



The effect of communication architecture on the availability, reliability, and economics of plug-in hybrid electric vehicle-to-grid ancillary services

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ABSTRACT

Researchers have proposed that fleets of plug-in hybrid vehicles could be used to perform ancillary services for the electric grid. In many of these studies, the vehicles are able to accrue revenue for performing these grid stabilization services, which would offset the increased purchase cost of plug-in hybrid vehicles. To date, all such studies have assumed a vehicle command architecture that allows for a direct and deterministic communication between the grid system operator and the vehicle. This work compares this direct, deterministic vehicle command architecture to an aggregative vehicle command architecture on the bases of the availability, reliability and value of vehicle-provided ancillary services. This research incorporates a new level of detail into the modeling of vehicle-to-grid ancillary services by incorporating probabilistic vehicle travel models, time series ancillary services pricing, and a consideration of ancillary services reliability. Results show that including an aggregating entity in the command and contracting architecture can improve the scale and reliability of vehicle-to-grid ancillary services, thereby making vehicle-to-grid ancillary services more compatible with the current ancillary services market. However, the aggregative architecture has the deleterious effect of reducing the revenue accrued by plug-in vehicle owners relative to the default architectures.

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1. Introduction

Plug-in hybrid electric vehicles (PHEVs) are hybrid electric vehicles that can draw and store energy from an electric grid to supply propulsive energy for the vehicle. This simple functional change to the conventional hybrid electric vehicle allows a plug-in hybrid to displace energy from petroleum with multi-source electric energy. This has important and generally beneficial impacts on transportation energy sector petroleum consumption, criteria emissions output, and carbon dioxide emissions, as well as on the performance and makeup of the electric grid. Because of these characteristics and their near-term availability, PHEVs are seen as one of the most promising means to improve the near-term sustainability of the transportation and stationary energy sectors [1].

Two primary types of power interactions are possible between the vehicle and the electric grid. Grid-to-vehicle charging (G2V) consists of the electric grid providing energy to the plug-in vehicle through a charge port. G2V is the traditional method for charging the batteries of battery electric vehicles and plug-in hybrid vehicles. A vehicle-to-grid (V2G) capable vehicle has the ability to provide energy back to the electric grid. V2G provides the potential for the grid system operator to call on the vehicle as a distributed energy and power resource.

Researchers have developed analyses and demonstrations of vehicle charging behavior, but the long-term infrastructure and information architectures required for a massive market infiltration of PHEVs are less defined. A few researchers have considered the effect of large numbers of plug-in vehicles on the electric grid. These studies have shown that the electric grid could assimilate a significant fraction of a hypothetical national fleet of plug-in vehicles performing G2V charging without significant infrastructure improvement and without centralized charging control [2–5]. Central utility control of plug-in vehicles performing G2V has been shown to have significant benefits for the grid system operator by enabling dynamic demand response, load profile flattening, and improved generation resource utilization [6–8]. Fewer studies have considered the impacts of wide-spread V2G. Demonstrations have shown that single vehicles can interface to the grid for V2G applications and that given sufficient information infrastructure, the grid operator could control power flow from and to the vehicle [9,10]. Conceptual V2G studies have calculated that there exists a significant return on investment for the purchase of plug-in vehicles that can perform ancillary grid services, particularly frequency support [9–17].

In order for V2G to achieve wide-spread near-term infiltration of the ancillary services market, V2G must satisfy the requirements of the two primary stakeholders in the V2G ancillary services transaction: the grid system operator and the vehicle owner. The grid system operator demands industry standard availability and reliability from the V2G system, and the vehicle owner demands a

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robust return on their investment in V2G hardware and vehicles. Studies of V2G have concentrated on quantifying return on investment with only cursory consideration of the requirements of the utility and grid system operator. This study attempts to address this knowledge gap by (1) defining and clarifying the command and control architectures of V2G that have been proposed in literature, (2) explicitly modeling the availability of V2G vehicles to quantify and compare the availability of V2G to that of other types of ancillary services providers, (3) modeling the reliability of V2G vehicles to quantify and compare the reliability of V2G to that of other types of ancillary services providers, and (4) modeling the economics of V2G using time series ancillary services pricing to assess the robustness of the average return on investment which has been identified in previous conceptual studies. The discussion makes use of this new information to assess the long-term feasibility of V2G ancillary services.

