Critical Elements of Vehicle-to-Grid (V2G) Economics

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Produced under direction of the U.S. Department of Energy Office of International Affairs and the Clean Energy Ministerial by the National Renewable Energy Laboratory under Task No. DSEV1030.

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Strategic Partnership Project Report
NREL/TP-5400-69017
September 2017

Contract No. DE-AC36-08GO28308

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List of Acronyms

AC	Alternating current
ACE	Area Control Error
AUD	Australian dollar
BLAST-V	Battery Lifetime Analysis and Simulation Tool for Vehicle Applications Model
DC	Direct current
DCFC	DC fast charging
DoD	Depth of discharge
EUR	Euro
EVSE	Electric vehicle supply equipment
GMR	Guaranteed minimum range
RPT	Required plugged-in time
SGD	Singapore dollar
SWIS	South West Interconnected System
UCSD	University of California San Diego
USD	U.S. dollar
V2G	Vehicle-to-grid

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1 Introduction

As electric vehicles have gained market share, policymakers, utilities, and grid operators have begun to address management of vehicle charging to smooth integration of electric vehicle loads on the grid. Various approaches have been proposed to shift vehicle charging to periods of low demand and ease impacts on the grid, especially on low-voltage distribution infrastructure. Many researchers (Guille and Gross 2009, Mullan et al. 2012, Drude et al. 2014, Gearhart et al. 2014, Habib et al. 2015) have suggested that vehicle-to-grid (V2G) capability—with electric vehicles acting as batteries with bi-directional flows of energy—is the next logical step in integrating electric vehicles onto the grid.

The requirements, costs, and benefits of V2G must be balanced among the three primary stakeholders: vehicle manufacturers, vehicle owners, and grid operators. Vehicles must be equipped with the capability to allow two-way flows of electricity between the vehicle and the grid. The vehicle manufacturer must be able to price V2G capability at a level that customers will be willing to pay. The owner of the vehicle must be adequately compensated for allowing the grid operator to use the vehicle to provide grid services and must be assured that the vehicle will be available for personal use when needed. The grid operator must derive enough benefit from the availability of vehicles to compensate for the additional cost of monitoring and controlling the vehicle-grid interactions, paying owners, and administering the system.

This report explores the critical elements of V2G economics. Section 2 summarizes the elements and costs of a V2G system. Section 3 describes V2G revenue-generating services and the business cases for providing these services. Section 4 notes real-world V2G applications. Section 5 lists concerns related to V2G. Section 6 concludes and summarizes V2G cost and revenue elements.

2 Elements and Costs of a V2G System

The basic elements of the V2G concept are illustrated in Figure 1. Each vehicle owner connects a vehicle to the grid, at which point the system operator can control charging and discharging of the vehicle's battery. Although each individual vehicle provides a very small amount of energy and is not always connected to the grid, many vehicles aggregated together can provide enough reliable capacity to be bid into energy markets. The primary physical elements of V2G systems are the electric vehicles equipped with battery-management software and hardware that allow two-way flow of electricity, communication technologies mediating between vehicles and grid operators, and electric vehicle supply equipment (EVSE) or alternative technologies connecting vehicles to the grid.

