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Vehicle-to-Grid developments in the UK

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Summary

Interest in Vehicle-to-Grid technologies has recently risen massively, partly due to relevant public investments such as the Innovate UK V2G programme. This £30m programme is the first suite of V2G-focused activities in the world trying to address current barriers to V2G at scale and for a variety of customers/vehicles. This paper details ongoing developments and reports the initial results from the programme and lessons learned since the inception of the activities. Albeit this paper focuses on the UK applications, many of the approaches and lessons learnt can be applied to other countries as well.

Keywords: V2G (Vehicle to Grid), demonstration, market development, smart charging, smart grid.

1 Introduction

The shift towards battery powered vehicles is gaining traction, with more and more vehicle manufacturers announcing the release of plug-in hybrid and battery electric vehicles (PHEV and BEV), sales targets for these vehicles and progressive phase out of diesel vehicles [1].

This situation represents the reflection of the market dynamics that are emerging. Not only EV sales are increasing, making an ever higher percentage of total sales in primary markets, but the growth is faster than market models can predict: this has led to continuous upward adjustments of EV penetration forecasts for 2030-2040.

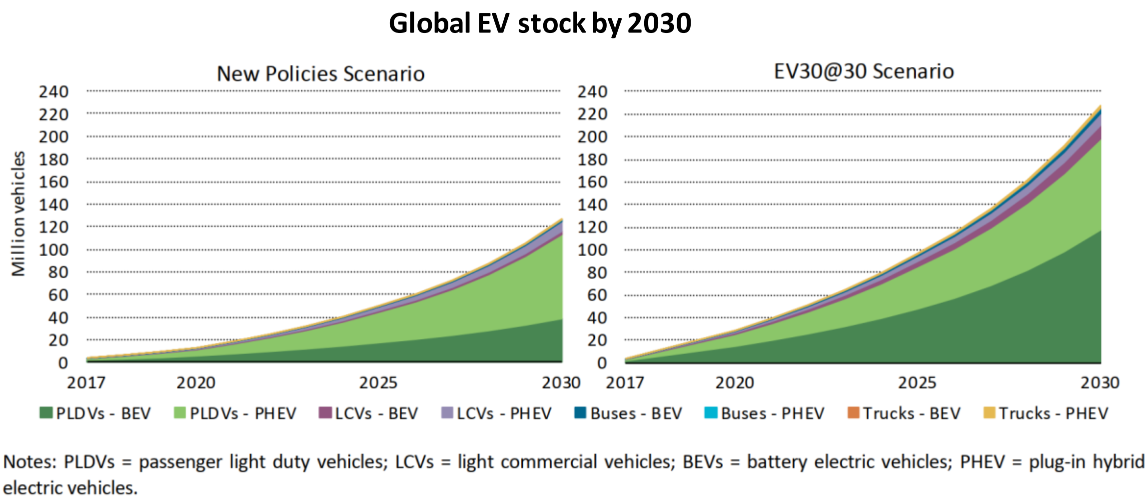

Figure 1: Forecast of global number of EVs on the road by 2030 [1]

Taking as a reference the IEA forecasts, depending on the scenario considered, between 130m and 230m of plug-in vehicles will be on the road by 2030 [1].

The impact that large number of EVs will have on the electricity network is significant: albeit the energy demand from EVs is a limited percentage of the total electricity consumption, with estimate placing EV related demand to 1800 TWh or 5% of total electricity consumption in 2040 [2], the biggest impact is determined by their power demand. In fact, if charged in an unmanaged way, EVs tend to concentrate their energy draw from the grid in few hours of the day, resulting in peak demand of up to 18 GW in the UK by 2050 [3].

This paper details the efforts undertaken in the UK for a tighter integration of EVs into the electricity network by turning them into distributed storage resources using vehicle-to-grid (V2G) technologies.

2 Integration of EVs into the Power Grid

The effective integration of large number of EVs into the power grid is a challenge which can present different issues depending on the specific state of the electricity network the vehicles need to be connected to. As such, different regions or countries can experience different constraints and challenges, albeit similar approaches can be followed to tackle them.

As mentioned in the previous Section, charging EV in an uncoordinated way determines coincident spikes in the load curve at specific times of the day. In the UK, the biggest impact of a surge in peak demand is on the distribution networks: these are frequently sized for an average household peak load of 1.5 – 2 kW, therefore are severely capacity constrained when needing to power large number of EVs at the same time. Without solutions to manage the way in which the vehicles are charged, up to £17bn worth of network reinforcements would be needed by 2050 to support the increased demand peak.

