters for frequency are likewise defined: EVSETargetFrequency and EVSENominalFrequency, which allow grid service of i.e., FCR type. Finally, one parameter for reactive power (EVSETargetReactivePower) and one for time (RemainingTimeToFullSOC) is defined, allowing the charger to assist in voltage level control [76]. In ISO 15118-2, only parameters for a completed charging session, stop and start control of the session, and target current and voltage to charge at were mandatory to be defined, which only permitted limited smart charging [91].

Thus, ISO 15118-20 specifies the parameters, in particular those related to power use and battery status for aggregated grid services and frequencies for i.e., FCR service, needed

**TABLE 4. List of Some Significant Standards Showing That Standardization is Catching up With V2G Technology Needs**

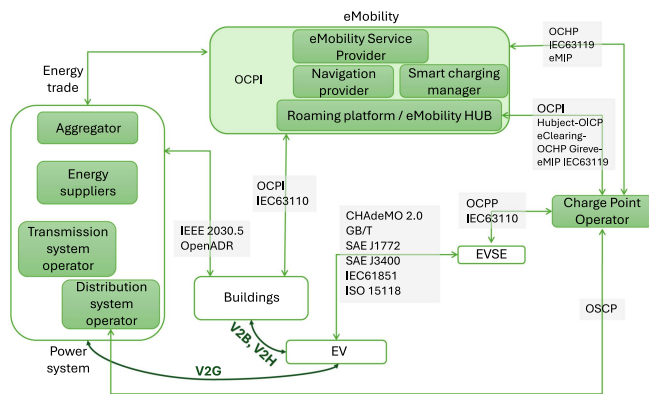
Category	Standard No. — Title	Protocol features	Remaining challenges
Connector (plug)	IEC 62196 -1 to -3 — Plugs, socket-outlets, vehicle couplers, and vehicle inlets, respectively.	Describes specific designs of SAE J1772-plugs and connections.	Ensuring backward and inter-plug compatibility with adaptors approved by all plug standards.
	SAE J1772, CHAdeMO 2.0 (or older), and SAE J3400 — CCS and CCS 2 plug, CHAdeMO plug, and NACS (Tesla) plug standards, respectively.	Plug-specific standards describing their construction. CHAdeMO were the first to establish V2X documentation, as mentioned in Section I.	NACS does not formally support bidirectional V2G charging, while the others do.
Communication at the charging station	ISO/IEC 15118 — Road vehicles (Vehicle to grid communication interface).	In Part 20: 2nd generation network layer and application layer requirements, especially, the requirements pertaining to V2G are established. Part 2: Road vehicles — Vehicle-to-Grid Communication Interface is in principle the predecessor to Part 20. Both are open international standards.	Existing infrastructure may require significant upgrades to support ISO 15118, to ensure security requirements set by the protocol. Differences between parts 2 and 20 are further explained in Section C.
	DIN Spec 70121 — Digital Communication between a DC EVSE and an EV for Control of DC Charging in the CCS.	DIN Spec 70121, a German national standard i.e., Deutsches Institut für Normung, was the first released standard (2012) to define bidirectional charging (DC only) based on a draft of ISO/IEC 15118.	DIN Spec 70121 was an intermediate solution when ISO 15118 was still in development to allow for bidirectional power flow, but only defined it for DC charging [45] and it lacks support of Plug&Charge (communication in elevated TLS layer) and V2G charging [12].
	IEC 61851-24 — EV conductive charging system (Digital communication between a DC EVSE and an EV for control of DC charging).	Part 24 defines the communication between the charger and the EV together with IEC 61851-23, with section A.6 defining bidirectional power flow through a flow chart for the control communication [77].	Compared to ISO/IEC 15118, IEC 61851 is more limited. It's not defined for wireless charging and enables only very simple communication through the setting of resistance and pulse width values - ISO/IEC 15118 can use Powerline Communication (PLC) [78].
Communication at grid level	IEC 61850 — Communication networks and systems in substations and IEC62746-10 — Open automated demand response.	Protocol groups defining utility side communication. IEC62746-10 is also known as OpenADR 2.0. Foundational standards for smart grids and connected Distributed Energy Resources (DER) [43], [79], [80].	These standards doesn't specifically cover EV charging and discharging, but adaptations have been proposed for IEC 61850 and IEC 62746 [81], [82].
	IEEE 2030.5 — Standard for communications between the smart grid and consumers.	Information exchanged using the standard includes pricing, demand response, and energy usage, enabling the integration of behind-the-meter devices [83].	Useful for behind the meter V2H, but needs complimentary standards for V2G integration.
	IEEE 1547 — Standard for Interconnecting Distributed Resources with Electric Power Systems.	Technical specifications for DER and their provided grid support, in use until IEC 63460 is published.	IEEE 1547 lacks implementation practices for EV charging but was a forerunner for standards considering DER interconnection [84].
	IEC 63460 — Architecture and use-cases for EVs to provide grid support functions.	Currently in writing, future standard, which will describe EVs as DER [85].	That it consistently will manage to bridge the differences between codes written for traditional grid service solutions and EVs as grid service providers.
	IEC 63584 — Open Charge Point Protocol.	Preceding this protocol was IEC63110 which targeted communication flows between different e-mobility actors and data flows within the electric power system [85], [86]. Its goal was to incorporate OCPP but it was cancelled in 2023 after failing to reach approval [87].	OCPP was recently adapted as-written as the international standard [87].
Grid codes	VDE-AR-N-4105:2018-11 — Power Generating Plants in the Low Voltage Network, G98/1 — Requirements for the connection of Fully Type Tested Micro-generators, G99/1 — Requirements for the connection of generation equipment in parallel with public distribution networks, and UL 1741 SA, UL 1741 SB, and UL1741 SC — Supplement A, B, and C, respectively, to UL1741.	The national standards (e.g., German (VDE), British (G98, G99), and USA-standards (UL)) speed up V2G implementation in their respective region, as they can be enacted faster than in-development international standards. They all relate to microgenerators, and the updates include a definition for bidirectional EV chargers so that the chargers are no longer categorized as loads.	These standards are intermediate, regional solutions. Eventually, they will be replaced by the international standards which covers similar areas (i.e., ISO/IEC 15118, IEC 63460, IEC 63110) [48], [88], [89], [90].

