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Vehicle-to-X (V2X) implementation: An overview of predominate trial configurations and technical, social and regulatory challenges

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ABSTRACT

The uptake of electric vehicles supports decarbonization and increasingly interconnects the electricity and transport system. While the integration of electric vehicles could challenge electricity grids, bidirectional power flows between vehicles and grids could support grid operations. Despite the globally increasing number of Vehicle-to-X trials, including Vehicle-to-Grid and Vehicle-to-Customer, an in-depth understanding of trial implementations and expert experiences has largely been overlooked although they are both crucial for technological development and deployment. Based on our analysis of a global Vehicle-to-X trial database and 47 interviews with experts from industry and academia, we (i) provide an overview of the implementation status of Vehicle-to-X and analyze predominate trial configurations, i.e. combinations of characteristics, (ii) identify important technical, social and regulatory challenges for the implementation of Vehicle-to-X and assess and discuss expert evaluations of these challenges and (iii) derive implications for different actors.

The most predominate trial configurations are Vehicle-to-Customer and transmission-level services provided by commercial fleets that charge at work due to current practical advantages of centralized approaches. From a technical standpoint, we find that although Vehicle-to-X can defer or even mitigate grid reinforcement at the distribution level, this potential is highly dependent on local conditions. Regarding social aspects, incentives and Vehicle-to-X operations need to be tailored to different vehicle users. Concerning regulation, it is imperative to avoid double taxation of electricity, simplify market participation for small providers, and further develop Vehicle-to-X standards. Implications for actors include the evaluation and enablement of portfolios with different flexibility assets, and stacking of services to increase revenue streams and reduce risk resulting from variations in driving patterns and charging behavior.

1. Introduction

To mitigate severe impacts of climate change, all sectors require decarbonization [1]. While electrification is an essential measure to decarbonize the transport sector [2–4], electric vehicles (EVs) can also support the decarbonization of the electricity sector. Consequently, these sectors are increasingly coupled, which results in both challenges and synergies. On the one hand, integrating high shares of intermittent, distributed renewable electricity supply and increased electricity demand load from low-carbon technologies such as EVs can challenge distribution grids [5,6] by potentially coinciding with residential peak demand [7–10]. On the other hand, smart charging could turn EVs into assets for transmission system operators (TSOs), distribution system operators (DSOs) and electricity suppliers [8,11,12]. If controlled charging is applied, mobile batteries from EVs can support the integration of intermittent renewable energy in the electricity system by providing flexible load [13,14], decreasing both electricity and transport emissions. Bidirectional power flows between vehicles and the electricity grid could increase this benefit even further and ease the integration of high numbers of EVs by expanding flexibility services[2] for the grid [15–18]. Moreover, using these existing batteries in the system can create additional revenue for vehicle owners while saving investment costs in battery storage for the electricity grid [19]. Despite this potential, bidirectional charging is still in the testing phase, with an increasing number of trials[3] and few commercial applications [20].

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[1] Definitions of these terms are provided in Appendix A.
[2] Categories of V2G services are summarized in Appendix A.
[3] We refer to trials as non-commercial V2X implementations in real-life contexts.

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List of abbreviations[1]

CCS	Combined Charging System
DSO	Distribution system operator
EV	Electric vehicle
IEC	International Electrotechnical Commission
ISO	International Standards Organization
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturer
OSCP	Open Smart Charging Protocol
PV	Photovoltaic system
SOC	State of charge
TSO	Transmission system operator
V2C	Vehicle-to-Customer
V2G	Vehicle-to-Grid
V2X	Vehicle-to-X

Although knowledge of unidirectional EVs, e.g. charging patterns and vehicle availability [21,22], can provide some indication, the potential use of both charging and discharging for grid services requires further research [23]. Academic studies on Vehicle-to-X (V2X), including Vehicle-to-Grid (V2G) and Vehicle-to-Customer (V2C),[4] have analyzed technical specifications (e.g. Ref. [24]), important uptake factors (e.g. Ref. [25]), supportive policy mechanisms (e.g. Ref. [16]) and the demand for more investigation from a social perspective (e.g. Ref. [26]). However, the increasing number of trial implementations has mostly been overlooked; only recently, grey literature has started to draw lessons from trials and expert experiences [20,27–29]. Therefore, there is significant opportunity to develop an in-depth understanding of trials and expert experiences. In particular, insights from trials can be crucial for technological development and deployment (e.g. Refs. [30–35]), which have been empirically shown for energy technologies such as wind power [36,37], solar photovoltaics [38,39], carbon capture and storage [40,41] and EVs [32]. Trials support several forms of learning for different actors [42], e.g. technical learning [31,34], thus reducing technical uncertainties [31] and societal learning, such as product information, public acceptance and user practices [31,32,43]. Lastly, trials can shape normative processes and policy learning [33,34], including institutional barriers and regulation [31], policy priorities of different stakeholders [43] and policy coordination [37].

Accordingly, this study investigates V2X implementation and its challenges. More specifically, we provide an overview of the implementation status of V2X based on a global trial database [44] and analyze predominate trial configurations, i.e. combinations of the characteristics: provided services, charging[5] locations, and vehicle use types. These three characteristics are not only relevant for commercial implementation, but also outside of trials, and their analysis is important to identify underrepresented but promising configurations to be investigated in future trials. In addition, based on 47 interviews with industry and academic experts, we identify important technical, social and regulatory challenges and assess expert evaluations of these challenges. In addition, we focus on Germany, the Netherlands, the UK and the U.S. since most trial activities occur in these countries.

The remainder of this paper is structured as follows. After reviewing the relevant academic and grey literature (section 2) and explaining our method (section 3), we identify and discuss (i) the currently most predominate V2X trial configurations in terms of provided services, charging locations, and vehicle use types and their combinations (section 4.1) and (ii) important challenges related to future V2X implementation combined with expert evaluations of these challenges (section 4.2). Lastly, we derive implications for decision-makers in trials, industry, policy and research (section 5.1) and close with a conclusion (section 5.2).

2. Technical, social and regulatory aspects in academic and grey literature

2.1. Technical aspects

Studies focusing on technical aspects of V2X implementation dominate the academic literature and recent insights from trials indicate that the technical functioning of V2X has been validated [27]. For example, some studies evaluate the impact of communication systems between different V2X technology entities [45–48] and associated privacy concerns [49–51] or propose EV charging scheduling algorithms for aggregators [9,52–60]. Other studies focus on the interaction with the transport system and consider mobility requirements [61–63] or unplanned changes in EV use for mobility [64].

The impact of V2X on battery degradation is a widely discussed and contested technical aspect in both academic and grey literature. Important influencing factors for battery degradation include battery chemistry and size, temperature, driving and charging behavior, and different V2X service types [65–68]. While some studies emphasize the uncertainty related to battery degradation [12,28,69,70], others claim V2X causes only negligible additional battery degradation [71]. V2X could even extend battery life [72] by about 10% [27] when appropriate charging strategies are applied [73,74]. Several V2X trials do not consider battery degradation in their charging schedule, thus inhibiting the economic benefit of providing services [73,75–77]. Even if battery degradation caused by V2X might be limited, it remains a concern for EV users and must be addressed with appropriate value propositions and communication [78,79].

The potential limit of the long-term value of V2X services for both the transmission and distribution level is also prominently discussed. The two most mature services today are frequency response (TSO level) and load shifting (DSO level), which are commercially available in Denmark and Japan, respectively [20].[6] In the future, however, frequency markets will become saturated [80] and DSO services will compete with grid reinforcements [78]. An additional revenue stream in this future situation could comprise low-cost renewable energy storage [81]. Additionally, the stacking of different services and their prioritization are likely necessary to generate sufficient revenues [54,78].

Although the potential to circumvent or postpone distribution grid reinforcements is considered as one of the most important benefits of V2X, distribution grid services are underrepresented in both trials [44] and academic research [54]. Many V2G studies primarily investigate TSO-level services (e.g. Refs. [24,82]); studies that include DSO-level services—only about 15% of articles [26]—typically focus on theoretical rather than real-life cases [69]. This might be due to unsupportive market regulation [16] and the difficulty in predicting load at the DSO-level, leading to uncertainties in their value [83]. The few studies investigating DSO-level services emphasize that their potential varies according to location, e.g. if the charger is connected in a congestion zone [78]. Further findings suggest that the spatial and temporal spread of EV loads decreases adverse impacts on distribution grids while at the same time adding to uncertainty for grid reinforcement planning [7].

[4] Definitions of these terms are provided in Appendix A.

[5] Throughout the paper, we refer to both discharging and charging when using "charging".

[6] Arias et al. [69] provide an estimation of when specific services might be implemented commercially.

2.2. Social aspects

Both academic [26] and grey literature [20,27] call for further investigation of social aspects, which have received limited attention so far. Only 27% of trials consider social aspects [20], whereas 98% incorporate technical investigations [44].

Vehicle users have a substantial impact on the potential and barriers of provided services. In particular, the plug-in rate, i.e. the percent of time the vehicle is plugged into a charging station, is considered as one of the main sensitivity factors [72,78]. A low plug-in rate of about 30% [78] results from people charging their vehicle only if the battery reaches a low state of charge (SOC) [15,84]. However, in one study, around 30% of EV users charged several times per day and 70% once per day [15]. These variations indicate the necessity of incentives to stimulate vehicle plug-in.