In other cases, the issue rests in the interplay between centralized generation, local generation, and loads. For example, in California the increase in renewable generation, mainly based on solar and concentrated during the middle of the day, and the rise in evening peaks – worsened in scenario of high EV penetration and unmanaged charging – is well represented through the so-called "duck curve". In these conditions, network constraints relate more to the steep ramp-up/ramp-down that need to be supported when solar PVs start/stop generating, rather than to capacity constraints in the distribution network.

The highlighted problems arise from treating EVs as any other uncontrollable load. However, looking at EVs as mobile batteries connected to the Power Grid while pugged-in, they effectively represent distributed storage resources.

As such, their power absorption can be controlled and staggered, so to smoothen demand peaks: characterised by uni-directional energy exchange, this is generally referred to as smart charging or V1G. In the UK, SC alone can contribute to save more than £8bn in cost of network reinforcements needed to support EV growth, and technical and regulatory steps are being taken to reach a country-wide SC implementation.

In addition, acting as distributed grid connected storage, EV batteries can also discharge energy into the grid: not only charge can be deferred, but EVs can support grid operations. This is commonly referred to as vehicle-to-grid (V2G).

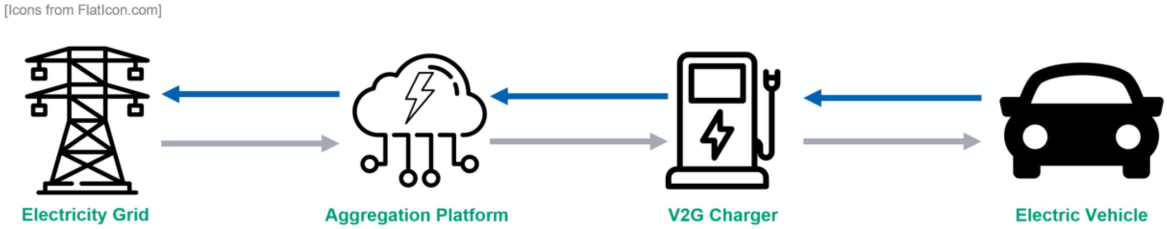

Figure 2: Representation of interaction among different players in a V2G framework

Both in case of smart charging and V2G a two-way communication is needed to achieve a tight EV-grid integration. A schematic representation of a V2G framework and its main actors is reported in Fig. 2. It must be noted that the different roles represented in Fig. 2 can be undertaken by one or multiple different actors, depending on the market structure, the specific application and implementation of V2G.

2.1 State of the art

Vehicle-to-grid, as a research topic, has been at the centre of numerous studies in recent years, with the first study on the subject often credited to be [4] dating back to 1997. While the bi-directional energy transfers from the vehicles is exploited also in vehicle-to-home (V2H) and vehicle-to-building (V2B) contexts – which have been proven to be feasible and deployable on a large scale, as done by Nissan in 2011 when the Leaf were used as relief support to power buildings after the Fukushima earthquake – the focus of V2G has always been about using bi-directional energy (and communication) exchanges to provide ancillary grid services.

Frequency regulation has long be the focus service for V2G implementations: a mix of high revenues, response times that the batteries can easily satisfy, and demand growing - as more local generation, controllable loads and renewables are embedded in the power system – makes regulation services incredibly attractive. In fact, V2G trials have initially focused on how to optimise vehicle, charger and communications technology to be able to support provision of ancillary services [5]-[7].

More recently, with direct support form vehicle manufacturers, bigger trials have proven the technology readiness, as well as the high revenue potential from ancillary services provided through V2G [7]-[10]: in particular, the Parker project in Denmark has seen V2G revenues between 955 and 2304 Eur/car/year , depending on market conditions, cost of implementation and user availability [8].

While investigations on technology viability have been successful, current research and industrial development study focus on scalability of applications, and commercial feasibility for large scale V2G deployments. In this contexts, large V2G trials have the advantage of both examining the implications of V2G for a wide range of users and settings, as well as providing a more realistic platform to evaluate costs and business models.

2.2 Potential drawbacks of V2G

Albeit a large amount of literature has been produced over V2G, proving the technology and the integration into the power system [7], some issues still require more definitive data.