to enable bidirectional charging and efficient energy management in EVs. This is recognized by the European commission who requires new and refurbished public charging points, as well as new private charging points, to support the standard from January 1<sup>st</sup>, 2027 [92].

**D. FEATURES OF OCPP 2.1**

The latest release of OCPP, 2.1 [93], includes features like Priority Charging, which can override other charging activities

to prioritize specific needs. It also introduces V2X operation modes that comply with local grid codes, making it suitable for various geographical regions. These modes include settings for external setpoints, external limits, central setpoints, and local frequency and voltage control. Idle mode minimizes energy consumption when neither charging nor discharging is required. OCPP 2.1 also extends transaction options to include fixed cost, energy, and time-based transactions, with the ability to resume after interruptions. It supports new



**FIGURE 5.** Protocols for communication and the interrelation between players enabling V2G based on [43], [79], [83], [96].

authentication methods, including prepaid cards and dynamic QR-code payments. Additionally, the protocol enhances smart charging capabilities and introduces support for battery swap stations.

The open communication protocols, such as OCPP and Open Automated Demand Response (OpenADR), do not always offer all the functionality necessary to operate V2G, as even though they have many optional features, in practice, a fraction of the full stack is used in implementations. Open protocols thus have the disadvantage that since they might be implemented only partially, V2G compliance issues arise between different brands of EVs and charging stations, even if both use the same fundamental protocol. In contrast, the IEC and ISO standards are slightly less flexible but ensure interoperability and this is why the incorporation of them as standards occurred, as indicated in Table 4 for IEC 63584 and IEC62746-10, respectively.

### E. COMMUNICATION AND INVOLVED ACTORS

The development of communication protocols for convenient V2G implementation is critical to ensure all actors can seamlessly and securely exchange information (regardless of the location of the charging station, i.e., Plug&Charge, part of ISO15118, or the EVs' location, as has been done with Geofencing [94], [95]).

Fig. 5 shows the actors involved in charging infrastructure communication, including commercial, public and private (user) participants. Fig. 5 includes all possible protocols which could be used, like IEEE 2030.5 (standard for communications between the smart grid and consumers) [83], OpenADR (two-way information exchange model and Smart Grid standard), more focused on exchanging information, whereas OCPP has more emphasis on control [97], Open Clearing House Protocol (OCHP), Open Interchange Protocol (OICP), and eMobility Interoperation Protocol (eMIP) (all three are related to information exchange via a roaming platform [43], [50]). The gradual increase in the implementation of communication and connector standards (of which more details are provided in the Supplementary Material

**TABLE 5.** Communication Between Charge Point and Charging Management System (Cloud Server). From the Surveyed Chargers, Over Half are Confirmed to Utilise the Open Protocol OCPP

Communication	Total chargers out of 25 (from Table 1)	Sr. no.
OCPP	13	1, 5, 6, 8, 12, 13, 15, 16, 17, 18, 19, 20, 21
Other, e.g., V2H2.1, ECHONET Lite	3	2, 4, 9
Nichicon proprietary	1	7
Unknown or NA	8	3, 10, 11, 14, 22, 23, 24, 25

and [98], [99], [100], [101]) is reflected by the gradual increase of V2X features in chargers, as seen in Table 2. For example, two surveyed chargers (no. 14 and 16) can offer V2L services in a standalone mode such that for a generalised household, plugging in your EV can power the household for about three days in average during a regional blackout.

