European Battery, Hybrid and Fuel Cell Electric Vehicle Congress
Geneva, 14th - 16th March 2017

A review of the state of research on vehicle-to-grid (V2G): Progress and barriers to deployment

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Abstract

A bi-directional power transfer between electric vehicles and the electricity grid, commonly referred to as vehicle-to-grid (V2G), offers the possibility to pair fluctuating electricity production with the fluctuating availability of electric vehicles parked at charging stations. V2G is envisaged as an option for grid balancing, in particular in regions aiming at a high penetration of renewable energy or a high penetration of electric vehicles. V2G could lower the need for stationary distributed storage by capitalizing on the existing batteries of EVs that are parked most of the time.

Given this apparent benefit, it may appear surprising that the V2G technology has not yet been deployed in a wider scale. To investigate this discrepancy, we review the status of research on V2G and the status of technical development and deployment. Our aim is to assess the barriers to V2G deployment by identifying the main open research questions from a technical and economic point of view. Based on this assessment, we point to R&D needed to overcome the current barriers.

Keywords: Vehicle-to-Grid, Decentralised Storage, Review, Technology, Economics

1 Introduction

Vehicle-to-Grid (V2G) is the idea of establishing a bidirectional power transfer between the electricity grid and electric vehicles. Since the introduction of the concept by Kempton and Letendre in 1997 [1], V2G has been said to path the way into a future with a high penetration of electric vehicles and power from intermittent renewable sources [2]–[7]. While electric vehicles (EVs) – be they battery (BEVs), plug-in hybrid (PHEVs), or fuel cell (FCEVs) electric vehicles – are connected to a charging station, they could offer several services to the grid such as reactive power support, active power regulation, load balancing, and current harmonic filtering [5], [8], [9]. Furthermore, in grids with a high penetration of decentralised electricity generation, V2G could reduce electricity transport losses by contributing to local consumption [5], [6].

The above benefits are not specific to V2G, but true of demand response (DR) in general [8], [10], [11]. However, V2G as a form of distributed storage offers a higher dispatch flexibility than controlled EV charging, which – with its DR function in mind – is sometimes referred to as grid-to-vehicle (G2V) or uni-directional V2G [4], [12]. What sets V2G apart from other forms of distributed storage is its lower expected capital costs, since it capitalises on the batteries purchased for the transportation function, which sit idle 96% of the time [2].

Although the technical feasibility of V2G for a single vehicle has been demonstrated by AC Propulsion Inc. in 2002 [13], the technology has not reached full commercial status to date. Since November 2014, the largest pilot is the Los Angeles Air Force Base with 36 V2G enabled vehicles [6], [11], [14]. In March 2015, the Spanish utility company Endesa [15] and the Japanese car maker Nissan announced plans to work together on V2G deployment. Nissan promised to factory-fit the Leaf and the e-NV200 for compatibility with Endesa's 5 and 10 kW bidirectional charging stations. The two companies plan to start first V2G applications in Denmark, the Netherlands, and Germany [16].

After fundamental articles by Kempton and Tomić [2], [17] in 2005, the research interest has really taken off from 2009 on to peak to over 200 publications in 2014, followed by a small decline to 166 articles in 2016 (Fig. 1).

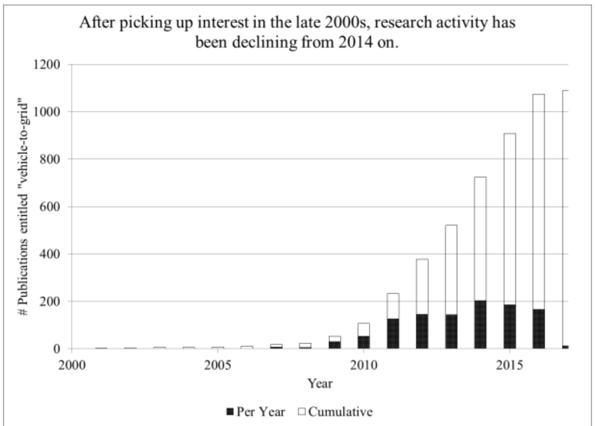

Figure 1: Research Interest in V2G

Through a meta-review of 17 review articles on V2G, we analyse the current status of research and development and investigate the reasons for which the technology has not been deployed yet, in spite of its apparent benefits. Finally, we discuss and conclude upon the economic merits of V2G.