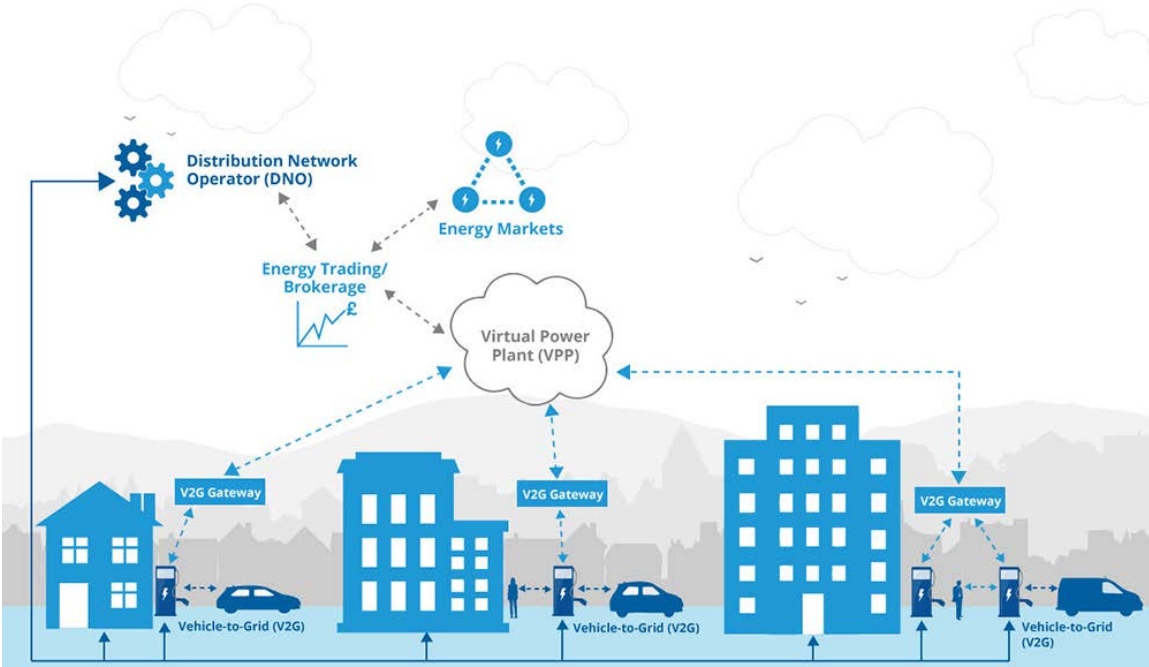

Figure 1. Schematic representation of V2G operation. Source: Cenex (2017).

In standard connections between the grid and vehicles, power flows from the grid to the vehicle to charge the vehicle's battery. For electricity to flow from the vehicle to the grid, the direct-current (DC) battery output must be converted to alternating-current (AC) power of the correct frequency to match the AC grid. The conversion from DC to AC current can be accomplished using an inverter built into the vehicle, as in the inverters supplied by Princeton Power Systems for the Honda Accord plug-in hybrids tested in the NRG Corporation/EVgo University of California San Diego (UCSD) Partnership in 2015 (Maloney 2015). Another option is to build the inverter into the EVSE, a concept that was also tested in the EVgo UCSD project (Sullivan 2015).

Implementation of V2G requires communication technologies and algorithms to sense grid status, determine whether vehicles should be providing or drawing electricity from the grid at any given time, ascertain the status and availability of vehicles for providing the services needed, and track the services provided by vehicles so owners can be paid for making their vehicles available. Numerous modeling studies have investigated how vehicles might be aggregated to optimize grid services and economics while accounting for driving behavior and adhering to rules regarding owners' requirements for availability of their vehicles (Gopakumar et al. 2013, Cardoso et al. 2014, Drude et al. 2014, Fazelpour et al. 2014, Hota et al. 2014, Morais et al. 2014, Colak et al. 2016). Other studies have addressed the issue of determining the optimal location and requirements for communications hardware and software (Gopakumar et al. 2013, Emmanuel and Rayudu 2016). Currently EVSE owners may pay a fee from $100 to $900 annually, depending on the type of EVSE (Level 1, Level 2, DC fast charging [DCFC]) and the unit's features, for network communications and back-office support (Smith and Castellano 2015).

The EVSE connects vehicles to the grid. Although most vehicles are parked most of the time (Kempton and Tomić 2005), currently electric vehicles are usually connected to the grid only through EVSE located at residences. Implementation of V2G would require a network of EVSE in both public (e.g., at grocery stores) and private (e.g., at businesses) locations so vehicles could be plugged in for a larger fraction of the time. An electric vehicle usually has a power capacity of 100 kW or more, but the power that can be supplied for V2G applications may be limited by the EVSE or power line (Kempton and Tomić 2005). Without upgrades, residential circuits in the United States have a power limit of about 10 kW. Commercial buildings or residential buildings with upgraded circuits could have power limits above 25 kW.