2. V2G ancillary services architectures

2.1. Description of the direct, deterministic architecture

Intrinsic to the V2G studies and demonstrations that have been performed to date is the assumption of a particular vehicle contracting and command architecture. In this study, we will refer to this default architecture for V2G command and contracting as the direct, deterministic architecture. The direct, deterministic architecture shown conceptually in Fig. 1, assumes that there exists a direct line of communication between the grid system operator and the vehicle so that each vehicle can be treated as a deterministic resource to be commanded by the grid system operator. Under the direct, deterministic architecture, the vehicle is allowed to bid and perform services while it is at the charging station. When the vehicle leaves the charging station, the contracted payment for the previous full hours is made and the contract is ended. The direct, deterministic architecture is conceptually simple but it has long-recognized problems in terms of near-term feasibility and long-term scalability.

First, there exists no near-term information infrastructure to enable the required line of communication. The direct, deterministic architecture cannot use the conventional control signals that are currently used for ancillary services contracting and control because the small, geographically distributed nature of V2G vehicles is incompatible with the existing contracting frameworks. For example, the peak power capabilities of individual vehicles (1.8 kW [1] to –17 kW [18]) are below the 1 MW thresh-

old that is required of many ancillary services hourly contracts [12].

In the longer term, the grid system operator might be required to centrally monitor and control all of the V2G subscribed vehicles in the power control region. This is understood to be an overwhelming communications and control task [19]. As these millions of vehicles engage and disengage from the grid, the grid system operator must constantly update the contract status, connection status, power available, state-of-charge, and driver requirements to contract the power it can deterministically command from the vehicle.

2.2. Description of the aggregative architecture

This study proposes a new command and contracting architecture for V2G-provided ancillary services which aggregates individual vehicles to make a single controllable power resource. The aggregative architecture is shown conceptually in Fig. 2. In this aggregative architecture, an intermediary is inserted between the vehicles performing ancillary services and the grid system operator. This aggregator receives ancillary service requests from the grid system operator and issues power commands to contracted vehicles that are both available and willing to perform the required services. Under the aggregative architecture, the aggregator can bid to perform ancillary services at any time, while the individual vehicles can engage and disengage from the aggregator as they arrive at and leave from charging stations. This allows the aggregator to bid into the hourly ancillary services market and compensate the vehicles under its control for each minute that they are available to perform V2G. As such, this aggregative architecture attempts to address the two primary problems with the direct, deterministic architecture.

First, the larger scale of the aggregated V2G power resources commanded by the aggregator, and the improved reliability of aggregated V2G resources connected in parallel allows the grid system operator to treat the aggregator like a conventional ancillary services provider. This allows the aggregator to utilize the same communication infrastructure for contracting and command signals that conventional ancillary services providers use, thus eliminating the concern of additional communications workload placed on the grid system operator.

In the longer term, the aggregation of V2G resources will allow them to be integrated more readily into the existing ancillary services command and contracting framework, since the grid system operator need only directly communicate with the aggregators. The communication network between the aggregator and the vehi-

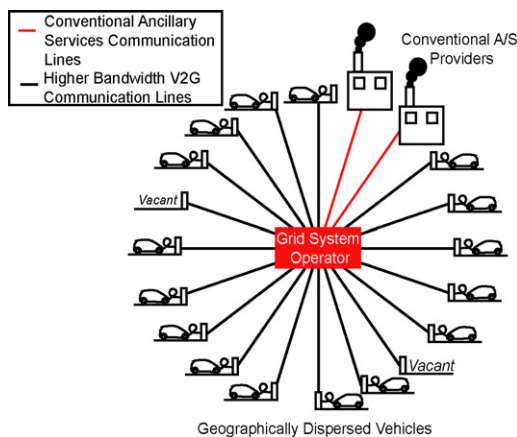


Fig. 1. Example plug-in vehicle-to-grid network showing geographically dispersed communications connections under the direct, deterministic architecture.