2 State of Technology Development

According to Yilmaz and Krein [4] the six components of a V2G system are : "1) energy resources and an electric utility; 2) an independent system operator (ISO) and aggregator; 3) charging infrastructure and locations; 4) two-way electrical energy flow and communication between each EV and ISO or aggregator; 5) on-board and off-board electrical metering and control; and 6) the EV itself with its battery charger and management."

The need for demand response, and thus also the need for V2G, in a given area depends on three factors: (i) the generation mix of the utility company, (ii) the absolute level and the intermittency of the electric load, and (iii) the grid infrastructure [18]. For this reason, electric utilities have some decision power in offering the appropriate framework conditions for V2G.

The remainder of the section addresses the R&D status for the components from the system operator to the EV.

2.1 Independent System Operator and Aggregation

The independent system operator (ISO) in the US or transmission system operator (TSO) in the EU is responsible for grid balancing and would decide the dispatch of V2G systems in the spot and the ancillary services markets. It usually sets minimum guaranteed power levels that market players need to fulfil to deliver control energy in the ancillary services market (e.g. 2 MW for the UK capacity market [7]). The aggregation of many electric vehicles into virtual power plants (VPPs) is needed for V2G meet these thresholds. The aggregation of small power plants or demand-side equipments such as heat-pumps has been researched for the implementation of VPPs since 2007 [19] and has become a "relatively well established industry" [7]. The challenge lies in adapting current aggregation concepts to EVs given the uncertainty surrounding the number of parked vehicles and the total energy and power they can commit to deliver to the grid at any given time. Guille and Gross [20] proposed a highly cited aggregation framework in 2009. Current research has moved from a purely technical level of how to implement aggregation, to the contract parameters aggregators should negotiate with EV owners [21].

2.2 Charging Infrastructure and Locations

Bi-directional chargers for electric vehicles exist at different voltage levels [4]. In 2013, Zhou et al. called for more research on how V2G affects the stability of the electrical grid [22]. In the last two years, the focus was on the standardization of the charging infrastructure and on smart V2G chargers. Ozansoy et al. [23] observe that currently there are an American, a European, and a Japanese standard for power plugs. They expect that an international standard will be agreed upon by the end of the year and imply that this will help EV deployment. Smart charging refers to the coordination of the charging behaviour of the individual vehicles so as to maximize the benefits of the services offered to the grid, while minimizing the battery degradation caused by the latter services. Determining optimal charging strategies is a field of active research [5], [23].

2.3 Bidirectional Power Flow and Communication

Since 2015, wireless connectivity of new cars is required by EU standards for automatic crash notification [12]. Ozansoy et al. point to the need for interoperable communication standards to manage transactions between the EVs and the grid operators [23]. Concerns of cyber-security have been raised in this context [12]. The implementation of some form of communication is expected to be a lesser barrier than the security of the communication and the interoperability required to maximize the number of aggregators, utilities, and grid operators the vehicle will be able to communicate with.
As mentioned in the introduction, the technical feasibility of establishing a bidirectional power flow has been demonstrated back in 2002 [13]. To date several bidirectional chargers have been installed in pilot projects [3], [6], [12], [23].

2.4 Electric Metering

Based on our literature review, the metering itself does not seem to be of particular concern for the deployment of V2G anymore. Gough et al. [7] do not mention it in their recent publication about the techno-economic feasibility of vehicle-to-grid. Ozansoy et al. point out that the interplay of the smart meter with the other system components requires substantial communication and coordination, but they do not question the technical feasibility of constructing an appropriate meter [23].

2.5 Battery Management

At the moment, the V2G induced battery degradation is the main technical barrier to V2G deployment. Current research recommends maintaining a state of charge between 30 and 90% when cycling the EV battery for grid support [24]. Even when doing so, the damage to the battery, may still be too high to justify V2G deployment [4], [25]. Beyond minimizing battery degradation by improving V2G chargers, further research is conducted on the batteries themselves both to increase their energy density and to lower their cost [6], as well as to reduce charging time [5], [12] and weight [4]. The four above factors should help the deployment of EVs and thus increase the potential applications for V2G.
Finally, Duong [26] called for an investigation of the temperature dependence of battery performance and the resulting consequences for V2G applications, as the need for grid services may increase with temperature in some regions, whereas battery performance decreases.

In 2005, Kempton and Tomić [17] did not consider battery degradation cost for fuel cell vehicles. Tribioli et al. [27] however do consider a battery in their fuel cell car, presumably as a buffer to smooth out the power demand from the car engine so that the fuel cell can operate in steady conditions. In their evaluation of co-benefits of battery and fuel cell vehicles in California, Felgenhauer et al. [28] assume that it will be the electrolysers needed for the supply of hydrogen that will take part in demand response and not the fuel cell vehicles themselves. It thus seem questionable whether V2G is a viable option for FCEV.