EVs can be classified into two broad categories of vehicle use types: commercial fleets and domestic vehicles [85]. Commercial fleets are considered as suitable first adopters of V2X as they operate according to pre-defined schedules and are parked in the same area, which reduces infrastructure costs [16,18]. As domestic vehicles are typically not used according to a schedule, smart charging solutions often require EV users to specify their departure time in advance, which may not be attractive for them [86]. Due to variations in mobility needs and plug-in rates, a combination of the two vehicle categories can lead to greater availability for service provision [28]. Results from trials confirm the need to investigate users with a wide variety of behaviors and values in order to maximize V2X potential [27]. Moreover, academic and grey literature call for more studies to better understand how to tailor V2X to different vehicle users [27,87].

In addition to vehicle users' behavior and engagement while using V2X, some studies investigate prominent barriers for V2X uptake, including cost, inconvenience, distrust, confusion, range anxiety, battery degradation and charging time [9,84,87–92]. Some trials address these barriers by allowing EV users to schedule trips and force immediate charging [87]. Economic benefits are not necessarily required if range anxiety can be overcome [25], while education is also important to increase V2X uptake [28,92]. For commercial fleets, grey literature claims that education can bridge the mobility and energy divisions of a company [27]. Therefore, the positive impact of V2X on grid stability and on the integration of renewable energy should be communicated more clearly [86].

While today's driving behavior is not commonly integrated into models, future mobility concepts such as car sharing and autonomous driving require further investigation [20,72,93] because they induce new driving behavior, which in turn affects EV ranges [94,95] and plug-in rates [72,78]. Concerns about car sharing relate to lower availability for V2X service provision due to the long-term effect of fewer cars in the system and increased vehicle use for mobility during daytime [96]. The sharing of EVs with unidirectional charging, E-car sharing [97], provides initial insight into expected opportunities and challenges for V2X. Although E-car sharing can decrease operational and maintenance costs while offering the same level of service [97], range anxiety remains an issue since users must account for the SOC and charging infrastructure [93,98]. In addition, users might not plug-in their vehicle after each use, which results in additional costs for incentives or staff to plug-in the vehicles [97,99]. However, these costs could be defrayed by potential revenues from V2X service provision [97,100]. While autonomous vehicles have rarely been investigated [97,101,102], their main advantage besides similar drawbacks to car sharing, is the ability to travel to different geographical areas according to electricity system needs [102].

2.3. Regulatory aspects

Regulatory barriers have been identified as more severe than technical barriers [8,69]. These include the market participation of small capacity service providers and the lack of definitions for storage technologies [16,20,27,28,103]. Small capacity service providers, such as V2X, face two challenges for market participation. First, the minimum bid size, particularly at TSO-level markets, requires large-scale aggregation, which is difficult to achieve at early uptake stages [8,28]. Second, the large aggregation of many small assets multiplies the costs of the verification process, compared to one asset of larger size [20,28]. As storage technologies are not yet formally defined within electricity regulation in many countries, V2X flexibility providers need to pay energy levies for both charging and discharging [16,27]. In addition, charging batteries for V2X service provision cannot yet be distinguished from charging for mobility services [20,28]. Both aspects are considered key barriers for V2X business model development [20].

To encourage market participation, researchers have studied different market designs and tariff structures for frequency [104,105] and voltage [106] services as well as auctions and tenders. Of the few studies that focus on DSO-level services, Knezović et al. [107] analyze potential future market structures to enable the acquisition of flexibility services for DSOs. In particular, the authors advocate for an open flexibility platform with transparency for all stakeholders to avoid adverse interactions between TSO- and DSO-level services. Furthermore, flexible electricity tariff rates, including a capacity and an energy component, could encourage participation in service provision [8,87]. In addition to market structures and tariffs, longer regulatory periods, definitions and transparent payments for DSO services as well as incentives for active distribution grid operations are required to foster innovation, including smart technologies and flexibility procurement [8].

Another barrier to V2X implementation relates to the development of technical standards [20,27,28]. The most prominent challenges in terms of standards for V2X relate to communication standards that enable bidirectional charging [20,96,108] and interconnection standards for bidirectional chargers to distribution grids [20,27]. To ensure interoperability between different equipment and stakeholders, widely accepted communication standards are required for several interfaces, such as between electricity markets, aggregators, TSOs, DSOs, chargers, and vehicles [8,28,96,109,110]. For interfaces without international standards, open application protocols[7] are relevant [8], which have started to integrate bidirectional charging and support the development of the respective standards [111]. For the interface between chargers and back-end systems of aggregators/charging station operators [8,28,112], a widely used open application protocol is the Open Charge Point Protocol (OCPP) governed by the Open Charge Alliance [113,114], leading to the standard IEC 63110 [111,113,114]. For the interface between chargers and vehicles, the CHAdeMO protocol allows for bidirectional charging, which has initially mostly been used by Asian Original Equipment Manufacturers (OEMs) [115]. However, the Combined Charging System (CCS), implemented in Europe and the US for the interface between chargers and vehicles, does not yet allow for bidirectional charging [116]. This is expected to change once the international standard ISO 15118-20 has been released, which is currently under development and expected to extend previous versions by including further value-added, charging-related features, such as bidirectional charging [117]. The lack of grid interconnection standards for V2X chargers – that are proportionate to their asset size – is another key barrier, particularly because these standards are typically country-specific, requiring the V2X system to adapt to different contexts [20,27]. As some V2X trials report interconnection

[7] In this context, we refer to communication protocols as protocols that define a set of rules to allow interactions between all involved actors by connecting their roles in a specific market through interfaces. Communication standards formalize widely accepted protocols and their ways to exchange the information of different use cases with the main objective to ensure interoperability between all involved actors [8,111].

requirements as key challenge, for instance in France, Denmark and the US, some countries have started to change respective standards, such as the UK [20,28].

In addition, the social and political implications of these technical standards should not be overlooked, e.g. international standards might require different management concepts in different geographical and institutional environments [118]. Lastly, while most policy recommendations are related to the electricity sector—neglecting the automotive industry and vehicle users [16]—it is crucial that key actors from the transport and electricity sectors collaborate, including automotive manufacturers, charging station manufacturers and operators, grid operators, governments, vehicle users and researchers [16,27,85].

In summary, the main technological, social and regulatory challenges for V2X commercialization indicated in the literature include uncertainty about battery degradation, decreasing prices in frequency response markets, a lack of data at the DSO-level, minimal vehicle user education about V2X, limited value proposition to users, unsuitable market structure for EV participation, and several challenges concerning the development of standards. However, the literature shows that current findings do not provide a holistic picture about V2X implementation, particularly concerning the configurations of V2X trials and ensuing challenges for implementation, such as service provision at the DSO-level, future driving behavior and the development of standards. In the following sections, we address these gaps by analyzing predominate configurations of completed and ongoing V2X trials as well as identifying important technical, social and regulatory challenges for V2X applications in general.

3. Method

Our method consists of two steps. First, we analyze the V2G Hub online database [44], comprising 80 V2X trials worldwide; second, we conduct interviews with experts from industry and academia. The projects featured in the database cover more than 6700 chargers installed in 22 countries. The highest share of V2X trials is based in Europe with 59%, followed by North America with 25%, and Asia with 10% [44]. The database provides several trial characteristics in which provided services, charging locations and vehicle use types[8] are also relevant for implementation outside of V2X trials. While analyses for individual characteristics are available [20,44], combinations of these three characteristics have not yet been analyzed. Therefore, we focus on the 47 trials in the database for which information about all three selected characteristics is available. We count how many of the 47 trials test the same configuration, i.e. combination of the three characteristics, to identify predominate configurations, which might indicate initial commercial implementations of V2X.

We used purposive sampling to interview experts from different backgrounds and stakeholder groups as well as those involved in trials with a variety of provided services, charging locations and vehicle use types. As most of the trials are still ongoing, publicly available data is limited which is why we conducted 47 interviews. In particular, we used semi-structured interviews to enable interviewees to raise new elements and justify their statements while at the same time being able to compare answers during analysis [119,120]. Furthermore, we structured all interviews according to technical, social and regulatory aspects and focused on interviewees' personal evaluations instead of general industry perspectives. Lastly, we continued to conduct interviews until we reached theoretical saturation.

While we focused on Germany, the Netherlands, the UK and the U.S. [20], we added interviews with experts from Canada, Denmark, France, Spain and Switzerland to increase diversity and limit bias in the sample. Table 1 details the different stakeholder groups with their respective number of interviews. The goal of this study was not to evaluate robust differences in expert evaluations between groups which would be subject to further research. Appendix C provides further detail about the interviews and trials in which interviewees are directly involved as well as reference numbers referred to in this paper.

Table 1
Overview of interviews.

Stakeholder group	Number of interviews
Consultancy	9
Charging Solutions Provider	8
Other Energy Infrastructure and Service Provider	6
Network Operator	6
Energy Supplier	5
Government	4
Academia	4
Car Original Equipment Manufacturer	3
Association	2
Total	**47**

Source: Authors.

4. Results

4.1. Predominate configurations of V2X trials

Fig. 1 demonstrates the trial configurations concerning the combinations of the aforementioned three characteristics: provided services, charging locations and vehicle use types. Based on this figure, we can make three main observations.