Costs for providing a non-residential grid connection vary widely depending on the capacity and other factors. According to Smith and Castellano (2015), a single-port EVSE unit costs $300–$1,500 for Level 1, $400–$6,500 for Level 2, and $10,000–$40,000 for DCFC, and installation costs vary greatly from site to site, from around $0–$3,000 for Level 1, $600–$12,700 for Level 2, and $4,000–$51,000 for DCFC. Willett Kempton (personal communication with author, 2017) estimates that a V2G-capable 10-kW (Level 2) DC (i.e., AC ↔ DC conversion performed by the EVSE, not the vehicle) EVSE unit would cost $4,500–$5,500, which is within the range of costs found by Smith and Castellano (2015). However, Jin and Meintz (2015) found that "the cost for EVSE capability to perform grid/building services is largely limited by the cost of hardware for enabling bidirectional control." One study estimates the annual maintenance costs for EVSE at 5% of the original equipment cost (Ercan et al. 2016). Wireless, or inductively coupled power transfer (ICPT), charging has been proposed as an alternative to large numbers of EVSE units (Gill et al. 2014). However, this technology is not yet commonly deployed.

Kempton and Tomić (2005) estimate the cost of the EVSE, power electronics, and onboard inverter needed to facilitate V2G for a 15-kW home grid connection at $1,900: $400 for conversion of the onboard vehicle components, and $1,500 for the 15-kW AC bi-directional (i.e., AC ↔ DC conversion onboard the vehicle) home EVSE. If integrated into the vehicle design, onboard power electronics would cost between $200 and $300 per vehicle. An onboard control module would cost less than $200 (Willett Kempton, personal communication with author, 2017). V2G-capable vehicles are not yet commercially available from vehicle manufacturers. A 2013 study of V2G-capable electric school buses at the University of Delaware estimates the cost for a 70-kW (continuous charge), 140-kW (maximum 1-minute discharge) onboard charger for the school buses at approximately $30,000, assuming it was included in the design/construction of the eTrans buses (Noel and McCormack 2014); a total cost of $260,000 per bus is assumed, including the cost of the onboard charger.

3 Business Cases

Potentially, V2G can balance the variable and intermittent output of renewable power generation, provide grid services such as voltage and frequency control, and supply emergency backup power (Guille and Gross 2009, Peças Lopes et al. 2010, Gearhart et al. 2014, Yamagata et al. 2014). One well-studied application is the use of V2G for integration of renewable energy generation, especially distributed solar (Fernandes et al. 2012, Morais et al. 2014). V2G-capable vehicles could provide three primary services: bulk energy storage, operating reserves, and frequency regulation.

Vehicle batteries could provide bulk energy storage, absorbing excess electricity when generation exceeds demand and providing energy when generation is lower than demand.

Usually the batteries would cycle once per day and would help to reduce the "duck curve" caused by high penetration of solar generation (Drude et al. 2014), or they would provide power during unusually high demand periods, for example, for air conditioning in extremely hot weather (Mullan et al. 2012). The economics of bulk storage could be challenging if the vehicle owner were only compensated for the electricity at the difference in market price between the high and low demand periods (Shang and Sun 2016). However, a feed-in tariff—such as the one proposed by Richardson (2013)—could make V2G for bulk storage economically attractive for vehicle owners.

Peak shaving—using V2G to mitigate high demand charges—is another variation of the bulk energy storage concept. Commercial and industrial electricity users are often assessed a demand charge based on the highest single demand period during each month. Reducing the peak demand during that single period can provide substantial savings for the facility. A recent demonstration at Colorado's Fort Carson Military base using two Smith electric trucks, with a combined total of 95 kW and 125 kWh of capacity, achieved 43 kW of peak shaving worth $860 (assuming a demand charge rate of $20/kW) (Millner et al. 2015). The high level of peak shaving was achievable because of the large power capacity of the EVSE.

Vehicle batteries could also provide regulation services. One of the primary functions of the grid operator is to maintain the balance between generation and demand on the grid (Zeng et al. 2015). The deviation between demand and generation is defined as the Area Control Error (ACE), which generally fluctuates up or down from zero because of instantaneous variations in demand. Regulation service providers are entities that can draw power from the grid (providing "regulation down" services) or provide power to the grid (providing "regulation up" services) for short periods to balance the grid. The ability to quickly respond to ACE signals is beneficial, because both the magnitude of the deviations and the probability of "overshooting" the target of a zero value of the ACE are minimized. Electric vehicles are well suited to providing regulation services, because they can provide both the load for regulation-down services by charging the battery and regulation-up services by discharging electricity to the grid on demand. Generally the ACE signal fluctuates up and down around a value of zero, so the net electricity to and from the vehicle is close to zero. In addition, unlike many generation sources, batteries—and especially the batteries in vehicles—can respond to signals from the grid almost instantaneously.