In particular, battery degradation and unproven business case for V2G are often discussed as potential drawbacks to the application of V2G technologies.

2.2.1 Battery degradation due to V2G operation

Battery degradation, in the context of V2G operation, has been a constant topic of research, with an immediate impact on the feasibility, and public perception, of V2G technologies.

It is well established in literature that lithium-ion rate of degradation is governed by so-called ageing stress factors, such as resting state of charge, depth of discharge, charging/discharging current, temperature and capacity throughput. Hence, one of the most common criticism to V2G is that, by driving additional battery cycles, it has to contribute to EV battery wear.

However, as our understanding of the intrinsic mechanisms that determine battery deterioration improve, so does the ability to forecast the impact of specific V2G cycles on battery longevity. For example, simulation-based studies from the National Renewable Energy Laboratory (NREL) in the US determine that V2G high cycle operations only impact 5% of battery health over 10 years. Nissan, one of the most active automotive manufacturers in promoting V2G technologies, extend their EV battery warranty to V2G usage, provided that the cycles the battery is subject to are pre-approved by Nissan themselves.

Multiple real-world trials have been conducted to understand the effect of provision of grid services on battery lifetime, coming in some cases to dramatically different conclusions [9], [10]. Key to put these results into perspective is understanding under which conditions were the results generated – namely, the way the battery is managed during the V2G operation. In fact, as highlighted in [10], there is no doubt that a strategy to V2G operations that only seeks to maximise the grid service provision, with no consideration for preservation of battery life or EV functionality, is heavily detrimental to battery life. Nevertheless, if V2G control algorithms are set up with consideration of effects of service provision on the EV battery life, the effect of battery degradation can be mitigated [10], [11]. In addition, in case a more in depth knowledge of the EV battery system structure and operations is available, smart control algorithms can be defined to allow V2G service provision, while at the same time operating the EV battery in the best possible condition: in this case, by intelligently controlling if and when to provide energy from the EV to the Grid, and vice-versa, battery life could even be extended compared to a base case of totally unmanaged EV charging.

2.2.2 Hardware and implementation constraints

Vehicle-to-grid is essentially a way to maximise economic return from already available storage assets (EVs). As such, it involves intrinsic round-trip inefficiencies, with each energy transfer having to undergo multiple conversions – from the EV battery to the DC/AC converter in the V2G charger, and vice-versa.

In order to evaluate feasibility, the business case for V2G need to account for the cost of implementing and operating the needed infrastructure. One of the constraints that has so far limited the commercial viability of V2G is, in fact, the cost of the needed charging hardware: albeit costs are predicted to reduce significantly with a volume production, these are still too high for mass deployment, reducing margins in the business model and, in turn, the attractiveness of V2G as commercial endeavour.

In addition to that, the services that V2G can exploit differ from market to market and, as mentioned, service provision need to be managed against preserving battery life and vehicle functionality.

User engagement and involvement is crucial for guaranteeing financial viability of the technology. Albeit some studies have highlighted the availability of a good percentage of the sampled EV customer base to participate in V2G operation, the widespread user reception, and suitability of V2G to the long-term needs and behaviours of EV drivers still remain uncertain.

Finally, only a handful of vehicles are so far support V2G operation: this is partly due to only CHAdeMO allowing the necessary command and control infrastructure (CCS support has officially been confirmed from 2025, leveraging on the second edition of the standard ISO15118), and to unwillingness of vehicle manufacturers to support cost of implementation of a feature without a certain business case.

In this context, defining a working business model for a V2G implementation is extremely complex.

3 Why vehicle-to-grid in the UK?

The UK is heavily invested in reducing its carbon emissions: initiatives undertaken over the past decades have led to a consistent reduction in the impact UK has on GHG emissions. As an example, the electricity system produces as much CO2 today as it did in the 1890, and the generation from renewables amounts to 27.9% of total generation in 2018.

Progressive reductions in the emissions from historically high-GHG producing sectors such as electricity generation and distribution, and industrial production, have led to transport being today the most impactful sector. Hence, many de-carbonisation activities to date target CO2 reduction from the transport sector.

Among these, policies aimed at incentivising zero emission vehicles (and their integration into the grid) and at smartening the electricity system have created an ideal eco-system in which V2G can be deployed and effectively integrated, with both user and supply chain benefits, and positive whole system impacts.