To conclude on the state of technology development, V2G can be implemented from a purely technical point of view, however battery degradation and reliable aggregation are the principal remaining issues that would hinder mass deployment should demand for V2G rise. More research is needed on (i) battery chemistries, (ii) charging and discharging strategies that limit battery degradation, (iii) aggregation strategies that allow for bidding in the electricity markets, and (iv) securing the communication between vehicle owners and grid operators.

As Yilmaz and Krein put it, controlled [one-directional] charging of electric vehicles for demand response “is a logical first step [towards V2G deployment] because it limits hardware requirements, simplifies interconnection issues, and tends to reduce battery degradation" [4].

3 Economic Prospects and Barriers

As seen in the technology section, V2G is harmful to the EV battery. To make economic sense, the revenues of V2G through ancillary grid services should not be offset by the loss of value of the EV due to battery degradation.

Our meta-review concludes that three main barriers currently prevent V2G deployment: (i) the cost of V2G, particularly that of battery degradation, is often too high in comparison to the current electricity market conditions [5]–[7], [23]; (ii) it is not settled under which business and aggregation model V2G could capture most economic value [7], [21]; (iii) EV owners may be concerned about the loss of range or availability of their vehicles if engaged in V2G programmes [5], [23], [24].

In their 2006 report to the United States Congress, the Department of Energy defines demand response as "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." [10]

In other words, demand response helps balancing electricity supply and demand in a distribution network. Depending on the time scale over which the balancing occurs, it is referred to as peak shaving (corresponding to periods of "high wholesale market prices") or as ancillary services (corresponding to instants during which "system reliability is jeopardized") Most of the literature sees the delivery of control energy for frequency and voltage regulation in the ancillary services market as the most promising economic opportunity for vehicle-to-grid. This is because of the availability payments that market players receive even without delivering any electricity to the grid, hence limiting the issue of battery degradation [3]–[5], [17].
Gough et al. [7] find that participating in both the peak power and the ancillary services market may prove the most profitable for V2G in the UK context. Through offering these services, demand response stabilises the grid, which may result in infrastructure savings for distribution grid upgrades – an aspect that is rarely analysed in the literature we reviewed.

The need for grid balancing services is driven by the increasing amount of fluctuating power generation and demand in the network. It is amplified when the distribution network comes close to its thermal limits at some points in time and space. In this case, demand response is needed to temporarily reduce the power flows. This implies that the penetration of intermittent renewable energy, in particular wind and solar, and the penetration of electric vehicles influence the demand for demand response.
Numerous studies have shown that a high penetration of EVs, which are not charged in a coordinated fashion, increases the peak load [4], [8], [29]. Since a higher peak load may lead to both higher wholesale market prices and lower system reliability, this observation suggests that EV deployment may increase the need for demand response. If V2G is competitive with other DR technologies, this need could at least partially be covered by the EVs themselves. To assess the competitiveness of V2G Mwasilu et al. [12] call for "more research and analysis […] to justify the adoption of the V2G framework over other energy storage systems." Even the economic prospects of stationary batteries as one of these other energy storage systems are – although they may be somewhat more clearly established than the ones of V2G – currently still under investigation [30].

In addition to battery degradation, the costs of V2G consist of setting up the charging infrastructure and of the transaction costs incurred by the aggregator to pool EVs. The learning curves for the deployment of charging stations was approximated by Gough et al. to be the same as for photovoltaic systems [7]. The exact nature of these costs is not clear yet, leading to additional uncertainty about the profitability of V2G. First estimates of the costs of setting up the charging infrastructure were provided in 2005 already, when Kempton and Tomić [17] pointed to the need for wiring upgrades to increase EV charging and discharging power from 6.6 to between 10 and 15 kW in residential settings. A higher line capacity, so their reasoning, provides more options for individual vehicles to participate in the power market. However, it also increases the overall system cost and reduces the overall charging time. After reviewing the literature, it is not clear to us whether the reduced charging time will increase or decrease the EV parked ratio and what the consequences for the vehicle aggregator might be.