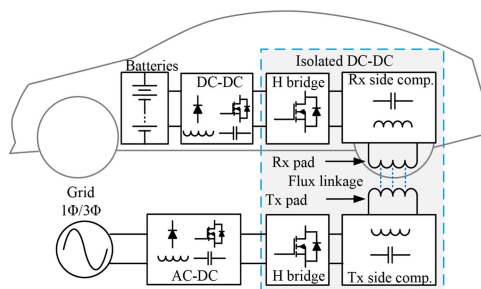
Different versions of OCPP are used in eight of ten cases, making it the most used open charging protocol. The twelve chargers that do not use OCPP can be explained by an earlier release date (before 2019). They use either a proprietary or other (semi)open protocol such as V2H2.1 (for CHAdeMO) or ECHONET Lite (Japanese control protocol for smart houses). Four chargers are announcements for future products, and the intended communication protocol has not yet been announced. Two are modules and not a final product, meaning a supported communication protocol is not relevant. Finally, two manufacturers do not specify any particular protocol, as shown in Table 5.

## V. DEPLOYMENT OF V2G CHARGERS

### A. OFF-BOARD AND ON-BOARD COMPARISON

For immediate V2G implementation, there are two options which are equally mature: on-board chargers (i.e., AC charging) or off-board chargers (i.e., DC charging). An on-board charger is inside the EV, and an off-board charger is outside. Both types are located between the point of connection and the battery pack, as shown in Fig. 2.

Although on-board chargers are convenient for customers (who do not need to purchase a separate off-board charger when they buy an EV [27]), they also have some drawbacks. These are limited space for the power module, increased vehicle weight, higher requirements for vibration tests and automotive standards, as well as stricter safety regulations, making them more expensive to design and manufacture [25], [28], [31]. These constraints are bypassed using an off-board charger that directly supplies DC power to the battery [27], [49]. Size requirements affect off-board chargers less [54], nonetheless, as discussed in Section II, installation costs are reduced with smaller chargers. Another complication for on-board chargers as V2G service providers is that their classification within the grid is more sophisticated. Since they are mobile, it decreases the accuracy of specific grid services.



**FIGURE 6.** Principle schematics of an IPT system, employing dual-side active H-bridges, which is compatible with bidirectional operation [102].

In some countries, on-board chargers also violate existing technical standards to be V2G service providers, because they do not have a permanent installation location. Specific examples of grid code and technical standards incompatibility with on-board chargers are discussed in the Supplementary Material [48], [49], [51]. Based on the aforementioned discussions, the surveyed chargers are off-board DC chargers, and for a survey on on-board chargers, we refer to [25].

## B. BIDIRECTIONAL WIRELESS CHARGING

EVs are currently charged via conductive charging technology, which requires drivers to pull and plug the charging equipment cable. A more convenient alternative to conductive charging technology is wireless charging technology, as shown in Fig. 6. In EV battery charging applications, wireless power is transferred through a magnetic link consisting of the transmitter (Tx) coil and receiver (Rx) coil, referred to as inductive power transfer (IPT) [103], [104].

Bidirectional wireless charging has several advantages over plug-in V2G. It eliminates the hassle of plugging and unplugging the charging cable, and the recharge of batteries can start automatically when the EVs Rx coil is coupled with a Tx coil of an IPT charger, which can improve the user experience and increase the participation rate in V2G. It also reduces the risk of electric shock and vandalism. It enhances the reliability and durability of the system by avoiding mechanical wear and tear, as well as dirt accumulation on the connectors. According to the international standards IEC 61980-3, ISO 19363, and SAE J2954, reference designs are recommended for four power levels: 3.7 kW, 7 kW, 11 kW, and 20 kW, and designs with a high power level are required to have downwards compatibility (i.e., an 11 kW charger can also supply power at 3.7 and 7 kW). Therefore, the interoperability among different EV models and IPT chargers can be improved, thereby improving EV adoption. IPT technology is maturing to the point where it can achieve safe and high-efficiency EV charging. Safe operation is ensured by limiting the magnetic field exposure, defined by the international standards in the frequency range of 9 kHz to 3 MHz, as summarised in [105], and for the magnetic field radiation, a reference design was simulated and found to be below the limitations in [106]. In [107], a magnetic resonance imaging-derived and high-resolution model

of the human body is used to examine the EMF exposure of a 3 kW IPT system operating at 30 kHz frequency, and the compliance with safety guidelines in the standard ICNIRP is verified. Compared to earlier review analyses such as [28], several improvements in both efficiency and safety have been made in recent years. Among the reported state-of-the-art high-power IPT prototypes with an air gap above 10 cm in [108], the highest rated power and efficiency are 100 kW and 97.2%, respectively. KAIST demonstrated a 100 kW power delivery with a DC-DC power efficiency of 80.8 % and an air gap of 26 cm [109]. ETH Zurich built a 50 kW IPT charger that can reach 95.8 % DC-DC power efficiency over a 16 cm air gap in 2016 [110]. TU Delft achieved 97.2% DC-DC power efficiency at 20 kW over a 15 cm air gap in 2022 [108]. In the given examples, it is worth noting that the values provided are for unidirectional conditions. The work in [110], [111], [112] deploys an active full bridge on dual sides, which enables bidirectional charging.