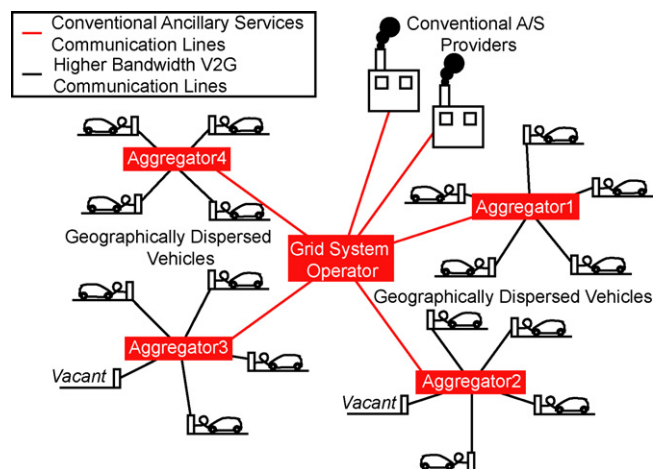


Fig. 2. Example plug-in vehicle-to-grid network showing geographically dispersed communications connections under the aggregative architecture.

cles is of a more manageable scale than communication network required under the direct, deterministic architecture. The aggregative architecture is therefore more extensible than the direct, deterministic architecture as it allows for the number of vehicles under V2G contracts to expand by increasing the number of aggregators, increasing the size of aggregators, or both.

We would like to quantify these purported benefits of the aggregative architecture, but to do so requires mathematical models of V2G that are more advanced than the deterministic and time averaged models that have been employed to date in V2G conceptual studies. To evaluate the relative effectiveness of these V2G architectures we must construct new models of V2G-provided ancillary services that can evaluate the system for stochastic qualities such as availability, reliability and robustness.

3. Availability of V2G ancillary services

For conventional technologies providing ancillary services, reduced availability reduces the value of a power plant as a tool for grid stabilization. V2G ancillary services have a unique availability profile because the presence of the ancillary services resource is dependent on the probabilistic (and uncontrolled) presence of vehicles at charging stations, and the location of the charging stations. In this section, we will derive metrics for the availability of V2G ancillary services for both proposed architectures using stochastic vehicle use data.

To quantify the availability of V2G ancillary services we will calculate its Availability Factor (AF). AF is a North American Electric Reliability Corporation (NERC) reported metric of the ability of an individual generation resource to enter into a contract with the grid system operator. To compare the availability of V2G and existing ancillary service providers, we can utilize the AF for gas turbine power plants, a probable competitor to V2G for ancillary services contracts. The NERC reports an AF of 92.91% for gas turbine plants in operation from 2003 to 2007 [20].

The availability of V2G as a resource is dependent on the presence of vehicles at V2G-enabled charging stations. To quantify the habits of US drivers we can use vehicle trip length and timing data from the National Household Transportation Survey (NHTS) [21]. The full (>50% completed) weighted NHTS dataset was processed to determine the presence of V2G vehicles at V2G-enabled charging stations for two scenarios: (1) vehicles can only perform V2G services when parked at home, (2) vehicles can perform V2G services when parked at home and when parked at work. For the home connection scenario, we can process the NHTS to find trip chains that end at home ($WHYTRIP(i) = 1$). The home connection scenario assumes that the vehicle is only available to perform V2G services during the time that it is stationary at home. For the home and work connection scenario, we construct trip chains from the NHTS dataset that end at home ($WHYTRIP(i) = 1$) or at work ($WHYTRIP(i) = 11$ or $WHYTRIP(i) = 12$). The NHTS vehicle connects only at the end of this trip chain. For instance, under the home and work connection scenario, a daily travel file that includes stops at a grocery, school, work, and home would be split into two trip chains, one between home and work and a second between work and home. The vehicle is available to perform V2G services only during the time it is stationary at home or stationary at work.