If the parked ratio decreases, we expect the aggregator to pool more vehicles for the same offer of grid services. As Nursimulu [31] showed, transaction costs are a key factor in determining the economic viability of demand response through aggregation of loads. The same would probably be true for aggregating V2G, although we have not found an explicit mention of transaction costs in the literature reviewed. In the context of V2G, transactions costs are the costs incurred by the aggregator for convincing EV owners to offer V2G services managed by the aggregator. The transaction costs are influenced by the minimum power capacity an aggregator needs to offer to participate in the ancillary services market, by the minimum duration over which these services are to be provided, and by the reliability with which these services should be delivered. These points are all subject to the regulations governing the system operators. Transaction costs for V2G may be higher than for other DR technologies, because EV owners might be more difficult to convince than e.g. heat pumps owners as the impact of offering V2G on car availability and battery degradation might be considered a higher burden than the mere loss of comfort through thermal charge interruption.

Based on the above, three necessary conditions for V2G deployment can be identified: (i) the EV penetration needs to be high enough to offer enough agents participating in V2G and thus a high enough parked ratio of EVs, (ii) there must be a need for decentralised storage, and (iii) the cost of V2G must be low enough to compete with other decentralised storage technologies. We discuss these three conditions below.

At the end of 2016, Norway had the highest EV penetration with 5% of all registered cars [32]. Most countries still lag far behind. This suggests that efforts on EV deployment are required to advance V2G applications.

To date, the growth prospects [33], [34] and the economic viability of V2G [6], [7], [21] are unclear. We suggest that one reason for this may be a market decline for control energy, as observed in Germany [35] and Switzerland [36]. If our suggestion holds true, this implies that future studies of V2G deployment should elaborate on the value the technology can offer to the grid at different points in time of the transition towards a more sustainable energy system.

Concerning the third condition, Beer et al. [37] have shown that removing batteries from EVs "at an early stage of their lifecycle creates considerable economic value". The removed batteries were to be used for stationary storage in a commercial microgrid in California. We therefore raise the question whether second-life batteries will directly compete with V2G. Depending on how much V2G deployment lacks EV deployment, there may be an abundance of second-life EV batteries for stationary storage, before V2G has the chance to establish itself as a technology. This is likely to depend on the fraction of batteries that is recycled into new EV batteries versus the fraction that is reused in stationary applications.

A second concern we raise is with regards to market gaming. In reaction to JP Morgan's gaming of the California electricity market [38], the then-Chair of the California Power Authority David S. Freeman [39] stated that: "If Murphy's Law were written for a market approach to electricity, then the law would state 'any system that can be gamed, will be gamed, and at the worst possible time.' And a market approach for electricity is inherently gameable." The question at hand is whether a V2G aggregator could make profits by intentionally stressing the grid and offering help to relieve the very same stress?

4 Conclusion

Based on a meta-review of 17 review articles, we find that the technical feasibility of vehicle-to-grid has already been demonstrated in 2002 for single cars with first aggregation functions. The main technological challenges that remain today are battery degradation, smart (dis-)charging, and reliable aggregation of electric vehicles offering grid services.

The economic merits of V2G are uncertain and the revenues that can be generated often not high enough to justify deployment under the current conditions offered by control energy markets. This may change in the future with the deployment of EVs and intermittent energy sources creating a larger need for demand response. The question at hand is whether the mobility and potentially low investment cost of V2G can more than compensate for the uncertain but potentially high aggregation (transaction) cost and the high operating cost due to battery degradation, when competing with other decentralised storage technologies? Specifically, how will V2G compete with second-life EV batteries that may be used for stationary storage?

The fundamental motivation behind V2G is to take advantage of the under-utilization of EVs. However, autonomous vehicles and car sharing schemes may increase significantly the operation time of vehicles. To estimate the prospects of V2G, it thus seems important to reflect on the evolution of both the absolute number and the utilization of electric vehicles. Beyond judging the economic viability of V2G, these reflections should inform the planning of the infrastructure required for V2G.

Finally, the options for a V2G aggregator to "game" the electricity market should be investigated.

Considering the uncertainty surrounding the economic viability of V2G and the still limited need for demand response, it is not surprising that the technology is still at the pilot stage. First applications might be military bases, where V2G would be used to increase grid reliability in the case of a black-out, with limited consideration for the economic viability of everyday operations. Furthermore, aggregation is easier, because all vehicles are owned and scheduled by the same entity. In fact, after military bases, commercial fleets could be a good start for civilian V2G deployment.

Despite the challenges on the long road to deployment, in their technology brief on electric vehicles published this February the International Renewable Energy Agency points out that smart charging and V2G "can help support a global doubling of the share of renewable energy by 2030 compared to 2015" [40].

Beginning with what is sometimes called "uni-directional V2G", i.e. a controlled charging of EVs managed by aggregators may be the first step on this road [4].

Acknowledgments

The authors acknowledge funding from the institut VeDeCoM.

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