To advance the progress of IPT technology towards massive EV charging applications, the remaining challenges lie in cutting material costs and improving reliability. Today, commercialization of IPT technology is led by companies like Plugless [113], WiTricity [114], BRUSA [115], and WAVE [116], who have released commercially-ready IPT solutions for EVs and electric buses. Plugless provides 3.3 kW & 7.2 kW IPT chargers for purchase by EV owners at a cost of about \$ 3,500 plus installation. BRUSA developed an 11kW IPT charger for BMW in 2018, the first IPT charger certified by IEC 61980 for EVs in the world [117]. The topology configuration proposed in [118] uses relays to either cable-connected charging or wireless charging, which reuses the six switches and diode pairs for each charging mode configuration. Combination designs such as [118] could make wireless charging more affordable.

## VI. TECHNOLOGY AND MARKET FEASIBILITY FOR V2G SERVICES

### A. V2G FEASIBILITY IN TRIAL PROJECTS

As mentioned in Section I, concepts for V2G services have had 30 years to form and mature, but despite this, are mostly unheard of in real market settings. For reference, a comprehensive description of V2G services can be found in Table 6 and in [26], [52], [119]. Most of the services that benefit the Distribution System Operator (DSO), Independent System Operator (IndSO) or Transmission System Operator (TSO) contribute to a delay in the need for infrastructural upgrades in the distribution and transmission networks, prolonging the usefulness of present resources.

Looking at some of the recently concluded V2G trial projects in the U.K., Belgium, the Netherlands, Germany, Denmark, and Norway, varying V2G services and energy trade models were tested and evaluated in [32], [74], [120], [121], [122], [123]. This list highlights some of their findings. An extensive reference to more pilot projects for V2G studies can be found in [4].

**TABLE 6. Overview of Various Grid Services, Their Properties and Benefiting Actors. Sorted According to the Approximate Response Speed of the Service, Which May Vary Depending on the Capacity of and Inertia Characteristics in Different National Grids. For Each, Bi-Directionality (discharging) Enhances the Service, but in Many Cases, It is Not Necessary to Provide the Grid Service, Which is Indicated by the Column “requires V2X?”**

Timescale for activation of service [119], [127]	Description of grid service	Requires V2X?	Actor benefiting from service	Trialed in reviewed project
Very short (micro to milliseconds)	Harmonic filtering and harmonic mitigation, e.g., done in [128], [129].	No	DSO	None
Short (< 1s)	Dynamic containment: Post-fault fast-acting frequency response service [32], [130]. It prevents frequency deviations from propagating on the transmission network in the event of a sudden demand or generation loss. Prevention of events which could lead to blackouts, requiring functioning monitoring devices [131]. It may be partially provided, allowing unidirectional chargers to participate [132].	No	IndSO, TSO	[32]
Short (seconds)	Reactive power compensation using Q-V (voltage regulation), Q-P (applied at the PCC, for power factor correction) or phase control, e.g., done in [133].	Yes	DSO	[122]
Short (seconds)	Phase imbalance management, realised with a 3ph inverter varying power drawn (or injected if V2X) in each phase or with multiple EVs charging with 1ph inverters, e.g., done in [134].	No	DSO	None
Short (seconds)	Improving partial load efficiency by swapping between 1ph and 3ph charging. Decreases electricity bills by increasing efficiency during the whole charging cycle, e.g., done in [135].	No	User	None
Short (seconds)	Firm frequency response or Firm frequency regulation (FFR): Particularly in the UK, the frequency response suite is used for real-time grid balancing and to describe both the primary response (in service for below 1 min) and secondary response (active for about half an hour) together [136], [137].	Yes	IndSO, TSO	[120]
Short (2-30 s) [119]	Fast frequency response (FastFR) services handle low system inertia by injecting or absorbing power and resisting changes to system frequency. Synthetic inertia solves the same problem by providing a controlled contribution of electrical torque proportional to the rate of change of frequency, specifically, thus not equivalent to FastFR [138]. Note that this FFR is different from <i>firm</i> frequency response in the UK [136], [137].	No	IndSO, TSO	[32]
Short (2-30 s) [119]	Primary frequency reserve or Primary frequency response (PFR): Active power reserves are used to modulate charging around a given setpoint and maintain frequency during normal operation [139], [140]. PFR should become more relevant as synchronous generation resources are gradually replaced with inverter-based DERs [141]. Frequency containment reserve or Frequency control reserve (FCR) are equivalent.	No	IndSO, TSO	[122]
Medium (minutes)	Voltage regulation using active and reactive, or reactive only, power control with EV bidirectional power transfer of active and reactive power, e.g., done in [142], [143], [144].	Yes	DSO	[121], [122], [140]
Medium (minutes)	Controlled charging with the objective of improving battery lifetime, e.g., done in [139], [145].	No	User	[120]
Long (hours)	Marginal emission factor (MEF): Data from the live energy mix on the grid (and local renewable generation, if available) informs when an EV should charge. It reduces or pauses charging when the energy mix is less low-carbon [122].	No	User, society	[120], [121], [122]
Long (day ahead or intra-day)	Energy arbitrage: Charging (and discharging if bidirectional) based on energy prices, using more electricity from local renewables and adapting to time-of-use tariffs, thereby reducing net charging costs.	No	User	[32], [120], [121], [122], [123]
Long (day ahead or intra-day)	Peak demand reduction, Peak shaving or Grid net exchange minimisation: Reduces charging power during net peak demand and thus manages grid congestion by demand side management of EV charging. It is also found under the term Demand response. If bidirectional, power can also be supplied to the grid, reducing load peaks even further.	No	DSO	[120], [121], [122], [123]