3.1 EV uptake in the UK

UK government has recently released the “Road to Zero” strategy document [12], mapping out the policy goals and initiatives to reduce carbon emissions from the transportation sector. As part of this strategy, the sale of new conventional petrol and diesel vehicles is going to be banned from 2040, with a 2030 target for at least 50% of new car sales to be ultra-low emission.

Albeit technology agnostic, the Road to Zero contains several interventions geared towards EVs. It contains grant and tax incentives for ultra-low emission vehicles, sets up a £400 million Charging Infrastructure Investment Fund to accelerate EV infrastructure deployment, defines the legislative framework to allow mandating: deployment of chargepoints at fuel stations; ad-hoc payment for all public charging infrastructure; minimum smart requirement for all chargepoints.

All these measures are intended to support the already positive trends on EV uptake in the UK: over 195000 plug-in cars have been sold as of February 2019, with market share of around 2.7% in 2018 and 75% of drivers considering an EV as their next purchase. Driven by a total cost of ownership (TCO) already lower for EVs than conventional petrol or diesel vehicles, there could be as many as 11 million EVs in the UK by 2030, ad 36 million by 2040 [13].

Together with the EV uptake, the UK charging infrastructure is growing rapidly as well: the total number of public chargepoint accounts for 20141 connectors – and 11628 devices – as of March 2019, with a growth of 3% over the previous month; meanwhile, over 60000 chargepoints have been installed in households, supported through government incentives.

3.2 An opportunity born of necessity

In Section 2, an estimate of the total cost of network reinforcements of £17bn by 2050 was mentioned.

By deferring the vehicle charge and smoothening the demand peaks, savings for around £8bn in network reinforcements can be achieved. National Grid, in their annual Future Energy Scenarios [13] assume that the majority of EVs will be charged through smart charging and V2G, effectively contributing to an increase in peak power demand of only 8 GW by 2040 (compared to a peak when EV charging is unmanaged of more than 10 GW). A recent study by Imperial college and OVO energy [14], adopting the same time references and scenarios as in [13], estimates the whole system benefits from smart charging alone (with a participation rate of 80%) in £1.1bn/year. Also, in [14], the whole system benefit increases to £3.5bn/year in the case of V2G.

Notwithstanding specific forecasted values, the trend is clear in predicting that smart charging and V2G can turn EVs from an unsustainable load to a useful resource, if integrated correctly into the grid operations.

3.3 Modernisation of the Electricity market

For any V2G implementation to be viable, the necessary market structure and conditions need to be in place. In the UK the electricity system is undergoing a rapid transformation to be able to adapt to new consumers and generators, and to accommodate innovative business models.

Renewables and local generation are increasing, while the efforts to reduce dependence on carbon fuels are determining an electrification of the heat systems. The regulatory framework is evolving as well, with introduction of time of usage tariffs and thrust for implementation of aggregators/smart energy services. Finally, the electricity market itself is evolving: National Grid is undertaking a process of simplification of its flexibility markets, and the transition from Distribution Network Operators (DNOs) to Distribution System Operators (DSOs) will create the conditions for setting up local flexibility markets as well.

The intrinsic open and deregulated nature of the UK energy market, together with the ongoing initiatives just described, make it a complex system but well suited to validate innovative business models and propositions, including V2G.

3.4 The UK journey towards smart charging

With a policy leaning towards a widespread implementation of smart charging, the government has launched multiple initiatives targeting its implementation. A so called "EV Energy Task force" has become a forum where industry and policy makers discuss the technical, business and social implication aspects of smart charging, with the outlook of gathering towards an industry-supported implementation.

Hence, smart charging will likely be the default method of charging by the time V2G implementations become customer-facing commercial propositions. This is particularly relevant for V2G acceptance from EV users: having accepted some form of external control of charging of their EV, users will probably be more receptive to V2G – if there is a clear economic or social incentive.

4 The Innovate UK V2G programme

In 2018 the UK government announced a £30m funding for R&D on V2G technologies. The programme, managed by Innovate UK, includes a portfolio of 20 projects, and it is currently the biggest and most diverse suite of projects and trials in this field.