This home charging scenario might represent a near-term V2G implementation, where V2G services are contracted to the electricity consumer through the consumer's home electric bill. The home and work charging scenario might represent a very long-term scenario where the V2G infrastructure has high penetration, the V2G services are contracted to the vehicle, and commands can travel with the vehicle to any location that has a V2G-capable plug. These scenarios assume that the vehicle is immediately connected

and disconnected to the grid upon arrival and departure, that the V2G services can be performed at all states of charge, and that any V2G-capable vehicle would be able to perform V2G services at the consumer's home and/or work. These assumptions represent nearly a best-case scenario in terms of V2G infrastructure and the behavior of V2G vehicles. Drivers who forget to plug-in the vehicle, home and work locations that are under different grid control areas, and state-of-charge limitations will decrease the availability of V2G resources from this baseline. It is important to note that no attempt was made to filter the NHTS database to remove vehicles or trips which are unlikely candidates for replacement with PHEVs in the foreseeable future. All vehicle types and all trip types were arbitrarily included. The NHTS dataset spans the days of the week and several US geographic locations, and therefore represents an averaged day and US driver population. Finally, the same electrical capacity ($P = 10$ kW) was assumed for all vehicles, regardless of size, matching assumptions made in previous studies [10].

3.1. Availability of the direct, deterministic architecture

For the direct, deterministic architecture, we assume that individual vehicles will be available to perform ancillary services whenever they are connected to the grid, but that they are connected to the grid only for a portion of the day. The availability of the communication system between the grid system operator and the vehicles is modeled to be 100%, and the vehicles are connected to the grid for 100% of the minutes they are parked at a charging station. Under these assumptions, the AF is equal to the average fraction of a day that the vehicle is present at a V2G charging station. Therefore a long-term average of the fraction of the day that a vehicle spends at a charging station (vehicle availability) can be equated to the AF of that vehicle to perform ancillary services.

The minute-by-minute availability of an average vehicle (A_{vehicle}) as calculated using the NHTS dataset is presented in Fig. 3. For the home charging scenario, Fig. 3 shows that the availability of vehicles is very high during the early portion of the day. Less than 0.5% of household vehicle trips in the NHTS do not begin at home. During the day, the availability of vehicles decreases as they drive to work or other intermediate locations. Between 10:45 am and mid-afternoon, approximately 35% of vehicles are not available to perform V2G services if these services can only be performed from the home of the vehicle's owner. Under the scenario where the vehicle can only provide V2G services from home, the minimum vehicle availability is 62.7%, and the long-term averaged AF which is equivalent to the daily averaged vehicle availability of 83.6%. For the home and work charging scenario, the availability

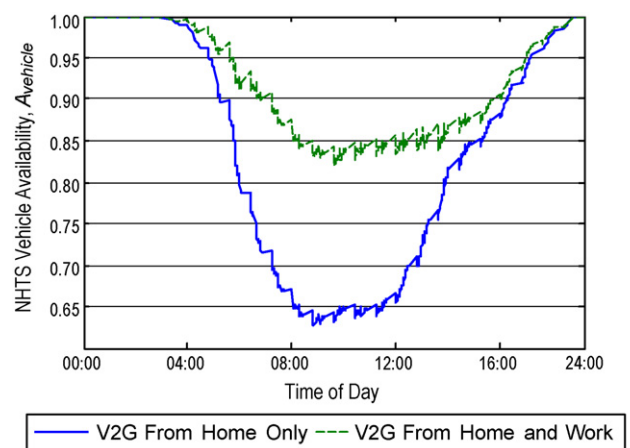


Fig. 3. Availability of vehicle-to-grid enabled vehicles as a function of time of day for two infrastructure infiltration scenarios.

of the V2G vehicles is improved because of increased charger penetration resulting in a minimum vehicle availability of 82.0% and a long-term averaged AF equivalent to the daily averaged vehicle availability of 91.7%.

Compared to the ancillary services baseline, the AF of the direct, deterministic architecture is lower than the NERC reported availability for gas turbine generators of 92.91%. Only in the longest term scenario, where vehicles always connect to V2G-capable charging stations at both home and work, could the direct, deterministic architecture approach industry availability norms.

3.2. Availability of the aggregative architecture

For the aggregative architecture, the aggregator's ability to enter into contracts with the grid system operator is independent of any individual vehicle's presence at the charging station. Because the aggregator can vary the size of its power contract when fewer vehicles are present at charging stations, it is available to bid for ancillary services contracts at any time of day or night. Under the assumption that the aggregator has no generation machinery to maintain, and that the communications connection between the aggregator and the grid system operator is always present, the AF of the aggregative architecture approaches 100%. Thus, the availability of V2G ancillary services under the aggregative architecture is therefore improved relative to the 92.91% of the baseline generator.