- Vehicles with larger battery sizes (of at least 40 kWh) could yield higher yearly V2G income than smaller batteries if considering energy-intensive applications and services, as their energy storage capacity allowed for more of the energy storage to be allocated to aggregated V2G services [32].
- When a pure cost minimisation strategy is used with Firm frequency response (FFR), V2G service without setting narrow boundaries on SoC levels and charging rates, it is especially harmful to the battery lifetime due to high utilisation [120].
- In grids with a high rate of congestion, V2G is a necessity. In [74], it was noticed that V1G charging managed to displace the evening peak demand by at most 30%, but only if charging was completely stopped at those times. With V2G, it is possible to guarantee 100 kW flexibility with fewer (i.e., 75) residential chargers connected, whereas 200 chargers were needed to meet this demand with V1G charging [74].
- Reactive power provision can minimise grid losses, and if the number of EVs increases by 50% in Denmark, there would be no need for grid updates [122].

- V2G is useful for peak reductions, especially where the penetration of variable renewable energy is proportionally higher than that of other energy generation [123].
- V1G chargers can make a limited profit on fast frequency response (FastFR). V2G chargers can make more than double the amount from FastFR [32].
- Mass deployment of V2G will deflate its profitability, as well as increase charging tariffs indirectly [123].
- Commercially available EVs can, without modifications, support the power grid both locally and at system level [33], [122]. FCR could be implemented satisfactorily by control of active power setpoint in accordance with system frequency when charging [122].
- Adopting different V2B/V2H strategies increases RES self-consumption and enables tariff optimisation, including demand charge reduction [120], [121]. For self-consumption to be efficient, it should be active only if time to departure is sufficiently far ahead and when the battery SoC is above a certain minimum value [121].
- User acceptance of V2G is harder to achieve due to the high initial investment cost [32]. Other reports evaluating user acceptance came to similar conclusions [33], [34]. For fleet managers, benefits such as greater energy independence, new revenue streams and an opportunity to significantly lower carbon emissions are important, but 67% of respondents say that financial incentives are crucial for their businesses to adopt EVs [35].
- User acceptance is also dependent on the level of insight and control the EV owner is allowed. Consumer survey results from over 3000 respondents from 40 different EU countries found that a majority want to participate in smart charging as long as they remain in control, i.e., are able to overrule a grid operator requesting energy services from their batteries [74].

Many of the surveyed trial projects [32], [120], [122] highlight frequency regulation as the most interesting V2G service in terms of economic gain for the benefactor. In [121], it was concluded that revenue potential is dependent on the vehicle, type of charger, type of load profile for the house, market prices and user behaviour and therefore, no particular V2G service was deemed more profitable. Thus, there is always a limit to the economic boost of V2G services. The authors of [123] compare the energy market impact of peak shaving in Norway and Denmark, and concluded that participant revenues, and simultaneously the peak demand reduction, differed greatly depending on how much variable renewable energy penetration there is. Especially, the energy region DK2 would benefit the most from V2G, while V1G charging mostly covers the peak shaving need of Norway, as projected for 2040. Most practical V2G studies have focused on off-board chargers, but an ongoing on-board V2G project based in Utrecht utilises fleet vehicles (fleet vehicles have the advantage that all EVs are owned and managed by the fleet owner including the charging points [124]) that can access over 500 charging stations throughout the city. The chargers are connected to a solar panel network so the cars can recharge

**TABLE 7. An Example Estimation to Gauge the Commercial Scale of FCR as a V2G Service Based on the Availability of a 10 Kw DC Charger for Each Plugged-In Vehicle**

Country or region	FCR need (MW)	Min. no. of V2G cars needed	Cars in use (millions)	Plug-in availability	Min. no. of V2G cars incl. plug-in availability
Finland	87.1 [147]	8710	2.75 [148]	56-61 % (for all countries) [32], [121]	14 300-15 500
Netherlands	113 [149]	11 300	9.05 [148]		18 500-20 200
Denmark	22 [150]	2200	2.72 [148]		3600-3900
ENTSO-E RG Continental Europe	±3000 [151]	300 000	115.27 [148]		492 000-536 000

simultaneously with PV generation. Since the charging is bidirectional, the EVs are also regarded as “batteries on wheels” for solar energy. The project is also one of the first to implement ISO15118, exposing the bidirectional communication protocol to real scenarios [125]. Another project applying AC V2G on a larger scale is *SCALE* [126].