Grid operators compensate regulation service providers based on their capacity and response time. For example, PJM, a regional transmission operator for wholesale electricity, offers two regulation signals derived from its ACE signal, one for relatively slow-responding conventional generators and one for fast-responding providers such as batteries (Zeng et al. 2015). Prices for regulation services often include a capacity component, which pays providers for guaranteeing that the resource will be available when needed, and an energy component that compensates the provider for the energy actually exchanged. The market for regulation services can consist of a day-ahead bid component and a real-time component. If the aggregator's day-ahead bid can affect market prices, the revenue per vehicle can decrease significantly as the vehicle pool size increases (Harris and Webber 2014). The size of the pool of vehicles needed to guarantee availability, the length of time each day that each vehicle is connected and committed to providing grid services, and the power rating of the EVSE (kW) or power line are primary determinants of the potential revenue (Harris and Webber 2014). Table 1 lists several examples of studies that have estimated the costs and benefits of V2G for providing regulation in various applications.

Table 1. Examples of V2G Economic Estimates for Regulation Applications

Study, Location [original currency, year]	Application	Net Revenue Estimate (2016 USD/vehicle-year)[1]	Major Assumptions and Variables
Kempton and Tomić (2005), United States [USD, 2003]	Calculations based on a single RAV4 electric vehicle	$2,250 (10-kW EVSE) to $3,320 (15-kW EVSE)	Vehicle is plugged in and available 18 hours/day. Study assumes $650 (2016USD 850) for residential wiring upgrades needed for 10-kW EVSE, $1,500 (2016USD 1,950) for 15-kW EVSE.
Agarwal et al. (2014), Singapore [SGD, 2012]	Pool of 10,000 private light-duty vehicles, 10-year vehicle lifecycle analysis	$1,508	Vehicles plugged in and available 22 hours/day. Market price of SGD 91.53 (2016USD 76.89) per MWh for regulation services.
Mullan et al. (2012), Australia [AUD, 2009]	Pool of 60,000 private light-duty vehicles	Revenue of $143 (deemed not profitable if costs are subtracted)	Based on data and costs from the South West Interconnected System (SWIS) in Western Australia. Assumes current budget of ~AUD 9.8 million (~2016USD 8.7 million) for regulation service.
Ercan et al. (2016), United States [USD, 2014]	Fleet transit or school buses	$17,384 (school bus), $6,170 (transit bus)	Lifecycle cost comparison with diesel versions in the California Independent System Operator region. Values shown are per-year revenue estimates over an assumed 12-year life.

AUD = Australian dollar, SGD = Singapore dollar, USD = U.S. dollar.
[1] Currencies are converted to units of USD2016 to provide some consistency between studies. Historical exchange rates are from OFX (https://www.ofx.com/en-us/forex-news/historical-exchange-rates/). Currency conversions are taken from the studies where possible. The Consumer Price Index is used for escalation to 2016 dollars.

Finally, vehicle batteries could provide operating reserves. Operating reserves provide electricity if a baseload generator fails. Operating reserves might also be used to “firm” electricity generation from variable renewable sources such as solar and wind. Reserve power could be called to fill in momentary dips in output—for example, from clouds passing overhead—to provide a predictable steady output from the renewable generator. Typically the utility or system operator contracts for a specified level of power generation to be available for a specified period. For example, the minimum contract for the Singapore grid is 1 MW for ½ hour (Ciechanowicz et al. 2015). Generators are classified based on their response time, which ranges from a few seconds to several minutes (Agarwal et al. 2014). Payments are made for keeping the generator available as well as for energy actually supplied. Large numbers of grid-connected vehicles aggregated together would be required to supply operating reserves. For example, Mullan et al. (2012) estimates that 60,000 vehicles (or vehicle owners) would be needed to supply the 285-MW reserve needed for 1 hour of operation on the Western Australia grid. The amount of time the vehicle is connected to the grid and committed to be available is a major determinant of the revenue potential for vehicle owners. Battery size and the amount of energy that can be supplied is also a significant determinant. Table 2 lists several examples of studies that have estimated the costs and benefits of V2G for providing operating reserves in various applications.