3.3. Comparison of availability among architectures

Based on the results of these analyses, we can compare the availabilities of the two proposed architectures. The direct, deterministic architecture is less available during large portions of the day because when the vehicle is away from the charging station, it is not available to perform ancillary services. Under the aggregative architecture, the aggregator can contract with the grid system operator at any time.

These analyses suggest that the aggregative architecture can improve the performance of V2G ancillary services based on the metric of ancillary services availability. Under the assumptions of the direct, deterministic architecture, the availability of the vehicle as a resource for the grid system operator is outside the normal ranges of conventional power generation units. The aggregative architecture allows the aggregator to achieve industry standard availability, simplifying the interface between the grid system operator and the V2G grid services provider.

4. Reliability of V2G ancillary services

The forced down-time of a power plant characterizes its reliability to fulfill ancillary services contracts. To quantify the reliability of V2G ancillary services we will calculate a Forced Derated Hours Ratio (FDHR). The FDHR is defined as the ratio of the NERC reported Equivalent Forced Derated Hours (EFDH) to the NERC reported Service Hours (SHs) [20]. The reliability (R) of a system to provide the contracted and commanded ancillary services is

$$R = (1 - \text{FDHR}) \quad (1)$$

For comparison between V2G and existing ancillary service providers, we can calculate the FDHR and reliability for gas turbine power plants, a probable competitor to V2G for ancillary services contracts. The metrics of EFDH and SH are reported by NERC for gas turbines in operation from 2003 to 2007, which result in a FDHR of 1.11% and a reliability (R) of 98.89% [20].

4.1. Reliability of the direct, deterministic architecture

To model the reliability of the direct, deterministic architecture it must be understood how an individual vehicle will fail to meet its contracted power commands from the grid system operator. In agreement with previous studies, we will assume that V2G regulation is a zero net energy service and thus the state-of-charge will not limit the reliability of the vehicle as a V2G resource. Again, the vehicle hardware and communications connections are assumed 100% reliable. The most important way that a vehicle will fail to meet its contracted power requirements is if it drives away from the charger during the contract period. To simplify the calculation of how often this will happen on average, we assume that: (1) the V2G vehicle is contracting in an hour-ahead market that closes at the top of the hour¹, (2) the hour-before checkout requirement is waived for V2G vehicles, (3) the grid system operator cannot prevent the driver from disconnecting from the grid at any time, and (4) the system has no foresight into the driver's intentions.

Under these assumptions, we can calculate the percentage of vehicles from the NHTS database that would be present for contracted services at the top of any given hour but would not complete that contract because the vehicle disconnected during the course of the hour. This analysis counts each hourly contract broken as a forced derated hour and each hourly contract as a service hour to calculate a FDHR for each vehicle in the NHTS. The daily average of hourly broken contracts of the NHTS fleet equals the FDHR for V2G ancillary services, and is found to be 4.65% for the home connection scenario and 5.13% for the home and work connection scenario. The daily average reliability (R) of the direct, deterministic architecture is therefore 95.35% for the home connection scenario and 94.87% for the home and work connection scenario. The direct, deterministic architecture is unable to meet industry standards for reliability, even under the longer term infrastructure infiltration scenarios.

4.2. Reliability of the aggregative architecture

The reliability of the aggregative architecture is determined by how often the aggregator is able to meet 100% of the power that it has contracted to provide the grid system operator. Under the assumption that there is a 100% reliable communication connection between the grid system operator and the aggregator, the reliability is determined by the ratio of the contract size to the minimum number of vehicles present at the V2G charging station over the course of the contracted hour. The mechanism that leads to the unreliability of the direct, deterministic architecture is not applicable to the aggregative architecture because of the presence of the aggregator. The aggregator is not required to contract for full power with every vehicle that is present at the top of the hour. Instead, the aggregator can manage the fleet size and contract size to maintain industry standard reliability over the course of each hour, day, and year.

Using the concepts of systems reliability, we can calculate the aggregator's total fleet size (n_{vehicles}) which allows the aggregator to fulfill an hourly contract for a certain power with a reliability equivalent to the reliability of the baseline gas turbine generator, $R = 98.89\%$. The fleet scaling factor (x_{fleet}) is used to determine the total fleet size (n_{vehicles}) and is defined by modeling the vehicles as parallel resources:

$$x_{\text{fleet}} = \frac{\ln(1 - R)}{\ln(1 - \text{AF})} \quad (2)$$

¹ This assumption is a slight deviation from the structure of some deregulated markets, which close thirty minutes prior to the hour.