This project gathered data from different test locations across Europe between 2023 and 2025 to prepare realistic conditions for business case development for AC V2G, and some preliminary results are included in the preceding list [74].

**B. SMART CHARGING OR V1G**

Unidirectional charging can offer some of the grid services V2G can offer (see the third column in Table 6). Still, it’s more limited due to only being able to regulate via charging and not discharging. At the same time, V1G might be enough if economic incentives are adapted accordingly, if the EV penetration has a lesser impact on the grid stability and capacity, and if charging infrastructure that supports said adapted incentives is developed in harmony with each region’s energy generation pattern. It would indirectly manage people’s charging patterns to maximise the usage of renewable energy and stabilise the grid [146]. According to [43], a certain penetration level of EVs needs to be reached before V2G is the correct strategy, which is also indicated from the results of the NeX2G pilot [123].

At least two commercial projects for smart charging are currently active, where automatic scheduling of the charging process ensures the EVs are charged with as much renewable energy as possible [156] or optimised to when tariffs are low and with a promise of electricity from renewable energy sources [157].

**C. SCALING V2G AND STANDALONE SERVICES TO EV AVAILABILITY**

Let’s compare the potential bidirectional EV availability with previously recommended services from trial projects, listed in Table 6. Comparing FCR to the total need for it per country, the total number of V2G capable chargers needed to fulfill the requirement can be roughly estimated; see Table 7.

In the event of using renewable sources for black starts, e.g., [152], [155], [158], [159], the examples are given in Table 8 and feature a coordinated black start of a local grid (2016 event in Germany), 1 million households (2015 event in the Netherlands) and a section of the transmission network (2020

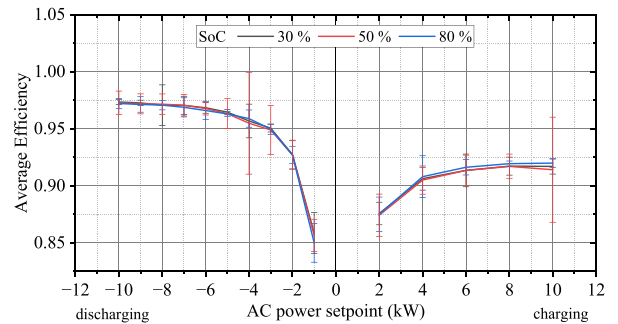
**TABLE 8. Three Events of Black-Starts Where Two Were Performed With RES, a Large-Scale Blackout in the Past Decade and a Fourth From Plans for the Electricity Grid Secured Entirely on RES. The Example Assumes the Same Plug-In Availability as for Table 7**

Country or region	Required power (MW)	Cars in use (millions)	Min. no. of V2G cars incl. plug-in availability
Germany (2016) [152]	5	48.2 [148]	820-893
Scotland (2020) [152]	69	3.1 [153]	11 300-12 300
Netherlands (2015) [154]	1000	9.05 [148]	163 900-178 600
United Kingdom [155]	35	36.4 [148]	5700-6300

event in Scotland), respectively [152], [154]. Requirements for being a black start service provider differ per country, and the U.K.’s requirements are also included (35 MW) [155] in Table 8. Note that for black start provision, further requirements, such as having the ability to energize part of the network with a specified amount of Mvar and running continuously at rated output for a minimum of a few days, are usually imposed. In a similar fashion, other grid services can be compared by their level of need with the theoretical amount of electric V2G vehicles that are plugged in. Assuming EVs will replace most fossil fuel car, not every vehicle must be able to do V2G, nor all support the same services since the need for FCR would be satisfied at  $\leq 0.5\%$ , and black-start from renewables would require between 0.00001% and 2%, depending on the scale of the black-out event. These examples take into account parked cars which can’t participate in V2G due to them not being plugged in [32], [121], and it is still not close to the number of cars in use. The examples in Tables 7 and 8 can be refined by including additional factors, such as chargers and cars with a capacity different from 10 kW for V2G service or a greater number of V1G (unidirectional) chargers offering grid services, when compatible. There is a need for variety in the V2G services offered, to not have too many EVs compete with each other for the same service provision. Should information exchange between grid operators, infrastructural planners and EV (charger) investors deepen, regarding, i.e., mandatory minimum energy provision from each service provider, the corresponding revenues would become more apparent.