First, trials focus on TSO services and V2C rather than DSO services. As DSOs do not know the current distribution grid load because they have not yet measured the required data, they cannot define required services for the grid [Int2, Int5, Int31, Int36, Int37, Int39, Int47].[9] Therefore, the value of the DSO services is unclear [Int5, Int21, Int25, Int30, Int31, Int36, Int45] while already established TSO-level markets provide transparent values of services, enabling service providers to estimate potential revenues [Int2, Int5, Int31, Int36, Int37, Int39, Int47]. Therefore, experts expect that initial commercial implementation will focus on TSO services [Int2, Int4, Int5, Int21, Int31, Int44, Int46]. In addition, V2C is currently easier to implement than V2G due to fewer regulatory barriers [Int10, Int21, Int32, Int37, Int44], seamless technology installation and operation, less collaboration across the value chain and no required market mechanisms or aggregations [Int9, Int34, Int36, Int45]. Furthermore, V2C is valuable for peak demand shaving if time-of-use tariffs based on peak demand are used, which is often evident in the commercial context [Int28, Int31, Int35, Int44]. In the domestic context, early adopters connect emotional value with V2C, as EVs can support photovoltaic system (PV) integration into their household energy system, increasing self-consumption [Int21, Int22, Int31, Int47]. This perceived emotional value could partly compensate for potentially lower financial value of V2C compared to the commercial context [Int25, Int31, Int34, Int35, Int45].

Second, many trials focus on work charging rather than home or public charging due to the practical benefits of centralized charging. Charging commercial fleets in depots reduces infrastructure installation costs as centralized infrastructure can serve more vehicles, and the assessment of the grid connection is only required at a single site [Int37], which reduces the required interactions between DSOs, charging station operators, and installers [Int18, Int19]. Additionally, the charging cycle of domestic vehicles at work aligns with PV generation and thus, can support its grid integration [Int4, Int8, Int36]. Home and public charging can be centralized in (domestic) car parks, which provide high predictability and high certainty that almost all charging stations will be

[8] The definitions of the three characteristics used in our analyses are specified in Appendix A.

[9] This reference notation refers to the interviews, as detailed in Appendix C.

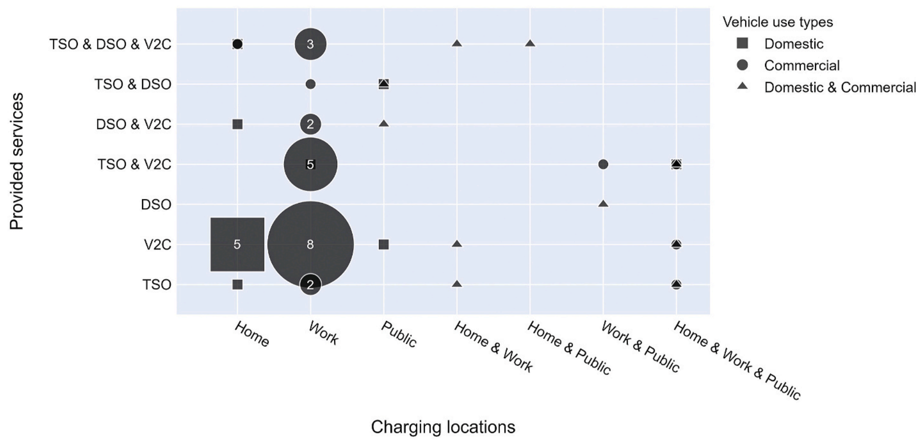

Fig. 1. Configurations of 47 completed and ongoing trials for which information about the provided services, charging locations and vehicle use types was available (Graph: Authors, Data source: [44]). The total shares of trials per option of the three characteristics are as follows: TSO (53%), V2C (81%), DSO (30%); Home (43%), Work (72%), Public (28%); Domestic (45%), Commercial (74%).

used [Int9]. Further details on suitable charging locations are discussed in section 4.2.

Third, we observe a clear dominance of commercial fleets over domestic vehicles. Commercial fleets involve fewer actors which are also familiar with collaborations and negotiation [Int2, Int22, Int32, Int37]. Therefore, a lower number of contracts is required to achieve capacity thresholds for service provision [Int9, Int10, Int11, Int33, Int34] and minimal educational efforts are needed [Int5, Int24, Int25, Int32, Int35, Int40]. Additionally, commercial fleet operators are expected to replace unidirectional charging with V2X sooner than domestic EV users [Int2, Int29], as the latter might not recognize the benefits of V2X since their decisions are predicated on emotions more so than economics [Int11, Int24, Int29, Int35]. Another issue is that domestic vehicles are less predictable [Int37, Int43, Int47]. As trials involve only a limited number of vehicles, it is more difficult to stochastically balance those variations, which could restrict possible V2X investigations [Int37, Int47].[10] However, commercial fleet operators, who have recently invested in electrifying their fleet, or charging station operators, who used policy incentives fostering unidirectional charging to expand the charging infrastructure, might be locked into unidirectional charging and hesitant to invest in V2X in the near term [Int1, Int3, Int11, Int15, Int21, Int35, Int36, Int37]. Moreover, fleet operators might require a cultural shift to consider their fleets as energy assets [Int32, Int33, Int37]. Some trials report that they have difficulties in recruiting fleet operators to participate – despite substantial financial support – because the business model is not clear yet [Int33, Int35, Int42].

In addition to combinations of the three characteristics, the incorporation of different options within each characteristic can outweigh uncertainties concerning the feasibility and future development of V2X implementation. Although service requirements at the TSO and DSO level may be conflicting [Int22, Int47] and trade-offs might exist, experts concur that these trade-offs are not necessary on a regular basis [Int22, Int25, Int34, Int47]. As one interviewee stated: *"These* [trade-offs] *would be very small-scale issues […] in theory yes, but on a larger scale no"* [Int22]. Furthermore, regulation could pose spatial or temporal restrictions on aggregators' service provision to achieve synergies between local and transmission needs [Int10, Int30, Int33, Int46]. For example, aggregators could be required to provide TSO services outside of peak hours or with EVs in areas that face less risk for congestion at the DSO level [Int2, Int11, Int21, Int22, Int46]. The combination of different services, both at different grid levels and together with V2C services, can increase the overall revenue of a portfolio, particularly when considering long-term developments [Int21, Int22, Int28, Int35, Int47]. We discuss this aspect further in section 4.2.

The combination of different charging locations and vehicle use types is important to diversify electricity demand in time and space, as it reduces adverse impacts on the grid [Int22, Int31, Int34]. In particular, the combination of home and work charging is considered as most suitable for V2X as cars have the longest dwell time at these locations [Int5, Int9, Int23, Int31, Int35, Int36, Int37, Int41, Int45]. Although the combination of home and work charging mostly refers to domestic vehicles, certain types of commercial fleets might also be charged at the employees' home overnight [Int37]. Moreover, households without off-street parking or available public chargers overnight could use work charging during the day [Int33, Int41].

Overall, trial activities show only little variety in the combinations of the investigated characteristics mainly due to current practical advantages of centralized approaches. While it is possible that V2X remains a niche activity for several years because business models only exist for specific applications [Int1, Int42], our interviews reveal that the primary value of V2X is associated with the combination of different configurations. As both commercial fleets and domestic vehicles can support service provision at the TSO and DSO level [Int2, Int7, Int30, Int32, Int38, Int46], services cannot be connected to a particularly suitable vehicle use type [Int4, Int22, Int32, Int36, Int38]. Similarly, services and charging locations can be combined independently, as service requirements depend on grid constraints of a given location.

4.2. *Identified technical, social and regulatory challenges and their expert evaluations*

Table 2 summarizes the challenges for V2X implementation that our interviewees considered as important, categorized into "technical", "social" and "regulatory". Our assessment of expert evaluations reveals "common evaluations", "different evaluations" and "knowledge gaps" in all three categories. Table 2 also indicates their uncertainty ("different evaluations") and their difficulty to be solved ("knowledge gaps"). However, comparing the severity of and prioritizing the challenges is not the goal of this study. The remaining part of this section is structured according to the columns of Table 2. Appendix B justifies the categorization of the challenges with quotes from the interviews, and we also include selected quotes that illustrate our findings. The "common evaluations" represent acknowledged challenges for V2X. While the "different evaluations" demonstrate that experts disagree on whether this aspect is a challenge for V2X or not, the different evaluations also partly emerge from different country contexts that induce varying grid

[10] More details on the driving patterns of different vehicle use types are discussed in section 4.2.

Table 2
Overview of identified challenges for V2X implementation, categorized into "technical", "social", and "regulatory".[a]

	Technical challenges	Social challenges	Regulatory challenges
Common evaluations	• *Battery degradation* caused by V2X: no technical but social challenge • TSO level: Future oversupply of *frequency services*	• *Implementation of decentralized charging*	• *Double taxation* of electricity • Hesitation of DSOs toward *smart solutions* • Enabling *small providers* to participate in TSO-level markets
Different evaluations	• Contradiction between *distribution grid requirements and economic attractiveness and technical potential* of V2G • Evaluation of the potential for *distribution grid reinforcement deferral and mitigation*	• *Plug-in behavior* of different EV users • Compatibility of *future mobility concepts* with V2X	• Development of *standards* for charging equipment and communication protocols
Knowledge gaps	• DSO level: *Future flexibility supply and demand* and the *impact of V2C*	• *EV users' actual interest* in participating in V2X and potential incentives • Effect of *increased scale* of V2X: interim stages and high diffusion	• Establishment and feasibility of *markets, tariffs, auctions or tenders* at the DSO level

[a] Economic aspects play a crucial role in all three categories and can hardly be decoupled from them.
Source: Authors.

stability and regulation and, therefore, provide insights on the context-specific challenges. "Knowledge gaps" represent missing information in the field, including unknown future developments, which makes these challenges particularly difficult to solve.