As detailed in Section 2, V2G technical feasibility has been repeatedly proven over the years. The Innovate UK V2G programme is instead aimed at scaling up technology and turning it into market-ready commercial propositions, by addressing current barriers to V2G at scale and for a variety of customers/vehicles. The goal is to tackle the key points that still prevent commercialization of V2G technologies: demonstration of reliable business cases for V2G in the UK; development of a supply chain able to scale up production of hardware and implementation of aggregation platforms, hence reducing cost of implementing and operating vehicle-to-grid frameworks; evaluation of long term impacts of V2G operations on EV batteries, in a variety of use case and settings; validate technologies with real customers in real markets, and define ways to engage EV users, and keep them engaged, to support V2G operations.

The programme consists of 20 projects, ranging from feasibility studies to collaborative research and development, to real-world demonstrators. It leverages on 72 individual organizations, with total projects value upwards of £46m. While the feasibility projects focus on analysis of business cases for short- and long-term revenue from V2G services, 4 project focus on development and industrialization of hardware and aggregation platforms, allowing the creation of a UK based supply chain for V2G technologies.

The 8 demonstrator projects account for 2700 EVs providing V2G services in different regions and settings, for different types of customers, and adopting radically different customers propositions. A picture of the demonstrator projects is provided in Fig. 3, and the Distribution Network Operator (DNO) regions involved in the programme are reported in Fig. 4.

Direct and indirect outcomes of the innovation funding include developing UK supply chains for both hardware and software, inclusion of V2G at the centre of the public debate and in the future scenarios concerning the Power System. In addition, detailed analyses of how the V2G operations can contribute to the energy system without disrupting the usage of EVs as transportation means, and ways to engage and retain customers are crucial activities in the programme, resulting in major player in the energy system announcing V2G-centred propositions. More details are provided in the following Section 5.

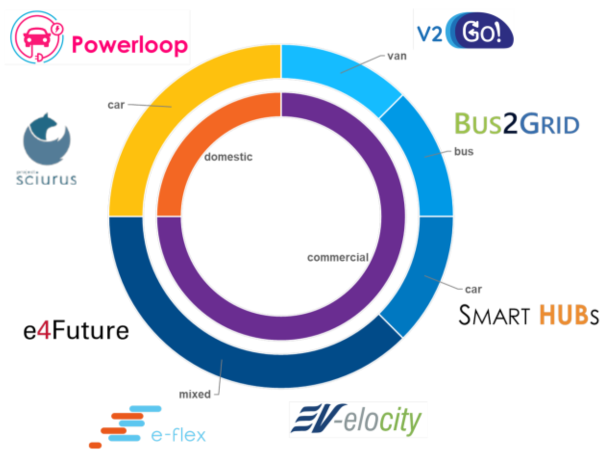

Figure 3: Profile of real-world demonstrator projects in the Innovate UK V2G programme

Figure 4: DNO regions involved in projects within the Innovate UK V2G programme

5 Commercializing V2G offering

The composition of services served, the distribution of value across the value chain and the definition of the customer propositions are critical for V2G deployment. EVs are means of transportation, and that still is their primary use: finding ways to engage and keep engaged the customer is key to the success of the technology. With this outlook, the customer proposition is the biggest uncertainty, but also the area where there are more opportunities and possible choices. In the following paragraph, an overview of the approaches adopted by projects in the UK is described. It is assumed that V2G units are aggregated in clusters, to either provide services to the DSO or to the ISO: the role of aggregator can be fulfilled by one or more actors, with functions dependent on the specific implementation and markets targeted.

5.1 Market values and business models for V2G

Historically, V2G trials and feasibility studies have revolved around provision of regulation services: this choice was encouraged by high prices the system operator paid for these services. However, albeit the total amount of frequency regulation needed will increase (forecasts for National Grid FFR service place requirement from current 600MW to over 1GW in 2030), as more actors able to support provision of these services enter the market, the value progressively decreases. As an example, in 2015-16, prices for dynamic FFR stood around £22/MW/h, while reaching values of less than £10/MW/h in the summer of 2018 as the market saturates.

Therefore, V2G implementations cannot be limited to targeting exclusively regulation services. As reported in Fig. 5, different grid services can be served by EVs in a V2G framework, each with different specifications and expected revenues.

Currently, most promising services are frequency regulation and behind the meter services, albeit most of the projects in the UK programme are exploring stacking of ancillary and behind the meter services, together with energy arbitrage.