Utilizing the daily averaged vehicle availability values $AF=83.6\%$ for the home connection scenario and $AF=91.7\%$ for the home and work connection scenario, the fleet size scaling factors that allow for reliabilities equivalent to the natural gas turbine baseline ($R=98.89\%$) are $x_{\text{fleet}}=2.49$ and $x_{\text{fleet}}=1.81$, respectively. This fleet scaling factor (x_{fleet}) determines the amount of power ($Pn_{\text{vehicles}}/x_{\text{fleet}}$) that the aggregator can contract while maintaining an industry standard reliability based upon the daily averaged vehicle availability. By increasing the size of the aggregator's vehicle fleet to greater and greater numbers, the reliability of the aggregative architecture in producing a fixed power service can be improved to match or exceed industry norms².

4.3. Comparison of reliability among architectures

Based on these calculations, we can compare the reliability with which each architecture can meet the contracted power requests of the grid system operator. The direct, deterministic architecture is intrinsically less reliable than the aggregative architecture because the reliability of the direct, deterministic architecture is entirely dependent on the uncontrolled behavior of the vehicle owners. Even under the long-term charger infiltration scenarios, the reliability of the direct, deterministic architecture is lower than that of the aggregative architecture and industry standards. The aggregative architecture however can control its reliability to meet industry standards by controlling its contracted fleet size, the contract size, or both. This shows that the aggregative architecture is more suitable than the direct, deterministic architecture from the viewpoint of the grid systems operator on the grounds of systems reliability.

5. Compensation for V2G ancillary services

Having compared V2G architectures on the basis of the grid system operator requirements, we can evaluate them on the basis of the requirements of the vehicle owners. In this section, we propose new economic models to calculate the potential revenue from V2G ancillary services. These models include the effects of NHTS vehicle availability data, reliability, and time series ancillary services pricing data for the years 2006, 2007, and 2008, from the CAISO OASIS database [22].

Previous studies of the economics of V2G have shown that there exists a significant return on investment for the owners of V2G-capable vehicles [10,12,16]. This hypothesized return on investment has become a motivator for the implementation of V2G since it is one of the primary proposed mechanisms for offsetting the higher purchase costs of V2G-capable vehicles. In this section, we will calculate and compare the revenue that is accrued by an average vehicle under each V2G architecture. These analyses assume: (1) a V2G vehicle only performs frequency regulation services, which previous studies have shown is the most lucrative and realizable ancillary service for V2G [16], (2) a V2G vehicle contracting and performing both regulation-up and regulation-down services results in a net zero energy transaction, avoiding capacity issues related to vehicle state-of-charge, (3) individual V2G vehicle owners (and their aggregators) are logical bidders in the ancillary services market and will not contract to provide regulation services

which are not cost-effective³, and (4) that V2G-capable vehicles providing ancillary services will not affect the economics of the ancillary services market.

With regards to this final assumption the literature suggests that the market for ancillary services will become saturated with a relatively low V2G market penetration [15,17]. We replicate these analyses from the literature so as to understand the effect of the communication architecture on the scale of a V2G fleet that will saturate the ancillary services market. The CAISO procured an average of 2429 MW for all ancillary services from 2006 to 2008. From this total 357 MW were procured for regulation-down services and 385 MW for regulation-up services [23,24]. Under the assumption that the vehicle connection is rated at 10 kW and that the V2G vehicles can contract for both regulation-up and regulation-down services simultaneously, the ancillary services contracts for CAISO could be met by $\sim 38,500$ V2G vehicles in the direct, deterministic architecture and $\sim 96,000$ vehicles in the aggregative architecture. Under these assumptions, V2G vehicles could supply the required frequency regulation for the CAISO region with a market infiltration of only $\sim 0.2\%$ of the California fleet for the direct, deterministic architecture and $\sim 0.4\%$ for the aggregative architecture [25]. For context, hybrid vehicles of all types made up 2.8% of US vehicle sales in the first 7 months of 2009 [26].