Table 2. Examples of V2G Economic Estimates for Operating Reserve Applications

Study, Location [original currency, year]	Application	Net Revenue Estimate (USD/vehicle-year)[1]	Major Assumptions and Variables
Agarwal et al. (2014), Singapore [SGD, 2012]	Pool of 200 private light-duty vehicles assumed to provide 1 MW capacity	$31 (secondary) to $545 (contingency)	Average prices (SGD/MWh): contingency reserve 15.89 (2016USD 13.35), secondary reserve 1.91 (2016USD 1.60), primary reserve 0.46 (2016USD 0.39).
Mullan et al. (2012), Australia [AUD, 2009]	Pool of 60,000 private light-duty vehicles	$338	Based on data and costs from SWIS in Western Australia.
Illing and Warweg (2016), Germany [EUR, 2014]	Pool of 10,000 to 1 million private light-duty vehicles	Aggregator profit $4/vehicle for 50,000 vehicles to $31/vehicle for 500,000 vehicles	Aggregator viewpoint. Current market for V2G in which the aggregator offers a 12-hour (overnight) commitment of vehicles. Cost drivers for the aggregator are information technology infrastructure, personnel costs, charging stations, and energy procurement.

AUD = Australian dollar, EUR = Euro, SGD = Singapore dollar, USD = U.S. dollar.
[1] Currencies are converted to units of USD2016 to provide some consistency between studies. Historical exchange rates are from OFX (https://www.ofx.com/en-us/forex-news/historical-exchange-rates/). Currency conversions are taken from the studies where possible. The Consumer Price Index is used for escalation to 2016 dollars.

4 Applications

The V2G concept has been tested in a number of applications. In one of these, NRG Corporation and EVgo, which licenses software developed by Professor Willett Kempton at the University of Delaware, partnered with UCSD to install bi-directional EVSE and V2G-enabled vehicles for testing in the UCSD micro-grid (Sullivan 2015). Nissan and Honda supplied the vehicles used in the test. Nuvve Corporation, which also licenses the software developed at the University of Delaware, has launched a V2G business model in Denmark, providing frequency regulation services using Nissan vans (Nuvve 2017). The vans can be programmed to limit discharge levels and be available for driving at a set point in time, while Nuvve uses the battery to help grid operators maintain a constant frequency. The Nuvve aggregator software is being used commercially in Denmark and the Netherlands. The Nuvve service deployed in Denmark is currently generating 1,000 to 1,400 EUR per vehicle per year for vehicles plugged in for 7,000 hours (Trahand 2017). The largest pool of vehicles participating in a single market is 15,000 in the Netherlands (Willett Kempton, personal communication with author, 2017).

Electric school buses are a particularly good fit for V2G applications because of their large batteries and long parked periods. In a lifecycle cost comparison among electric school buses, electric transit buses, and their diesel equivalents, Ercan et al. (2016) found that the lifetime net revenue for school buses providing regulation services was nearly three times higher than for transit buses (see Table 1). The difference is largely attributable to the length of time school buses and transit buses are plugged in and available. School buses are parked up to 21 hours per day during the school year and 24 hours per day in the summer, whereas transit buses are only plugged in 8–12 hours per day. Electric buses have several other advantages over conventional buses, including an overall reduction in greenhouse gas emissions and elimination of bus emissions of criteria pollutants such as nitrogen oxides, which form ground level ozone, smog, and acid rain (EPA 1999). Eliminating criteria pollutants where buses operate is especially important in the case of school buses. Ercan et al. (2016) conclude that battery-electric transit and school buses providing V2G could reduce electricity-generation-related greenhouse gas emissions by 1,067 and 1,420 tons of CO_2 equivalence (average) and eliminate $13,000 and $18,300 of air pollution externalities (average), respectively, over their lifetimes. Electric buses also require significantly less maintenance than conventional buses do. A number of school districts have purchased electric buses, entering into partnerships with utilities and clean energy groups to help offset the high purchase price.[1]