4.3. Technical challenges

Experts from OEMs, aggregators and electricity service providers share the evaluation that *battery degradation* does not pose a technical challenge for V2X [Int4, Int5, Int13, Int14, Int26, Int31, Int32, Int34, Int35, Int45, Int46] but can be considered a social challenge [Int24, Int35, Int45, Int47]. As one interviewee from an OEM explained: "*I think it's* [battery degradation caused by V2X] *not really a topic anymore* [...] *I see it as an OEM and obviously we pay the warranty costs. We've been looking into it very, very, very thoroughly"* [Int26]. However, the degree of battery degradation depends on the type of provided grid service and other parameters, such as temperature and driving behavior [Int4, Int31, Int36]. Charging strategies that maintain a SOC around 50% are most conducive for supporting battery life [Int14, Int31, Int34, Int45]. For vehicle use types involving dwell times of several weeks, e.g. domestic vehicles during holidays or school buses during summer breaks, V2X could even extend battery lives [Int4, Int14, Int46]. To optimize revenue at a certain point in time, aggregators should incorporate battery aging costs for the prevailing conditions [Int3, Int4], which requires more long-term data for many different conditions [Int9, Int32, Int37, Int39, Int45]. Although some car manufacturers have started to incorporate the number of charging cycles in their warranty based on different EV user profiles [Int5, Int26, Int38], greater transparency and more data on differences in battery lifetime, both with and without V2X, and the associated revenue for providing services could be beneficial for both value propositions and battery valuation for warranty purposes [Int13, Int 14, Int24, Int37, Int38, Int45]. As one interview asserted: *"Even if it* [battery degradation] *doesn't exist, the user has the perception of battery degradation, which means that it has to be compensated financially otherwise they will not participate"* [Int9]. Moreover, car OEMs can play a crucial role in this communication: *"So it's easier, I would say, for a car manufacturer to mention* [...] *V2G* [referring to V2X] *to the final user rather than for an energy company. The connection is closer. This is where the OEM can bring its value"* [Int5].

Experts widely share the notion that *frequency services* mainly provide short-term revenues due to market saturation [Int2, Int3, Int14, Int21, Int24, Int31, Int32, Int36, Int41, Int46]. The UK and the Netherlands have already observed a drop in market prices for frequency services as more supply became available [Int23, Int32]. Frequency services typically generate low revenue because they are only highly valued during a short period [Int21, Int22, Int23, Int32, Int34, Int35, Int37, Int47]. However, generating high returns over relatively short periods might make frequency services essential as part of a business model [Int2, Int21, Int34, Int36]. Once V2G infrastructure costs decrease with higher V2G uptake, other typically less lucrative markets, such as secondary and tertiary reserve markets, become more attractive [Int2, Int31]. Further revenue streams could emerge from contracts with renewable energy generators to avoid costs resulting from the violation of generation predictions [Int31, Int47]. As it becomes easier to integrate different services, e.g. using agile platforms to capture the highest value at any time, higher total revenue can be achieved [Int21, Int22, Int35, Int47].

Experts appear to be divided about whether the *economic attractiveness and technical potential* of connecting a V2G charger to the grid *contradict distribution grid requirements* [Int30, Int34, Int46]. While constrained distribution grids can benefit most from V2G services [Int6, Int35, Int42]—particularly in cases of high solar penetration [Int22, Int39, Int42]—higher installation costs in those constrained grids can reduce the economic attractiveness of V2G [Int32, Int33, Int35]. In some cases, the respective DSO might prohibit the installation of V2G chargers to prevent disproportionate investments in grid expansion or reinforcement that would ultimately increase grid charges [Int18, Int20]. Additionally, electricity export limitations for chargers in constrained grids can limit the technical potential of V2G [Int5, Int31, Int32, Int35, Int42]. Thus, the benefits of V2G in those grids need to be demonstrated for DSOs [Int42], and incentives to install V2G chargers in those grids and to charge in a way that supports grid requirements might be necessary [Int18, Int19, Int23].

While some experts note the potential of V2G for *distribution grid reinforcement deferral and mitigation* as challenging [Int4, Int11, Int30, Int35], others argue that grid reinforcement cannot be avoided [Int2, Int18, Int19, Int20, Int27]; still others are convinced that grid reinforcement will not be required if smart solutions are applied [Int3, Int6]. In addition, some experts expect a balance between reinforcement and smart solutions depending on local grid conditions, flexibility supply and the resulting costs of the respective solutions [Int10, Int23, Int24]. Distribution grid reinforcement is considered as one of the main values of V2G [Int2, Int22, Int33, Int35, Int47] since labor market constraints, finance issues and the required building permits make it impossible to reinforce many grids within a short period [Int16, Int19, Int20, Int22, Int30]. In the long term, distribution grid reinforcement mitigation is particularly relevant [Int2, Int3, Int6, Int27] as the value of V2G for DSOs decreases over time if reinforcement cannot be avoided [Int6, Int22]. It is, however, currently challenging to fully evaluate whether reinforcement will be necessary. As one interviewee explained: *"Theoretically yes* [V2G can avoid grid reinforcement], *and in specific situations yes, but we can't quantify it; we can only talk about very general or very specific situations"* [Int35]. A common measure to evaluate benefits from V2G for a distribution grid is the level of constraints in the grid [Int3, Int6, Int10, Int21, Int40]. This largely depends on local grid conditions, meaning that the typical classification into rural, suburban and urban

Table 3
Vehicle use types and their predicted plug-in rate.

	Plug-in availability	Plug-in predictability
Commercial fleets	Notably different patterns depending on company type [Int7, Int37]	High predictability due to fixed schedules [Int2, Int5, Int11, Int30, Int33, Int34, Int37, Int39, Int46]
Domestic vehicles	96% of the time not used for mobility purposes [Int7, Int31, Int32]; New EV drivers typically plug-in whenever possible due to range anxiety [Int3, Int31]; After three to four months, they plug-in their vehicles only two to three times per week [Int3, Int31, Int34]	Lower predictability [Int3, Int31, Int32, Int46]; Individual driving patterns of domestic EV users are quite predictable, but every individual has their own regularity in their driving patterns [Int6, Int35]
School buses and car parks at airports	High availability as school buses are parked for 80–85% of the year [Int44] and cars at car parks at airports for several weeks [Int3, Int6, Int40]	High predictability [Int44, Int3, Int6, Int40]
Car sharing vehicles	Lower availability for V2X of about 30% [Int2, Int21, Int31, Int34, Int35, Int38]	Rather high predictability (depending on booking system) [Int22, Int45]
Autonomous vehicles[a]	Depending on ownership model, cars might be used more often, resulting in lower availability [Int9, Int21, Int23, Int34, Int36]	Depending on ownership model/booking system [Int23, Int36]

[a] This future mobility concept could impact all other listed vehicle use types.
Source: Authors

grids is unsuitable for the evaluation of required grid reinforcement [Int22, Int30, Int31, Int34, Int36, Int38, Int44, Int46]. However, the lack of data makes it difficult to evaluate whether a distribution grid is constrained or not [Int1, Int4, Int11, Int18, Int19, Int20, Int30, Int35]. Smart meters, which may be a crucial element of a monitoring system [Int18, Int19, Int31, Int41], cannot measure all required parameters, such as voltage [Int30]. Therefore, DSOs need to establish monitoring systems for their grids to measure current load factors [Int22, Int30, Int31, Int36, Int43]. In addition, the reliability of demand response programs that involve different flexibility assets need further investigation [Int1]. As one interviewee stated: *"It's going to take a whole lot of data and learning to generate the expectations and targets* [related to demand response programs]" [Int1].

While some experts argue that there is substantial potential for economically valuable services at the DSO level [Int33, Int38, Int44, Int47], the *future supply and demand of flexibility* at the DSO level and the *impact of V2C* are unknown [Int11, Int16, Int18, Int19, Int20, Int33, Int34]. While flexibility demand might increase due to the integration of intermittent renewable energy [Int10, Int46], flexibility supply from increasing penetration of devices such as EVs and heat pumps could lead to oversupply [Int11, Int21]. Simultaneously, the uptake of V2C, typically resulting in increased self-consumption, reduces flexibility demand in distribution grids [Int33, Int41]. As one interviewee mentioned: *"Private people should first balance out their own energy demand throughout the day—and the same applies to commercial businesses or industry—to reduce the requirements for system services"* [Int11]. Therefore, the interactions between V2C and V2G and future flexibility requirements need further investigation [Int3, Int33, Int34].

4.4. Social challenges

Experts assess the *implementation of decentralized charging* as challenging. Both longer travel for maintenance [Int2, Int3] and required evaluation of the impact of each charger on the grid at each site [Int1, Int32, Int42] increase the effort for decentralized charging. As one interviewee explained: *"It's like a three-year and very expensive process to actually connect to the grid"* [Int1]. Therefore, work charging, which is typically centralized at one site, has most frequently been implemented in trials thus far. However, the longer the dwell time compared to the charging time, the more suitable the location for service provision [Int34]. Accordingly, decentralized charging at home with long dwell times is beneficial for V2X, whereas decentralized public charging with short dwell times [Int22, Int31, Int34] is unsuitable for V2X. Public chargers at destinations are usually sized according to the expected charging time of vehicles [Int9, Int16, Int34]. Nevertheless, at destinations where people are expected to stay for 6–8 h or overnight, such as shopping centers or parking in residential areas, public charging should be investigated [Int34].