This study adopts the revenue and cost framework that has been defined by Tomic and Kempton [16]. Regulation-up service is broken into two terms: a contract payment ($p_{\text{cap}} P$), and a payment for the delivery of energy to the grid ($p_{\text{el}} P R_{\text{d-c}}$), where (P) is the vehicle V2G power capacity (p_{cap}) is the yearly average ancillary service contract price, and the ($R_{\text{d-c}}$) is the ratio of energy dispatched for regulation as a proportion of contracted power and contracted time. The revenue for a single regulation-up services contract ($r_{\text{Reg-Up}}$) is the sum of these two terms, multiplied by the time that the vehicle is under contract (t_{plug}):

$$r_{\text{Reg-Up}} = t_{\text{plug}}(p_{\text{cap}} P + p_{\text{el}} P R_{\text{d-c}}) \quad (3)$$

For regulation-down, it's assumed that V2G owners will only receive payment for the contractible power and no payment for the actual energy service. This avoids a situation where the utility pays V2G vehicle owners to charge their vehicle's batteries. Therefore, the revenue for a single regulation-down contract ($r_{\text{Reg-Down}}$) includes only the contracted power term:

$$r_{\text{Reg-Down}} = t_{\text{plug}}(p_{\text{cap}} P) \quad (4)$$

To define the costs associated with providing regulation services, we use the assumption made in [16] that if a PHEV is providing regulation-up and regulation-down services then the cost of regulation-down is zero (again because of its functional similarity to charging). The cost associated with a single regulation-up contract ($c_{\text{Reg-Up}}$) is defined over a period t_{plug} shown in (5), where (P), (t_{plug}), (p_{cap}), and ($R_{\text{d-c}}$) are the same values defined and used for the revenue calculations. The cost per unit energy (c_{en}) is a function of: electrical purchase price (c_{pe}), efficiency of the charger (η_{conv}),

² An example can help to clarify the aggregative architecture fleet size scaling factor (x_{fleet}). Under the scenario where the vehicles can only charge at home, $x_{\text{fleet}}=2.49$. If each vehicle can provide 10 kW of ancillary services and the aggregator has contracted with $n_{\text{vehicles}}=1000$ vehicles, the aggregator can contract to provide 4.0 MW h^{-1} of ancillary services with a daily average reliability of 98.89%. To provide a 10 MW h^{-1} contract with an industry standard equivalent reliability, the aggregator must enroll $n_{\text{vehicles}}=2490$ vehicles to improve the probability that the vehicles will be available to perform grid ancillary services.

³ For this study we will assume that the breakeven bid price for regulation services is based upon the average price for regulation-up and regulation-down for each hour. This assumption is made to maintain the assumption of net zero change in battery SOC. This bidding assumption is technically correct in the NYISO and PJM markets where up- and down-regulation services are contracted in a single market, and technically incorrect in the CAISO and ERCOT markets, where up- and down-regulation services are contracted in separate markets. Markets such as the CAISO and ERCOT would either have to change their bidding structure to accommodate V2G vehicles or V2G vehicles would have to bid separately into each market and take a risk of winning the bid for only regulation-up or regulation-down. A vehicle placing a winning bid in only one of the two markets would violate the assumption of net-zero change in the vehicles SOC thus creating additional limitations on the amount of, or reliability of, regulation services a vehicle could provide.

Table 1
Economic modeling parameters for the study of the direct, deterministic architecture.

Parameters	Description	Value	Units	Comments
P	Vehicle V2G power capacity	10	(kW)	As in [16]
R_{d-c}	Ratio of energy dispatched for regulation services as a proportion of contracted power and time	10	(%)	As in [16]
p_{cap}	Hourly ancillary service contract price	Varies	(\$ MW h ⁻¹)	Taken from [22]
R	Probabilistic vehicle hourly reliability	Varies	(%)	Derived from [21]
$A_{vehicle}$	Probabilistic vehicle hourly availability	Varies	(%)	Derived from [21], refer to Fig. 3
c_{en}	Cost per unit of energy	0.21	(\$ kW h ⁻¹)	Calculated from (5)
p_{el}	Market selling price of electricity	0.10	(\$ kW h ⁻¹)	–
c_{pe}	Electricity purchase price	0.10	(\$ kW h ⁻¹)	Equal to p_{el}
η_{conv}	Inverter energy conversion efficiency	0.73	(%)	As in [16]
c_d	Battery degradation cost	0.077	(\$ kW h ⁻¹)	Calculated from (5)
E_s	Battery storage capacity	5	(kWh)	–
c_b	Battery cost	300	(\$ kW h ⁻¹)	As in [16]
c_L	Battery replacement cost	240	(\$)	As in [16]
L_C	Battery life	1500	(cycles)	As in [16]
DoD	Battery depth of discharge	100	(%)	As in [16]