In addition to that, the field of DSO services is rapidly rising as the one holding the most potential for V2G. The transition from DNO to DSO is still underway in the UK, but the shift to a decentralised system offers vast potential not only for the integration of local distributed resources, but also to more effectively manage smart loads at a local level. In fact, the distribution network is the part of the grid with more capacity constraints, and is going to be stressed even more with high EV penetration: the need for local services able to support the local grid will then be both highly effective, and in high demand.

The open nature of the UK electricity system also means that there are multiple routes to market for V2G solutions: as an example, taking as a reference the scheme in Fig. 2, the role of aggregator can be fulfilled by one single service provider, or by a chargepoint operator and a Virtual Power Plant operator, or perhaps directly from the EV manufacturer. In the same way, service provision can be specialised from EVs in a V2G framework, or vehicles can be aggregated together with other loads and sources.

Different routes to market directly affect economic viability of

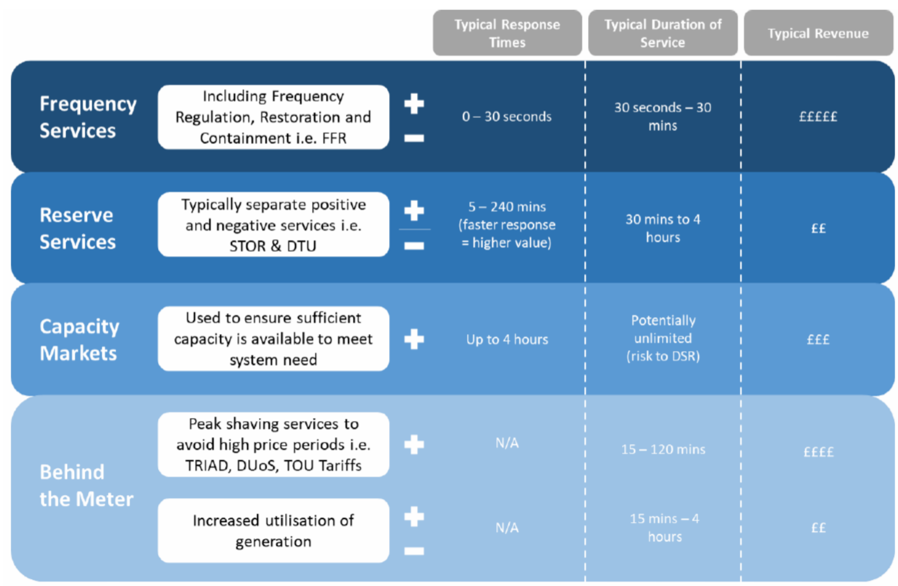

Figure 5: Grid services EVs could contribute to in a V2G framework in the UK [15]

V2G. As there need to be sufficient incentive for each actor in the value chain to support V2G operations, complex interactions between several parties inherently diminish the returns from V2G operations. However, on the other hand, what is becoming apparent from the UK projects is that, where complex market relationships are established to support a V2G framework, each individual party is not active on V2G alone, but tends to differentiate its offerings by including access and control to other distributed resources.

5.2 A user-centric deployment of V2G

In the UK vehicle usage is decreasing: vehicles are driven for less than 20 miles per day on average, spending 97% of the time parked. If current trends continue, and vehicles are plugged in most of the time they are parked, that is a vast potential of distributed storage resources that can be harnessed through V2G.

Today more than 70% of EV charging is carried out at home [16]: despite fleets will likely be the first customer to embrace V2G when rolled out at a commercial scale, applications to domestic settings can be extremely valuable in particular for provision of DSO services.

Critical for the viability of V2G in the UK is being able to engage customers, and keep them engaged. For example, short term revenue modelling [17] shows that increasing plug-in rate from 28% to 75% quadruples the revenues available from grid services.

In most of cases, the incentive from customer participation can come from being rewarded for the service provision. Interestingly, a recent study from Amsterdam university of applied sciences and Engie in Netherlands [18] found out that, while customers are incentivised in their participation by being compensated for the service, the amount of the reward is not necessarily important. Also, compensation can take forms other than monetary reward: the same study highlights how green credits or free charging can convince EV users to use V2G systems.

Finally, user engagement is typically high during first adoption, then tends to fade: more interactive systems can be put in place to maintain customer engagement. Within the Innovate UK V2G programme, project GenDrive is exploring how game-based systems can be used to keep users involved in V2G, after successful application of similar systems within smart metering programmes.