While the plug-in rate is considered to be the most important aspect for V2X [Int8, Int35, Int37], experts debate whether the *plug-in behavior,* i.e. the plug-in duration (maximum availability for V2X) and the plug-in predictability of different EV users, constitutes a challenge for V2X. While some experts argue that plugging-in will become a habit similar to locking one's car [Int22, Int45], others contend that incentives are required for longer plug-in rates; therefore, it is important that EV users are compensated for providing capacity rather than for the actual services they provide [Int31]. Although plug-in behavior depends on individual EV users, it is typically connected to different vehicle use types, as summarized in Table 3. Trials aim to explore the extent to which domestic EV users might return with a higher SOC—i.e. higher availability for discharging—than commercial vehicles since they drive shorter distances [Int33]. As one interviewee stated: "*We assume that the availability of the battery* [of commercial fleets] *is lower than for average residential users*" [Int38]. The high predictability of commercial fleets allows aggregators to bid for different grid services with confidence [Int34, Int45]. In addition to the two main categories of commercial and domestic vehicles, the most suitable vehicle use types are school buses and vehicles with long dwell times, such as vehicles parked at airports, as they combine high availability with high predictability [Int3, Int6, Int22, Int40, Int44, Int47]. The combination of different vehicle use types and the resulting diversity in temporal and spatial use patterns decrease the risk of aggregators not being able to deliver the agreed amount of capacity at any point in time [Int22, Int31, Int35, Int46]. As one interviewee emphasized: *"I agree that ultimately to solve the global problem, you cannot just have one category of customers, you need to have a variety of customers and figure out the ones that are very complementary"* [Int46].

The "immediate charge" button influences *plug-in behavior* as it decreases both availability for V2X and plug-in predictability. This option allows EV users to stop grid service provision and charge at full speed, which has considerable value for both commercial fleet operators and domestic EV users [Int1, Int4, Int31, Int34, Int35, Int38]. Although experts agree that it is crucial to offer an "immediate charge" button as EV users prioritize the mobility purpose of vehicles, they disagree on whether this feature is a challenge for V2X since the value of plug-in predictability decreases with higher V2X uptake as more vehicles improve the stochastic predictability of the portfolio [Int11, Int31, Int46]. As one interviewee asserted: *"It is important to offer that option* [the "immediate charge" button] *because mobility is the first priority of the car. Sometimes they use it* [the "immediate charge" button] *but there is very different frequency for different people; there isn't more data available yet"* [Int4]. Experts suggest that domestic EV users use the "immediate charge" button mostly in the beginning when they do not yet trust the V2X system [Int38, Int47]. Moreover, for commercial fleets, the "immediate charge" button ensures that they do not need to sacrifice their primary business purpose for V2X [Int32, Int33, Int35]. Regarding this aspect, another interviewee added, *"Companies will definitely not change their schedules for V2G unless they get a lot of money for it"* [Int37]. Although trials aim to collect more data on the use of "immediate charge" buttons, their findings might be biased or insufficient given that trial participants might be contractually required to plug-in their vehicles whenever possible and that is it not possible to account for the impact of larger battery sizes on future plug-in behavior [Int35].

Future mobility concepts constitute further vehicle use types, such as car sharing and autonomous vehicles [Int2, Int23]. Experts disagree on whether these concepts are compatible with V2X. Both V2X and car sharing schemes aim to increase vehicle use [Int2, Int29]; thus, some experts argue that car sharing will negatively affect V2X due to the lower plug-in availability of about 30% [Int21, Int31, Int34, Int35, Int38]. Others consider V2X and car sharing as complementary because cars can still provide services during the night and thus could improve the business model of car sharing companies [Int14, Int15, Int22, Int29, Int38, Int45]. Moreover, fleet-based mobility services have the advantage of centralized approaches [Int8, Int25], as discussed in section 4.1. The expected long-term effects of fewer cars on the road due to car sharing might increase the value of service provision [Int35, Int45]. Some experts also argue that autonomous vehicles support V2X due to automatic plug-in [Int3, Int26, Int47] and their ability to move to places where services are needed [Int45, Int47]. Others assume that autonomous vehicles will operate with a sharing concept, with their increased use leading to a corresponding decrease in availability for V2X [Int9, Int21, Int23, Int34, Int36]. Depending on the ownership model, autonomous vehicles might demonstrate a similar plug-in predictability to car sharing vehicles or domestic/commercial vehicles [Int23, Int36].

An important knowledge gap is *EV users' actual interest* in participating in V2X. This is difficult to investigate in trials [Int34, Int35] since they provide high incentives and typically involve engaged early adopters [Int1, Int33, Int35]. As one interview stated, "*Do people want to participate and value smart charging? We need to answer that question fairly soon because we can't assume that V2G* [referring to V2X] *will be wonderful if we can't make customers to behave in a way that enables V2G* [referring to V2X]" [Int34]. Trials often provide free chargers or vehicles to incentivize people to participate [Int2, Int4, Int21, Int35, Int38]. However, free equipment cannot be justified in real-life situations. Regarding this sentiment, an interviewee noted, *"Realistically, it comes down to the cost of the charger—it is just a total business case killer right now"* [Int35]. While many experts argue that financial incentives are necessary for mass adoption [Int3, Int4, Int9, Int23, Int45], others contend that providing education and information is equally effective [Int25, Int34, Int41, Int42]. Furthermore, one interviewee stated, "*Sometimes there is still range anxiety and not understanding how the system works, so there is a big role for education"* [Int46]. Thus, incentives for participating in V2X might need to be varied according to different user types [Int21, Int23, Int36]. One expert explained: "*We did interviews with people and asked them why they participate in the trial and the financial aspect came on the third place: first place was that they like the idea of being independent and second was climate goals"* [Int22]. User propositions should be simple and users need to be able to set boundary conditions such as departure times or a minimum state of battery charge at any time [Int9, Int21, Int23, Int35, Int36, Int45]. One interviewee emphasized: *"What the users care about is that their car is ready when they need it but they don't care about what service they provide"* [Int46].

The effect of *increased scale* of V2X on service provision and the wider electricity system is unknown [Int36, Int37]. Potential challenges for V2X diffusion, particularly interim stages of 10%, 20% or 30% V2X uptake, include neighboring effects leading to the clustering of charging loads [Int22], uncomplimentary space-time patterns of EV users, potential low predictability combined with low availability of vehicles, and limited capacity at early stages [Int35, Int37]. Therefore, larger fleets combined with other flexibility assets play a crucial role at early uptake stages [Int21]. High diffusion can also entail unknown challenges because trials can typically only include a limited number of vehicles, which does not allow for assessing impacts of several thousand V2X-vehicles in the system [Int36].

4.5. Regulatory challenges

Common evaluations refer to required regulatory changes to overcome current challenges. The main regulatory challenge to develop business models for V2X is *double taxation* of the charging and discharging of batteries in several countries, such as Denmark, France, Germany, the Netherlands, the UK and the U.S. [Int2, Int4, Int14, Int22, Int23, Int31, Int32, Int36, Int38, Int46].

Furthermore, current regulation in some countries makes DSOs hesitant to explore *smart solutions* as opposed to grid reinforcement given the lack of economically attractive and/or reliable use cases [Int8, Int23]. Accordingly, governments should support a focus on smart solutions rather than grid reinforcement [Int6, Int8, Int10, Int19 Int25, Int30, Int36, Int43]. One expert mentioned: *"It* [establishing smart solutions] *makes no sense because, at the end, they* [DSOs] *will not receive money for that; the regulator has to encourage them*" [Int30].

At the TSO level, *small providers* face impediments in participating in existing reserve markets, as they require a large volume of dispersed assets to meet the typical minimum bid size [Int1, Int31, Int36, Int37, Int39, Int41, Int42, Int43]. Moreover, the typical sale cycles of one week or one day are too long for vehicles [Int6, Int31, Int37, Int47]. However, Denmark has started to decrease the minimum bid size to 0.1 MW and shorten the sale cycles to 4 h and it is expected that other countries will follow [Int21]. Another obstacle is that measuring and verifying many small providers is costly and it is unclear whether the current requirements can be applied at the portfolio level rather than the asset level since vehicle characteristics differ in vehicle type and battery age, for instance [Int21, Int22, Int36, Int38, Int39, Int43].

While experts agree that *standards* for charging equipment and communication protocols are required [Int2, Int9, Int21, Int25, Int31, Int34, Int37, Int47], there are different evaluations about the (i) benefits of a standard for V2X diffusion at the expense of innovation, (ii) difficulty of establishing a standard and (iii) the role of different actors. Standardized communication protocols enable small aggregators to connect several geographic areas given that the use of chargers is not restricted to a selected number of actors or specific areas [Int3, Int36]. On the one hand, standards could indicate the existence of a viable business opportunity and thereby foster technology diffusion [Int1]. On the other hand, innovation might decrease once a standard is established, and considerable costs for compliance might arise, which particularly disadvantages small actors at the early stages of technology development [Int3, Int15, Int19, Int27, Int43]. Regarding this, one interviewee noted that *"[...] you want to have a standard, but once they have the standard* [...] *there's no room for innovation anymore.* [...] *it's the worst performing standard—most expensive standard"* [Int27]. While specific standards might be established in the near term [Int9], there could be a lack of drive toward a standard by different actors: *"The OEMs say, 'we will* support *it* [the standard] *once the charge point providers will do' and the other way round, and the customers are not shouting for it because they don't know they need it—so there is no market force to create that drive at the moment"* [Int34]. Moreover, the development of standards can also be a strategic issue for actors as details in the standard may determine the role of actors and the value they can capture, e.g. whether car OEMs or charging station providers control the charging session [Int20, Int21, Int29].