5 Concerns Related to V2G

Operating in a V2G mode can increase battery wear and shorten battery life. The extent of these impacts and measures that can reduce battery degradation have been studied extensively (Peterson et al. 2010, Marongiu et al. 2015, Ribberink et al. 2015). The total number of battery charging and discharging cycles, depth of discharge (DoD) for each cycle, and temperature effects are the primary V2G-related determinants of battery degradation and lifespan. Although most studies have concluded that mitigating measures (e.g., limiting DoD to 80% of the battery's capacity) can limit battery degradation to acceptable levels, the extent of battery degradation assumed has a large impact on the estimated economics of various V2G applications. Researchers can use the National Renewable Energy Laboratory's Battery Lifetime Analysis and Simulation Tool for Vehicle Applications Model (BLAST-V) to evaluate the longevity and performance of vehicle batteries in several contexts, including with V2G technology enabled or with frequent use of high-speed charging (NREL 2017a). In addition, the tool can be used to model optimal locations for placement of public EVSE, including DCFC. BLAST-V can be coupled with the Battery Ownership Model to assess lifetime battery costs and vehicle economics (NREL 2017b). Batteries now cost less than $300/kWh, and research in chemistry, design, and manufacturing is expected to continue to lower battery costs (DOE 2017).

Batteries that have reached the end of their useful life in vehicles could be given a "second life" in purely grid applications (Debnath et al. 2014). Second-life batteries would be housed in a temperature-controlled environment and would be available continuously for grid services. The degradation rate for these batteries likely would be faster than for newer batteries, and the batteries would have poorer performance (less total energy per cycle), but they could still provide an economic benefit. Debnath et al. (2014) estimate that second-life batteries could provide up to about 19% of the initial battery purchase cost through grid services.

Providing communications and management for a large network of charge points, vehicles, and customer information entails security and privacy concerns. Although these challenges are not

[1] Examples exist in Minnesota (Jossi 2017), Massachusetts (Commonwealth of Massachusetts 2016), and California (Gray 2017).

unique to V2G applications, they impact V2G economics. Some of the primary security challenges arise from the quantity of data exchanged and the number of distributed devices in the "smart grid" system, which are likely to be several orders of magnitude greater than the amounts in the current utility grid (Khurana et al. 2010, Delgado-Gomes et al. 2015). Providing routine maintenance, ensuring data integrity, and monitoring cyber security may have significant costs (Colak et al. 2016). Mullan et al. (2012) estimate annual communications costs for a network of 60,000 vehicles participating in a V2G program in SWIS in Western Australia at $30 per vehicle for supplying spinning reserves using low-cost wireless service and $360 per vehicle for supplying spinning reserves and load balancing, which they assume requires more reliable copper-wire service. Communications hardware, software, and data-management costs would be borne by the system aggregator, who would also require some margin of profit for providing these services. The system aggregator may require 40%–50% of revenue obtained for V2G services for its operating expenses and profit (Harris and Webber 2014; Willett Kempton, personal communication with author, 2017).

A more extensive network of EVSE would be required for V2G than is currently in place. Many studies assume a fully built out infrastructure that allows for vehicles to be plugged in whenever they are not in use. However, only a few of the studies reviewed for this report have considered the costs and location requirements for the public and semi-public EVSE that would be needed for widespread adoption of V2G (Fazelpour et al. 2014, Nworgu et al. 2016).

Requirements for V2G such as minimum plugged-in time and the potential for owners' occasional loss of vehicle use would have to be carefully balanced against the needs of utilities and aggregators. Several studies have addressed the need for specific contractual arrangements between vehicle owners and aggregators and the need for vehicle owners to gain sufficient benefit from participation to overcome the inconvenience factors (Richardson 2013, Parsons et al. 2014, Shang and Sun 2016). In a consumer preference survey conducted in 2014, Hidrue and Parsons (2015) found that respondents placed a very high value on convenience and flexibility in the use of their vehicles. The researchers estimated minimum required compensation for contracts with increasingly restrictive terms. For the contract that offered the most convenience to vehicle owners—guaranteed minimum range (GMR) of 75 miles and required plugged-in time (RPT) of 5 hours—the median required yearly compensation for V2G services was $2,368 (2016USD 2,652). The estimated minimum compensation requirement rose to $8,622 (2016USD 9,657) for the most restrictive contract (GMR = 25 miles and RPT = 20 hours). Comparison to the values listed in Table 1 indicates that private vehicle owners might hesitate to participate in V2G at current estimated compensation rates, especially under very restrictive contract terms. Schmalfuβ et al. (2015) at the Technische Universität Chemnitz conducted a field experiment in which users evaluated several smart-charging systems for electric vehicles. Users set various parameters such as their expected departure time and acceptable minimum state of charge via a smart-phone application. They reported on how they experienced the system and how they perceived the benefits and drawbacks of managed charging. Results indicate that users were, for the most part, able to integrate management of charging into their daily routine. Reported drawbacks were less flexibility and less range owing to the minimum state-of-charge requirements.