5.2.1 Finding suitable users: customers archetypes

Fleet customers are often indicated as the potential first adopters of V2G technologies. Several trials have been quite successful in harnessing centralised control and predictable patterns of fleet users to extract significant revenues from V2G service provision.

However, fleet customers are not the only potential users of V2G. While not all EV users represent a good match, in order to define potential markets for V2G and develop a viable commercial proposition it is necessary to determine how each customer’s behaviour influences the potential to generate revenue through V2G. In [17], 34 reference customer archetypes are identified, among both commercial and domestic users. Factors such as type of vehicle, usage patterns of EV and chargepoint, where users charge are considered to define an index of “applicability to V2G” for each archetype. With reference to the UK market, a list of the most high-value customer archetype the study identifies is reported in Table 1.

Archetype	**Location of V2G chargepoint**	**Potential quantity of archetype in the UK**
Council fleet - Pool cars	Business	10k-100k
EV Car clubs	Business	10k-100k
Company car park	Business	>10M
The Retired Professional	Domestic	1M-10M
The Eco-Professional	Domestic	1M-10M
The Run-around (EV as 2nd Car)	Domestic	1M-10M

Table 1: High-value customer archetypes for V2G [17]

5.3 Different approaches to V2G customer offering

Defining the customer proposition represent perhaps the biggest uncertainty of a commercially viable V2G implementation. On one side, there is the need to maximise revenues and compensate each actor supporting the operations; on the other, the customer proposition needs to be acceptable and engaging for the EV user.

This uncertainty creates also room for more opportunities and possible choices. Project within the Innovate UK programme are already testing innovative customer-facing proposition radically different one from the other. Some examples are reported below.

A first example is a direct "hands-on" approach, with customers having direct control over the V2G processes. In this case, the energy transferred to the EV and the one provided back to the grid are presented to the user as separate flows: the user pays for the energy to the vehicle and receives a reward (minus a fee from the service provider) when participating into V2G services, determining effectively separate transactions. Traceability of both energy flows and revenues is required up to national or local markets, in order to provide valid and updated information to the user. This approach is more indicated for advanced users and might not be applicable to all customers.

A drastically different approach has been chosen by the PowerLoop project. In this case, the basic principle is to make V2G participation it as easy as possible for the user (specifically, a domestic customer). This "hands-off" approach presents the customer with an all-inclusive monthly payment figure, which includes: the electricity needed for transportation and compensation for V2G services; lease payments for the EV and its maintenance; repayment for V2G charger. The advantage of such proposition is in the appeal to users who don't want to be heavily involved in the technology itself, can easily relate with the monthly payment format and can therefore directly quantify their benefit.

An approach that sits as a middle ground among the two described above is the one chosen for the Scirius project. EV charge and discharge are managed simultaneously: essentially, revenues from V2G compensate the cost of energy for transportation. The advantage to the user is that, while charge/discharge management is provided as a service, there is no operational cost to use the EV as a transportation mean.

6 First Takeaways and Open Points

The Innovate UK V2G programme is a world leading suite of projects, in terms of both size and diversity. Some direct impacts, as described in Section 5, are the inception of customer facing V2G propositions and the focusing of UK EV charger manufacturers on V2G hardware and services development. An example of this is the OVO V2G charger, represented in Fig. 6, supported by the OVO-owned aggregation platform vCharge.

Figure 6: OVO single phase 6 kW V2G domestic charger

However, the size of the programme, and the relevant amount of public funding destined to it, have already determined some indirect consequences. The increased attention to V2G, and demand for hardware able to support it, is driving the cost of V2G chargers on the market down: estimates suggest a 40% reduction on price of V2G hardware available on the market. At the same time, not necessarily with a UK focus, multiple manufacturers and energy operators are announcing products for V2G: examples are the recent announcements of V2G compatible products from New Motion and Wallbox.

The Innovate UK programme will last until 2021, with demonstration projects running trials with real customers and real environments: an independent data collection and monitoring process across all demonstrator will allow a system-wide assessment of V2G technologies.

Nevertheless, some key takeaways are already emerging as important lessons learnt from the ongoing projects.