At the DSO level, it is unknown which *markets, tariffs, auctions or tenders* will be feasible and provide the most attractive solutions for flexibility provision [Int8, Int12, Int24, Int31, Int47]. One challenge for establishing flexibility markets at DSO level involves determining the most suitable geographical scope [Int10, Int25, Int31, Int43]. Each distribution line, typically encompassing 20–30 houses, could potentially have different needs for load management [Int36]. As small DSOs might not have the capacity to develop markets at such a local scale

[Int10, Int11], they could cooperate with TSOs operating in the same geographical area [Int21]. However, a substantial amount of V2G chargers within a small location would be required to enable local markets [Int22, Int31] and avoid dominant actors, leading to market power issues [Int12]. As one interviewee explains: *"There are ideas to create smaller flexibility markets. But the smaller such markets are the more you can expect to run into market power issues – so, in the end, it is not going to be a market anymore"* [Int12]. Some aggregators have started to geotag their services and demonstrate platforms that map the spatial availability of services in real-time for DSOs [Int8, Int35, Int38]. Some experts claim that different types of time-of-use tariffs, which are more tangible than frequency markets and distribution grid services [Int32, Int35, Int38, Int43, Int47], are likely needed to provide incentives [Int11, Int23, Int26, Int32]. Others argue that flexibility auctions or tenders at TSO level [Int39] and low voltage level [Int6, Int33] could emerge, with one interviewee stating that *"it looks like it's going to be more like a bidding process. Looks like that's more flexible than the tariff"* [Int5]. The combination of tariffs with other approaches to procure flexibility is also possible, as one interviewee explains: *"In an ideal world, you would have people on a time-varying tariff to lower the overall base level of demand. And if that's not enough in a particular region, then the DSO will procure extra flexibility. It's hard to tell at the moment which is going to be the best approach"* [Int43].

5. Discussion and conclusion

5.1. Implications

Overall, our findings lead to several implications for decision makers in trials, industry, policymaking and research. As V2C and TSO services provided at work by commercial fleets dominate current trial configurations, future trials should investigate a broader variety of the combinations of provided services, charging locations, and vehicle use types, including combinations of different options within these three characteristics. In particular, the interdependence of TSO, DSO and V2C services; the combination of home and work charging; and the potential correlation between vehicle use types and grid types require further investigation. Furthermore, more real-life data on battery degradation for different conditions and service types may reduce persisting concerns regarding battery degradation and valuation. Regarding social aspects, future trials should collect real-life data on plug-in habits as well as the availability of vehicle use types for different services and their reliability. In addition, trials can support education to foster higher V2X uptake and identify appropriate propositions for a variety of users.

While industry decision-makers depend on future trials in some respects—e.g. industry could use the data from trials to provide transparent battery warranty, and information about potential degradation and revenues from providing services—there are also implications for industry independent of trials. Industry actors should establish agile platforms that allow for service provision based on the highest value at any point in time to enable stacking of services and increase revenues. Furthermore, to gain clarity about service requirements, a monitoring system for distribution grids should fill the lack of data about current distribution grid loads to reduce uncertainty regarding future flexibility requirements and market development. Overall, actors from the electricity and the automotive industry need to cooperate by leveraging IT solutions.

Concerning policy-makers, our study confirms the importance of (i) avoiding double taxation of electricity (ii) establishing suitable compensation for service provision, (iii) avoiding a lock-in to unidirectional charging infrastructure through existing policy incentives (iv) supporting smart solutions at the DSO level, (v) simplifying market participation for small providers, and (vi) supporting the development of standards. Double taxation for the charging and discharging of batteries represents a primary regulatory barrier to developing business models for V2X in several countries. Accordingly, a suitable legal definition of batteries that avoids taxation as a consumer and as a generator is needed. It is also imperative that EV users are compensated for providing capacity rather than for the actual services they provide to incentivize longer plug-in rates. Regarding technology competition, there is a risk that existing support policies for charging infrastructure create a lock-in for unidirectional charging as infrastructure providers are incentivized to scale output as opposed to providing new, innovative solutions such as bidirectional charging. Moreover, policy-makers could support DSOs to explore and implement smart solutions according to the grid type, including financial support for reliability tests and the above-mentioned monitoring systems. Furthermore, policy-makers can make existing markets at the TSO level more accessible for small capacity service providers by reducing minimum bids or shortening sale cycles. Similarly, regulation needs to enable stacking of services, aggregation at different levels, and the operation of flexibility platforms. At the DSO level, additional concepts for service provision should be considered, such as markets, tariffs, auctions and tenders. The role of actors such as DSOs and potential market facilitators as well as potential collaborations between TSOs and DSOs, particularly in countries with many small DSOs, also needs to be specified. Finally, the required international cooperation and collaboration between the transport and electricity sectors for establishing standards should be supported, e.g. via funding conferences or subsidizing joint projects.

Further research is required to better understand several technical and social aspects. For example, studies should investigate service requirements of different distribution grid types and the interplay between increased V2C and V2G services. To assess which combinations of EV users are most beneficial, potential correlations between EV users and their charging locations as well as the required grid services at those locations should be evaluated. Additionally, future research could help to develop value propositions for different EV user segments and examine various types of companies and their motivation to participate in V2X. Lastly, future research can complement trials by incorporating real-life data in modelling approaches, covering larger portfolio sizes and a wider variety of configurations.

5.2. Conclusion

Based on insights from V2X trials with a focus on Germany, the Netherlands, the UK and the U.S., our study makes three contributions. First, we provide an overview of the implementation status of V2X and analyze predominate trial configurations. Second, we identify important technical, social and regulatory challenges for the implementation of V2X and assess and discuss expert evaluations of these challenges. Third, we derive implications for different actors.

Overall, efforts from different actors and collaboration are required to overcome the challenges identified in this study. Large portfolios consisting of diverse EV users, vehicle use types, flexibility assets, and stacking of services could solve many of the technical and social challenges as well as generate sufficient revenues and decrease risk. While this positive effect of diverse portfolios has been identified in grey literature on V2G [78], some researchers have found similar benefits for other clean-energy technologies including stationary batteries [121, 122]. As mobility services have the highest priority for mobile batteries, a large portfolio size is particularly important to balance driving patterns and outweigh uncertainty related to charging behavior and the use of immediate charge buttons. Stacking of TSO, DSO and V2C services can increase long-term revenue, particularly when distribution grids have been reinforced in some areas and frequency markets are saturated.

Our analysis, however, does not come without limitations. Our interview sample may have resulted in biases resulting from our study design. First, as interviewees self-select by accepting our invitation, only those with substantial interest or strong opinions might volunteer to participate. Second, all interviewees work in the area of electric mobility or V2X, which might increase the probability of having a positive attitude about V2X. Third, interviewees might neglect aspects not related to their expertise. This may specifically be the case for issues concerning technical requirements and processes beyond the interconnection point with the grid. Lastly, the regulation of the electricity system and related market aspects are country-specific, which means that generalizability is limited. Although individual perspectives are still able to highlight important challenges [123], this study mainly provides a current snapshot of V2X. Therefore, further research and monitoring of V2X developments as well as the completion of ongoing and future trials are needed to foster commercial implementation.

Credit author contribution statement

Christine Gschwendtner: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, and Writing – reviewing and editing. Simon R. Sinsel: Conceptualization, Methodology, Investigation, Writing – reviewing and editing. Annegret Stephan: Conceptualization, Methodology, Writing – reviewing and editing, and Funding acquisition.

Declaration of competing interest

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

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Appendix A. Definitions

Table A.1
Definitions and categories.

Term	Definition
EV (= Electric vehicle)	Refers to battery (BEV), plug-in hybrid (PHEV), and extended-range EVs
V1G (= Vehicle-1-Grid)	Unidirectional charging from grid to vehicle; Controlled charging manages electricity load to provide services to the grid [20]
V2G (= Vehicle-to-Grid)	Vehicles provide services to distribution or transmission grids; bidirectional charging, including exports [17,20,81]; While some people refer to V2G if a vehicle provides grid services independently of whether unidirectional or bidirectional charging is involved [124], in this paper, V2G only refers to the case of bidirectional charging.
V2C (= Vehicle-to-Customer)	Includes V2B (= Vehicle-to-Building) and V2H (= Vehicle-to-Home); V2B refers to the integration of EVs into non-residential buildings, providing behind-the-meter services; V2H refers to services to home (residential buildings) with chargers behind-the-meter [20].
V2X (= Vehicle-to-X)	Bidirectional charging; includes V2G and V2C
Service	"A defined technical product provided to System Operators, Network Operators, utilities or consumers, such as frequency response or constraint management" ([20], p. 14).
Vehicle use types based on literature (e.g. Ref. [20]) and our interviews	We divide vehicle use types into five groups: • "Commercial fleets" include light duty vehicles and employee cars used according to a duty cycle • "Domestic vehicles" include the private use of EVs and employee cars used for commuting • "School buses" refer to the American and Canadian system of the yellow school buses that are only used for students' transfer • "Car-sharing schemes" are a special case of commercial fleets that provide mobility services • "Autonomous vehicles" can belong to any of the above categories with the special characteristic of no driver
Charging locations based on literature (e.g. Ref. [20]) and our interviews; for better readability we do not use the term "(dis) charging locations" although we refer to both charging and discharging	We distinguish between the following charging locations: • Home: includes single family homes and car parks for blocks of flats • Work: charging at workplace, including in depots • Public: on-root, lamppost charging
Grid types	Grids with different topology, distributed generation, stationary storage, low-carbon technologies (e.g. heat pumps) and at different constraint levels
Grid reinforcement	Replacement of grid infrastructure
Smart solutions	We define smart solutions as grid operations based on information technology to enable communication (e.g. based on signals) between electricity producers, end-user devices, and the grid; typically involves an intelligent monitoring system
Aggregators	Commercial middleman between a system operator (SO) and plug-in EV to collect capacity of many dispersed vehicles [125, 126].

Source: Authors

Table A.2 categorizes V2X services by grid levels (transmission and distribution), and customer services. Other authors however categorize V2X services in a technical sense, referring to active power support, reactive power support and renewable energy sources integration support [69]. Weiller and Neely [17] categorize energy services from EVs into supply of balancing and reserve services, supply of energy, controllable load and storage.