6 Conclusion

Vehicle-to-grid capabilities could provide important services to grid operators, including balancing renewable peaks and valleys, providing excess capacity and bulk storage, providing spinning reserves, and balancing frequencies. Deploying V2G economically requires an understanding of the local markets, a sufficient number of vehicles to bid into energy markets, equipment to provide power back to the grid, and an aggregator to manage the project. Feed-in tariffs would help incentivize early deployments by strengthening the business model. Researchers have developed case studies to test cost-benefit tradeoffs in real-world scenarios, and a number of demonstration projects have been undertaken. V2G has been commercialized in Denmark and The Netherlands.

Accurate estimates of the costs and benefits of V2G for all participants are critical to determining the best applications and successfully integrating V2G into the electric grid. Much work has been done to model driving behavior and develop algorithms for optimizing the pooling of vehicles to guarantee availability of power and energy levels needed to bid into various electricity ancillary markets. The impact of increased battery cycling on battery life and thus costs has also been extensively analyzed. Costs for communications software and hardware and aggregator business models have garnered less attention. Table 3 and Table 4 outline some of the primary cost and revenue elements that are critical to accurate formulation of business models for V2G services.

Table 3. Cost Elements Critical to Formulation of V2G Business Models

Cost Element	Description
Battery wear	Providing V2G services may shorten the battery life owing to increased cycling and DoD. Assumptions about battery wear can have a large impact on cost estimates.
Battery replacement	Batteries currently cost less than $300/kWh. Costs for battery replacement would, in most cases, be borne by the vehicle owner.
Power electronics for V2G capability	Conversion between AC grid and DC vehicle current can be accomplished with power electronics incorporated into the vehicle or EVSE. V2G capability is not yet available from vehicle manufacturers, but would be expected to add $200–$400 to the price of the vehicle. Willett Kempton (personal communication with author, 2017) estimates that a 10-kW (Level 2) DC (i.e., off-board DC ↔ AC conversion) bi-directional EVSE unit would cost $4,500–$5,500. Hardware costs for bi-directional capability may be a barrier to EVSE performing grid/building services.
Network of non-residential EVSE	Most vehicles are parked most of the time and could be available for V2G services for many hours per day if EVSE were available at workplaces and other locations where vehicles are parked during the day. Many studies assume full buildout of EVSE infrastructure, which allows for many plugged-in hours per day. Accounting for public and workplace EVSE could add from $1,000 to more than $19,000 per EVSE unit for Level 2 charging.
Residential EVSE upgrades (e.g., electrical upgrades)	Revenue for providing V2G services is highly dependent on the power (kW) that can be provided by the vehicle. Typical residential circuits limit power to about 10 kW. Upgrading residential circuits could be cost effective for providing V2G services.
Communications hardware and software	Communications hardware and software are needed to network vehicles and control vehicle charging and discharging. Most studies reviewed for this report do not address costs for this service.
Aggregator	The aggregator manages the networking and control of vehicles, bids into electricity services markets, manages contracts with vehicle owners, and may provide other products and services. The aggregator may require 40%–50% of V2G revenue to cover expenses and profit.

Table 4. Revenue Elements Critical to Formulation of V2G Business Models

Revenue Element	Description
Pool of aggregated vehicles	Owners' driving patterns, requirements for state of charge and availability, and electricity market rules determine how many vehicles must be aggregated to provide V2G services.
Vehicle plugged-in hours	The number of plugged-in hours per day is a primary determinant of V2G revenue and profits. Non-residential EVSE must be available to fully realize the potential for vehicles to provide V2G services.
Power (kW) available	The power level that can be instantaneously available from vehicles is a primary determinant of revenue, especially for regulation services. Upgrading residential circuits to allow for higher power levels could be cost effective for vehicle owners providing V2G services.
Energy (kWh) available	Light-duty electric vehicle batteries have a small energy capacity in relation to the energy requirements of even micro-grids. Many vehicles would need to be aggregated together to provide bulk energy storage. The economics of price arbitrage between low and high demand periods could be challenging without large feed-in tariffs or other incentives.

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