First of all, V2G is feasible and suitable to be commercialised in the short term. However, in case only import savings and avoidance of peak household demand using energy from EV batteries are considered, smart charging captures 85% of the value of V2G: near term, for V2G to be a viable proposition it will need to provide grid services. In [17], when providing grid services, V2G is shown to generate revenues of £436 under current market conditions in the high plug-in rate scenario. Compared with application of smart charging in similar conditions, V2G is shown to provide significant higher revenues. In the longer term, there will be an enduring value from smart charging and V2G to the electricity supply chain, most prominently in energy arbitrage as well as in provision of local flexibility to the distribution grid.

Secondly, V2G is not applicable to every user: any commercial implementation needs to identify target customers. Users with long plug-in times and EVs with larger batteries are at present the most suited to V2G applications: a higher availability rate leads to a quadrupling of grid services revenues. Customer education is needed to move users to plug-in the vehicle as often as possible: in this sense, the ongoing efforts to implement smart charging programmes can help in shifting user charging patterns, with consequent benefits to V2G applications as well.

Thirdly, albeit revenues are achievable from V2G, a viable business case is dependent on the cost of hardware, still too high today. However, V2G compatible changepoints are becoming cheaper as demand grows, and supply chains are established. Moreover, a successful V2G implementation requires an attractive value proposition for all actors involved, with transparency in how costs and revenues are allocated across the value chain.

Finally, V2G can offer rewards that go beyond the purely economic gains. Environmental and social benefits are powerful motivators for both domestic and commercial EV users to participate in V2G operations.

6.1 Open points

Vehicle-to-grid is progressing rapidly towards commercial offering. However, there are a number of issues that need to be solved before V2G can become a mass market technology. At the same time, the mobility landscape as a whole is evolving rapidly, with emerging market trends and developing customer behaviours potentially having a direct effect on the potential and attractiveness of V2G.

In the following, some of these issues and trends are presented.

As mentioned in Section 2, the V2G implementations currently trialled all rely on the CHAdeMO system, impacting the availability of models that can support vehicle-to-grid operations. Standardisation activities are ongoing to finalise edition 2 of the IEC15118 standard, which will allow CCS system to officially support V2G from 2025. However, these protocols only define the communication between the vehicle and the chargepoint: while this allows for more flexible and innovative implementations on the aggregation side, it also makes more difficult to develop EVs and chargepoints that can work seamlessly across different V2G implementations. To this end, standardisation activities such as the development of the IEC 63110 standard (which takes the learnings of the OCPP protocol, the de-facto standard in most implementations) are crucial.

Battery degradation plays an important role in determining the viability of V2G. Consideration of the impact on battery life is starting to be embedded in the control algorithms of some V2G systems, modelling it as a cost for provision of services. While technically is feasible to deliver grid services while preserving the battery, the integration of battery degradation costs within the V2G business models require deeper consideration, particularly on how the cost of a potential battery degradation is spread across the whole V2G value chain.

Customers are evolving as well: their behaviours will diverge not only from current EV adopters, but from current vehicle drivers as well. Most of V2G propositions are being built using data from trials: by being bound to present EV drivers, not necessarily these will be suited for future customer trends. A greater consideration of the social and behavioural aspects, and their evolution, is needed.

Finally, the mobility trends are shifting towards shared ownership and Mobility-as-a-Service (MaaS), and it is not yet clear which impact this could have on V2G operations. On one side, a shared EV might see higher utilization rates, reducing the time it can spends plugged-in and providing grid services in a V2G scenario; on the other, several shared EVs used by commuters might be parked and plugged-in in the same area, offering a larger reserve for grid services, with predictable patterns albeit with availability for a shorter amount of time. The uptake of autonomous vehicles (AVs) could likely generate similar impacts.

7 Conclusions

Vehicle-to-grid can turn EVs into flexibility resources, generating value for customers, making the Power System more reliable, increasing penetration of renewables. While viability of the technology has been repeatedly proven, turning V2G into a mass market technology requires validation of the business models in real commercial propositions with real customers. In the UK, a smartening electricity system and open energy markets represent the ideal setting for introduction and validation of V2G technologies. A varied suite of projects constitutes the first V2G programme in the world trying to address current barriers to V2G at scale and for a variety of customers/vehicles.

First results show that V2G is suitable to be commercialised in the short term, and there will be an enduring value for V2G in the electricity supply chain. By correctly understanding, choosing and educating target customers, vehicle-to-grid applications can generate relevant revenues. As hardware costs decrease, sustainable business models can be defined: these will need to be able to adapt to evolving energy landscapes and mobility trends.

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