Table A.2
Categories of V2X services.

	Services
TSO (= Transmission System Operator)	• Frequency response: fast acting service seeking to keep system frequency within specified limits [69] • Frequency regulation: the process by which the alternating current in any electrical grid is maintained within the right tolerance bounds by synchronizing generation assets for electrical grid stability [69] • Spinning reserve [69] • Congestion management: operating reserves [69] • Black start provision [69]
DSO (= Distribution System Operator); for consistency reasons, we do not distinguish between DSOs and traditional distribution network operators (DNOs); depending on the country, the transition from DNOs to DSOs is at different stages	• Constraint management [69] • Congestion management [69] • Load shifting [69] • Peak shaving [69] • Valley filling [69] • Voltage control [69]
V2C (= Vehicle-to-Customer)	• Behind-the-meter services: V2B/V2H, emergency back-up, reducing the electricity bought from a utility, e.g. through time shifting [20] • Imbalance trading [20] • Arbitrage: buying energy at low prices and selling at high prices [20]

Source: Authors

Appendix B. Justification of evaluation groupings with exemplary quotes

Table B.1
Technical challenges.

	Technical challenges	
Common evaluations	Battery degradation caused by V2X: no technical but social challenge	*"The impact of V2G* [referring to V2X] *on the battery degradation is considered quite low; smart charging and V2G* [referring to V2X] *can even be a benefit for the battery"* [Int4].
		"V2G [referring to V2X] *can increase battery lifetime if it's done correctly"* [Int31].
		"Maximum charge and discharge rate is a tiny fraction of what the car experiences during its normal usage when accelerating or breaking" [Int34].
		"Even if it [battery degradation] *doesn't exist, the user has the perception of battery degradation, which means that it has to be compensated financially otherwise they will not participate"* [Int9].
	TSO level: Future oversupply of frequency services	*"We have already seen this* [market saturation] *in the capacity markets and frequency response markets where prices have dropped because more and more people have been involved"* [Int32].
		"The frequency response market [...] will saturate with way less than one million EVs; for sure, frequency response isn't the future solution [for V2G revenue]" [Int36].
	Contradiction between distribution grid requirements and economic attractiveness and technical potential of V2G	*"The weaker the network, the more V2G has benefits over smart charging [...] benefits are more [...] but the costs are more*" [Int34].
		"The weaker the distribution system, the more value you can get out of V2G; but you can't always extract the value" [Int46].
		"If retailers promote smart charging [...] it's [the installation of V2G chargers at constrained networks] *even at the same price or cheaper [than at strong networks]"* [Int30].
Different evaluations	Evaluation of the potential for distribution grid reinforcement deferral and mitigation	*"Monitoring of distribution networks is needed to get the data*" [Int36].
		"A key point for DNOs is the substantial lack of real-time data at substation level. Enabling transparency even at street feeder level is very valuable for DNOs going forward" [Int38].
		"Theoretically yes [V2G can avoid grid reinforcement], *and in specific situations yes, but we can't quantify it; we can only talk about very general or very specific situations"* [Int35].
		"*We can definitely postpone investment on the grid"* [Int30].
		"I'm very, very sure that you don't need to enforce the grid in many locations" [Int3].
		"In our opinion, no additional network reinforcement is required [when smart solutions are in place]" [Int6].[1]
		"You have to upgrade [the distribution grid] *ultimately. [...] You can't avoid it"* [Int2].
		"This isn't going to work. We need to put more cables in the ground" [Int27].
Knowledge gaps	DSO level: Future flexibility supply and demand and the impact of V2C	*"We [DNO] need to understand the synergies and conflicts of V2B/V2H with V2G; if V2B will reduce the potential for V2G or not"* [Int33]. *"As renewable energy increases, more flexibility is required but that doesn't grow exponentially"* [Int34].
		"*There is high uncertainty about how much flexibility we need in the future; it is relatively clear that there will be enough flexibility available; I think there is rather too much flexibility supply"* [Int11].[1]

[1] Quote was translated from German.

Table B.2
Social challenges.

	Social challenges	
Common evaluations	Implementation of decentralized charging	*"The manufacturers of charging stations are very small and the quality of the different stations hasn't been very good. And I did not want to have charging stations spread across a large area. I want it to be easy so that if there is an issue, I don't need to go to so many different locations"* [Int3].
		"Whenever you want to connect a piece of equipment onto the grid, they will look at the worst case scenario at that site" [Int32].
		"If you can place infrastructure at the same location you can save costs because you can use the same amount of infrastructure for more vehicles and it is also better for the upgrade of the electricity network, which might be quite costly […]" [Int37].
Different evaluations	Plug-in behavior of different EV users	*"Even I forget sometimes to plug-in my car although I am an expert and I know I need to do it"* [Int46].
		"*People don't forget to plug-in their cars; you never forget your keys in the car or to put petrol in your car*" [Int22].
		"*We don't know yet what would be required to make people plug-in their car whenever it is stationary*" [Int34].
		"We assume that the availability of the battery [of commercial fleets] *is lower than for average residential users"* [Int38].
		"Fleets are better suitable for V2G [referring to V2X] *because you have a more consistently defined duty cycle"* [Int45].
		"For a fleet manager, the knowledge that they can hit the emergency button is a good one. […] That's what the trial is for [to find out how often customers actually use the emergency button]" [Int35].
	Compatibility of future mobility concepts with V2X	"*Car sharing programs are a big opportunity for V2G* [referring to V2X]*: with V2G* [referring to V2X] *you can make money out of a parked car"* [Int22].
		"*The utilization of the vehicle increases dramatically* [with car sharing] *which means there is less scope for V2G* [referring to V2X]. *So car sharing hinders V2G* [referring to V2X]" [Int34].
		"*Autonomous driving has a positive effect on V2G* [referring to V2X]*: you can have the vehicle move from one place to another to provide V2G* [referring to V2X] *services and the more automated the easier to participate in V2G* [referring to V2X]" [Int47].
		"*Intuitively, it* [the concept of autonomous vehicles] *is going to bring down the plug-in frequency. However, because we remove the human factor out of it, that's a way to counterbalance that trend*" [Int26].
Knowledge gaps	EV users' actual interest in participating in V2X and potential incentives	"*Do people want to participate and value smart charging? We need to answer that question fairly soon because we can't assume that V2G* [referring to V2X] *will be wonderful if we can't make customers to behave in a way that enables V2G* [referring to V2X]" [Int34].
		"*You have to work really hard to sell this stuff because people don't understand it; they don't see what the value will be*" [Int35].
		"There is definitely potential for financial and non-financial benefits; it depends on what kind of behavior you can drive with incentives" [Int33].
	Effect of increased scale of V2X: interim stages and high diffusion	*"Yes, we can do it* [V2X] *with 1 and 10 EVs but can we still do it when there are millions outside the lab?"* [Int36]
		"What does a situation look like with 10 or 20% V2G [referring to V2X] *uptake? What are the possible scenarios for upscaling and diffusion? Not only considering the technical part but also the implementation in all the space-time routines of people and organizations"* [Int37].

Table B.3
Regulatory challenges.

	Regulatory challenges	
Common evaluations	Double taxation of electricity	"*In some countries, we also need to look at double taxation: you get taxed when you charge and again when you discharge"* [Int36].
		"When you get energy in, you pay the full price—incl. taxes etc.; When you push energy back: you only get an 8th *of the price if it goes to the other side of the meter"* [Int46].
		"*These [taxes, levies etc.] need to be paid when stored in mobile battery but not when stored in stationary batteries. This needs to be solved when the potential should be used"* [Int31].
	Hesitation of DSOs toward smart solutions	*"There is no regulation that says DSOs have to procure customer solutions rather than network solutions"* [Int36].
		"The energy regulation is not very much stimulating flexibility. And when this is done, probably there is also the emerging of markets" [Int25].
		"The problems [for V2G uptake] *are clearly related to the powerful position of the DSOs"* [Int10].[1]
	Enabling small providers to participate in TSO-level markets	*"The sale cycle is relatively long which makes it hard for companies to participate"* [Int47].
		"*Look at the measurement and verification plan: they should take into account the portfolio level rather than the asset level when it comes to residential technologies"* [Int38].
		"In the trials, you will never get to that threshold [minimum bidding capacity], *so you need an exception. For wider implementation, the regulations will need to be adapted at some point"* [Int37].

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Table B.3 (*continued*)

	Regulatory challenges	
Different evaluations	Development of standards for charging equipment and communication protocols	*"The OEMs say, 'we will support it* [the standard] *once the charge point providers will do' and the other way round and the customers are not shouting for it because they don't know they need it—so there is no market force to create that drive at the moment"* [Int34].
		"V2G [referring to V2X] *is an important topic that is more and more demanded, so it will not be a big challenge to establish a norm for bidirectional charging"* [Int9].[1]
		"So you want to have a standard, but once they have the standard, everybody has to set for the rules [comply with the standard] *and will have the same price. And there's no room for innovation anymore. And I dare to say that the automotive industry in Europe is not very good with this standard—it's the worst performing standard —most expensive standard"* [Int27].
		"International standards and also having regulatory bodies and clear signals is also extremely helpful as a way to coordinate, you know, signaling that there is a business opportunity here and making sure that it is straightforward and possible for all the different parties to play their own role. So, you know, making it clear to vehicle and charging manufacturers there is a business for this if you make the equipment and also the ability for them, for those mobility players or the owners or drivers of vehicles, to actually access the grid value" [Int1].
Knowledge gaps	Establishment and feasibility of markets, tariffs, auctions or tenders at the DSO level	"*Only with data you can tell whether you have a problem at street vs. community vs. regional level*" [Int36].
		"*DNOs are looking for a secure and cheap solution: if markets are the most secure platform isn't clear, but probably the most efficient solution. Nobody knows whether network reinforcement or active load management can keep up with this*" [Int8].[1]
		"It's very unclear how that market is going to evolve" [Int24].