**D. TECHNICAL CONSTRAINTS AND PRACTICAL NON-IDEALITIES**

The reviewed projects, as listed in Table 6, assess the suitability of bidirectional charging for the provision of various grid services. While some services, such as frequency reserve or peak demand reduction, are studied in multiple projects, others are less explored in practice (including combined P/Q provision and harmonic mitigation). Since the latter topics are mainly investigated in simulation environments, practical technical constraints, and non-ideal characteristics are often underrepresented. Real-world data is scarce and usually includes charging session duration and transferred energy only [160]. Reconstructing charging profiles from this data is only possible if considerable assumptions are made. Only a few datasets have been published that include high-resolution



**FIGURE 7. Partial load DC charger efficiency at different SoC for Honda e Advance charging through EVTEC coffee&charge.**

measurements, allowing conclusions about charging characteristics and grid influence over time [161], [162], [163]. However, these datasets do not comprise V2G measurements, leading to a lack of data availability to improve bidirectional charger models or derive large-scale integration studies considering practical non-idealities. Although several studies include charging measurements in a laboratory environment, published data typically includes only the analysed results but not raw data, making it difficult to use these measurements for further studies. To the author’s knowledge, only one public dataset [164] is developed and collected in a general-purpose way to study both static and dynamic characteristics of V2X. Using such datasets, the decreased efficiency of EV chargers when operated below their rated power can be addressed. The topic is of high relevance as shown in several other studies for both OBCs and DC chargers [25], [165], [166], and yet, as seen in Table 1, only charging efficiency at the rated power level is published in the datasheets. High losses might impact user acceptance negatively when it comes to participation in certain services which require reduced charging power. Fig. 7 shows exemplary analysis results from [164] emphasizing both significant differences between charging and discharging as well as a major decrease in efficiency at decreased power. In discharging mode, efficiency drops from 97 % to 85 % when active power is reduced from 10 kW to 1 kW. Conversely, in this example, the efficiency is nearly independent of the EV’s SoC. The measurements are obtained from charger no. 1 in Table 1 and a Honda e Advance, Table 3.

In addition to varying efficiency, practical implementations of algorithms providing V2G services have to consider other non-idealities. The most prominent is the delay between the updated power setpoint and the change in power flow, which

**TABLE 9. Categories of Charger Costs and Which of the Costs Could Be Reduced**

Item no.	Cost breakdown	Possible price reduction
i.	Grid code protections	NA
ii.	Charge controller	Development of in-house controller, economies of scale
iii.	Eichrecht metering	Development of in-house controller, economies of scale
iv.	IMD	Development of in-house controller, economies of scale
v.	Housing	Custom-made housing (injection moulding) have high investment costs, but can be reused for new housing (economies of scale).
vi.	Charging cable and plug	Expensive part, not many suppliers (expected to become much cheaper in the future)
vii.	Cooling	NA
viii.	HMI-display	Optional, not needed (phone may be used)
ix.	Software license	NA
x.	Grid services	NA
xi.	Power Module	NA

**TABLE 10. Categories of Charger Costs and Their Contribution to the Total Cost**

Item no.	Category	Cost in %
i.	Printed circuit board assemblies (PCBA, includes labor and test)	35
ii.	Power semiconductors	17
iii.	Magnetic components	13
iv.	Mechanical support parts (sheet metal)	3
v.	Cooling (e.g., fans, heatsinks)	3
vi.	Screws, cable ties, glue etc.	3
vii.	Packaging	1
viii.	Assembly costs (labor, robots)	14
ix.	Final product test costs (pre-tests, functional tests, burn-in)	7
x.	Transport costs, duties, insurance	4

is highly individual for the charger and EV models. Delays up to 50 seconds are observed in [164] but can also be as low as a few seconds in other scenarios. This challenge comes into effect when targeting grid services bound to comparably low activation time scales (see Table 6).

**VII. COST ANALYSIS OF BIDIRECTIONAL OFF-BOARD CHARGERS**

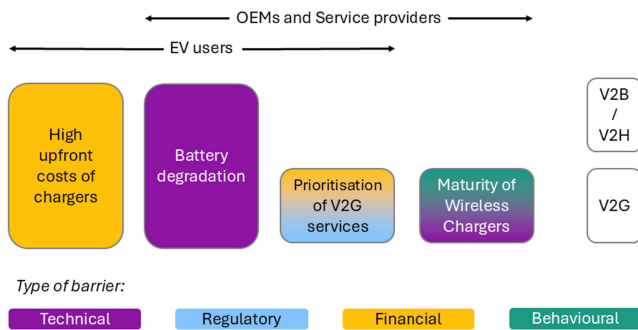
There are several contributing factors as to why installing a charger with bidirectional capabilities is, for the majority, not an option, as mentioned in Section VI. The production cost for a charger remains high due to low production volumes. When the technology is used commercially and not mostly in trial projects, the costs of V2X DC chargers is expected to decrease by five times, similarly to the trend of solar inverters [167], [168]. Further analysis is presented in Table 9 with eleven different categories identified, and Table 10 with ten different parts of the cost and their respective contribution to the total cost, determined with help from industry experts in charger manufacturing.

Item *iii* in Table 9 refers to the German calibration law regulations for EV charging [169]. It is considered one of the more rigid regulations on energy trading by means of bidirectional charging written to date, and it is expected that other

countries within Europe, such as Austria and France, will soon adapt equivalent regulation. This law make the pricing of electric charging more similar to re-fueling at a gas station by use of kWh consumption-based billing, which is intended to create user familiarity [169], [170]. To produce a meter which complies with the German calibration law regulations, it has to be calibrated and create one or more digital signatures for enabling validation of the charging session compared to the billing. A key pair has to be created when charging, and the user must get visual feedback via a display that shows it alphanumerically or via the generation of a QR code. Finally, only certified technicians are allowed to perform on-site maintenance of the charging system and the charger, and its meter has to be certified [169], which all increases the charger manufacturing costs.