[1] Quote was translated from German.

Appendix C. Method

We contacted potential interviewees via email, LinkedIn or contact forms on official trial websites, including a short description of our project. To compile the interview guides, we analyzed project reports from trials and adapted questions based on the stage of the trials and the public information available. The interviews lasted between 22 min and 1 h 12 min, with an average duration of 50 min, and took place between November 2019 and March 2020. We conducted two additional interviews to verify our results, which took place in May and June 2020, and conducted further interviews during the review process in February 2021. We conducted most interviews via phone, 15 with video calls, and one in person. Most interviews involved one interviewee except for five interviews involving two interviewees. 26 interviews were conducted in English and 16 in German, which we translated ourselves. We asked for consent on recording and anonymity arrangements at the beginning of each interview. We were allowed to record all interviews but one, in which the interviewer took notes. We used transcription software to generate transcripts of the interview recordings for coding and quotes.

Table C.1
Information about 47 interviews.

Reference number	Country	Stakeholder group	Position of the interviewee(s)
Int1	Canada	Energy Infrastructure and Service Provider	Senior Manager V2G and E-mobility
Int2	Denmark	Academia	Senior Researcher Vehicle-Grid Integration
Int3	Denmark	Consultancy	Self-employed Consultant for V2G and E-mobility
Int4	France	Car Original Equipment Manufacturer (OEM)	Engineering Researcher in Smart Grid Projects
Int5	France	Car Original Equipment Manufacturer (OEM)	V2G Business Development Manager
Int6[1]	Germany	Energy Supplier	Head of Platforms and Operations in Domain E-mobility and Project Leader of Research and Innovation Program
Int7	Germany	Charging Solutions Provider	Business Development Manager
Int8	Germany	Energy Infrastructure and Service Provider	Deputy Head of Distribution and Decentral systems
Int9	Germany	Consultancy	Director of E-mobility Communication Standards
Int10	Germany	Energy Supplier	Head of Regulatory Affairs
Int11	Germany	Energy Infrastructure and Service Provider	Product Manager Smart Charging
Int12[1]	Germany	Government	Policy Advisors E-mobility
Int13	Germany	Consultancy	E-mobility, CEO
Int14	Germany	Association	E-mobility, Board Member
Int15	Germany	Charging Solutions Provider	Director of Business Development
Int16	Germany	Network Operator	Head of New Business
Int17	Germany	Charging Solutions Provider	CEO
Int18	Germany	Network Operator	Head of Network Planning
Int19	Germany	Network Operator	Head of Innovation
Int20	Germany	Network Operator	Head of Asset Management
Int21[2]	Netherlands	Consultancy	Consultant and Product Owner V2X & Smart Charging
Int22	Netherlands	Consultancy	Chief International Officer and Vice President E-mobility
Int23	Netherlands	Charging Solutions Provider	Virtual Power Plant Product Manager
Int24	Netherlands	Academia	Assistant Professor Electrical Engineering
Int25[1]	Netherlands	Government	Senior Policy Advisors E-mobility

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Table C.1 (*continued*)

Reference number	Country	Stakeholder group	Position of the interviewee(s)
Int26	Netherlands	Car Original Equipment Manufacturer (OEM)	General Manager EV Business
Int27	Netherlands	Charging Solutions Provider	CEO
Int28	Netherlands	Energy Supplier	Business Owner
Int29	Netherlands	Energy Infrastructure and Service Provider	Director of E-mobility
Int30	Spain	Energy Infrastructure and Service Provider	Head of E-mobility
Int31	Switzerland	Charging Solutions Provider	Director of Corporate Strategy, Management Board Member
Int32[1]	United Kingdom	Energy Infrastructure and Service Provider	Senior Commercial Manager and Senior Manager for Business Development & Technical Lead
Int33[1]	United Kingdom	Network Operator	Innovation Manager for Low-carbon Technologies and Leader of Innovation Project V2G
Int34	United Kingdom	Consultancy	Head of EV Infrastructure
Int35[2]	United Kingdom	Consultancy	Infrastructure Strategy Lead
Int36	United Kingdom	Academia	Group Leader Vehicle-Grid Integration
Int37	United Kingdom	Academia	Senior Researcher Innovation and Mobility
Int38	United Kingdom	Energy Supplier	Commercial Manager V2G
Int39	United Kingdom	Network Operator	Senior Operations Manager
Int40	United Kingdom	Energy Supplier	EV Development Manager
Int41	United Kingdom	Association	Head of Innovation and Development
Int42	United Kingdom	Government	Head of Innovation V2G & EV Charging
Int43	United Kingdom	Government	Senior Manager Grid Operations
Int44	U.S.	Consultancy	President for Innovation
Int45	U.S.	Consultancy	Director Smart Mobility Initiatives
Int46	U.S.	Charging Solutions Provider	CEO
Int47	U.S.	Charging Solutions Provider	Co-Founder

[1] 2 interviewees.
[2] 2 Interviews: data gathering and additional verification interview.

Table C.2
Information about V2X trials in which interviewees are directly involved (Source: Authors; data from interviews and [44]).

Project name	Country	Years	Volume	Focus	Charging type	Charging location	Vehicle use types	Services tested
Elia V2G	Belgium	2018–2019	40 chargers	Technical and commercial	DC	Home and Work	Domestic and Commercial	TSO • Frequency response
Peak Drive	Canada	2019–2021	21 chargers	Commercial	DC	Home and Work	Domestic and Commercial	DSO, customer • Distribution services • Time shifting for energy users
ACES	Denmark	2017-ongoing	50 chargers	Technical and commercial	DC	Work	Commercial	TSO, DSO, customer • Frequency response • Distribution services • Time shifting for energy users
Parker Project	Denmark	2016–2018	50 chargers	Technical and commercial	DC	Work	Commercial	TSO, DSO • Frequency Regulation (FCR-N) to the Danish DK2 grid • Distribution services • Arbitrage
Grid Motion Project	France	2017–2019	15 V2G chargers (50 unidirectional smart chargers)	Technical, commercial and social	DC & AC	Work	Commercial for V2G (Domestic for unidirectional charging)	TSO, customer • Frequency regulation with market participation

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Table C.2 (*continued*)

Project name	Country	Years	Volume	Focus	Charging type	Charging location	Vehicle use types	Services tested
								• Time shifting for energy users • Arbitrage
NewMotion V2G	Netherlands	2016–2018	10 chargers	Technical, commercial and social	DC	Home, Work and Public	Domestic and Commercial	TSO • Frequency response
Direct Solar DC V2G Hub @Lelystad	Netherlands	2020–2023	14 chargers	Technical and commercial	DC	Work	Commercial	TSO, DSO, customer • Frequency response • Distribution services • Time shifting for energy users • Emergency back-up
Share the Sun	Netherlands	2019–2021	80 chargers	Technical, commercial and social	DC	Public	Car sharing available to domestic vehicles	DSO, customer • Distribution services • Time shifting for energy users
Bus2Grid	UK	2018-ongoing	28 buses	Technical, commercial and social	AC	Work	Commercial	TSO, customer • Frequency response • Time shifting for energy users • Arbitrage
e4Future	UK	2018-ongoing	1000 vehicles	Technical, commercial and social	Unknown	Work	Commercial	TSO, DSO, customer • Frequency response • Time shifting for energy users • Arbitrage • Distribution Services
PowerLoop	UK	2018-ongoing	135 chargers	Technical, commercial and social	DC	Home	Domestic	DSO, customer • Time shifting for energy users • Arbitrage • Distribution Services • Emergency back-up
Sciurus	UK	2018-ongoing	1000 chargers	Technical, commercial and social	Unknown	Home	Domestic	TSO, DSO, customer • Frequency response • Time shifting for energy users • Arbitrage • Distribution services
V2Street	UK	2018-ongoing	Targeted at the 60–70% of Londoners without off-street charging capability	Technical, commercial and social	Unknown	Public	Domestic	TSO, DSO
V2GO	UK	2018-ongoing	At least 100 EVs	Technical, commercial and social	AC	Work	Commercial	TSO, customer • Frequency response • Time shifting for energy users • Arbitrage
E-Flex	UK	2018-ongoing	200 vehicles and charging stations	Technical and commercial	Unknown	Work	Commercial	TSO, DSO, customer • Frequency response • Time shifting for energy users • Distribution services
Electric Nation	UK	2016–2019	3 chargers	Technical	Unknown	Home	Domestic	Unknown
Isles of Scilly	UK	In design phase	10 electric vehicles and 25 charging points	Technical, commercial and social	Unknown	Public	Car sharing scheme available to domestic vehicles and commercial businesses	TSO, DSO
BlueBird School Bus	U.S.	2017–2020	8 electric school buses	Technical and commercial	DC	Work	Commercial	TSO, customer • Frequency response

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Table C.2 (*continued*)

Project name	Country	Years	Volume	Focus	Charging type	Charging location	Vehicle use types	Services tested
								• Time shifting for energy users • Emergency back-up
Chrysler Group-Next-Energy V2G	U.S.	2011	4 electric minivans	Technical and commercial	Unknown	Work	Simulation of commercial fleet driving profile	Customer, microgrid • Peak shaving • Spinning reserve

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