**VIII. CONCLUSION AND FUTURE RESEARCH DIRECTIONS**

This article has investigated why V2G technology has not already been widely implemented, reviewing all topic areas that affect its implementation. In addition to the implementation barriers mentioned in other article, we identified four key themes crucial for making V2G technology more attractive: 1) battery charging algorithms to avoid degradation, 2)



**FIGURE 8.** Graphical summary of the conclusion and the four key barriers, classifying them into their specific typology. The map also indicates if these barriers exist in the context of V2G or V2H/V2B. Some of the barriers affect more than one stakeholder.

wireless chargers, 3) enabling short-time V2G grid services, and 4) smart cost management by charger manufacturers. This is illustrated in Fig. 8, alongside who is affected, and what type of barrier it is. While these four barriers are synthesized from insights from the existing reviews, this survey introduced a newly structured classification tailored specifically to DC off-board bidirectional charging technologies. Other potential barriers to the implementation of V2G technology, not included in Fig. 8, such as cyber security threats, how block-chained based market design and renewable energy forecasting affect the future EV charging market, and long-term environmental impacts (e.g., battery production), have not been addressed in this survey.

Even when not accounting for emissions from battery production, one significant barrier to mass deployment of V2G technology by OEMs is battery degradation. These concerns can be addressed by taking both calendar ageing and cyclic ageing into account to prioritize battery health when optimizing the charging algorithm. This would encourage OEMs to offer more bidirectional EVs. Our review of trial projects highlights the importance of short timescale grid services in an established V2G trading market. The grid services provided by V2G compete with the ramp-up of other electric flexibilities, such as stationary batteries. Since a number of grid services can be used with unidirectional charging as well as bidirectional charging, an accurate estimation of the required number of V2G vehicles and chargers can be made when the availability of electric flexibility is known. This also encourages OEMs to offer more bidirectional EVs. Developing a V2G-service demand tool with data from distribution and transmission system operators can ensure that bidirectional chargers are installed at the right locations. Additionally, the increased implementation of wireless chargers would eliminate the need to physically plug in a charging connector, thereby increasing the availability of EVs for V2G services. Moreover, reducing manufacturing costs will make V2G technology more economically viable. Cost reduction can be achieved by replacing components that are not strictly necessary in a charging station (e.g., a high-resolution display

can be replaced with a web interface, and the metal casing can be replaced with a plastic mold-cast casing), as well as scaling up production. Adherence to international standards such as ISO-15118 also ensures uniform adoption and global compatibility, which can enable the upscaling of V2G-related equipment (i.e., charging stations, compatible EVs, and metering).

When battery degradation is well understood, and the initial investment needed to purchase a bidirectional charger has decreased, *user acceptance* of V2G technology can become *user appreciation*. Green home system integration can be simplified from the user perspective if V2G operation is automatically activated. However, it is important that the user has insight into the charging process, its effect on battery health, and can remain in control. The EV user must, for example, be allowed to abort V2G operation (referred to as Priority charging), a feature available in OCPP 2.1.

Collaboration between the mobility and energy sectors is crucial to overcome the remaining challenges in communication protocols relating to V2G operation. National standards must complement and not contradict international standards such as IEEE 2030.5, OpenADR, OCPP, and ISO-15118. It requires a common framework incorporating communication protocols, information exchange, response specifications, and cybersecurity requirements. For this, a platform for collaboration on V2G-suitable protocols between the mobility sector and energy entities may be set up to avoid interoperability and implementation conflicts - Ongoing efforts are, i.e., Task 53 led by the International Energy Agency.

To explore topics not covered in this survey, future research can investigate the risk of V2G system compromise through cyberattacks. Although standards such as ISO 15118 and IEC 62443 offer robust security measures, vulnerabilities may still exist. Market dynamics, as discussed in Section VI, could shift if smart charging and V2G adopt blockchain-based trading, enabling fractionalized digital assets and thus benefiting small trades, possibly reducing reliance on aggregators. Improved renewable forecasting may also lessen the need for V2G capacity (briefly explored in Section VI-C), as accurate weather data allows tighter energy storage margins. Both blockchain-driven markets and renewable energy forecasting have an impact on V2G economics that warrants further study. Additionally, a comprehensive lifecycle assessment of emissions related to V2G, including those associated with battery production and the operational demands of bidirectional energy flow, remains an important research area. In summary, by setting clear constraints in battery charging algorithms to prevent premature degradation, reducing manufacturing costs, developing a suitable trading market which includes the EV users' wishes and advancing wireless charger technologies, V2G can be improved and made more attractive. With continued efforts in these areas, V2G technology has the potential to accelerate the transition to a grid which only uses renewable energy as V2G levels out the intermittency and imbalance on the grid introduced by wind, solar, and hydro-based power generation.

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