and battery degradation (c_d). The battery degradation (c_d) is a function of: the total energy storage of the battery (E_s), battery cost per kWh (c_b), battery replacement labor and time (c_L), and the number of cycles during the battery's life (L_C) based on the battery's depth of discharge (DoD). The annualized capital cost (c_{ac}), is the capital needed to upgrade a vehicle to V2G capabilities:

$$\begin{aligned}
 c_{Reg-Up} &= (c_{en} P R_{d-c} t_{plug}) + c_{ac} \\
 c_{Reg-Down} &= 0 \\
 c_{en} &= \left[\frac{c_{pe}}{\eta_{conv}} \right] + c_d \\
 c_d &= \frac{(E_s c_b) + c_L}{3 L_C E_s DoD}
 \end{aligned} \tag{5}$$

The assumptions above implicitly assume that the cost of energy is constant throughout the day. This calculation does not quantify communication costs, any costs or profits taken by the aggregators, or degradation of vehicle systems other than the battery.

5.1. Compensation for V2G ancillary services—direct, deterministic architecture

Under the assumptions of the direct, deterministic architecture, the V2G contract revenues and costs (3–5) must be modified to take into account the varying contract price of ancillary services (p_{cap}), the time varying availability of the individual vehicle under study ($A_{vehicle}$), and the time varying reliability of the individual vehicle (R). Under the direct, deterministic architecture, vehicle owners can only collect revenue or incur costs when they are connected to the V2G charger. By multiplying the revenues and costs (3–5) by the hourly availability of the V2G vehicle at the top of each hour ($A_{vehicle}(k)$), the time varying reliability of the average vehicle over the course of each hour ($R(k)$), and the hourly pricing ($p_{cap}(k)$ and $p_{el}(k)$), we can calculate the expected values of the hourly revenues and costs to an average V2G vehicle owner under the direct, deterministic model:

$$\begin{aligned}
 r_{Reg-Up}(k) &= A_{vehicle}(k) R(k) ((p_{cap}(k) P) + (p_{el}(k) P R_{d-c})) \\
 r_{Reg-Down}(k) &= A_{vehicle}(k) R(k) (p_{cap}(k) P) \\
 c_{Reg-Up}(k) &= A_{vehicle}(k) R(k) (c_{en}(k) P R_{d-c}) \\
 c_{Reg-Down}(k) &= 0
 \end{aligned} \tag{6}$$

For this study we assume the home connection scenario and that each V2G vehicle is capable of providing $P=10$ kW of power. The vehicle owner is modeled as a selective bidder who will not bid on hourly contracts where the costs of providing ancillary services are greater than can be covered by revenues. The cost calculations for

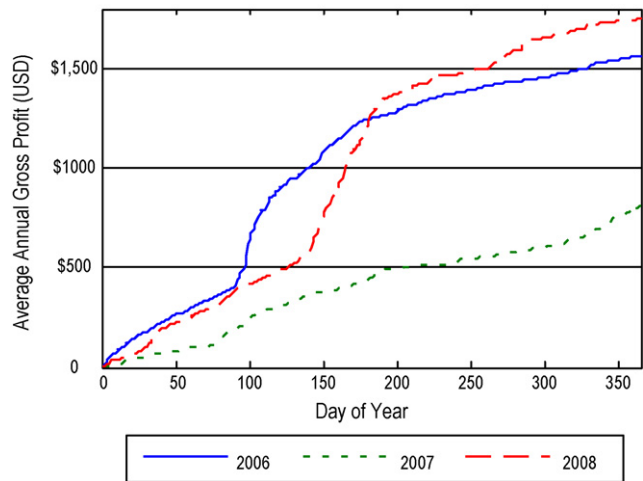


Fig. 4. Cumulative average annual gross profits for an average vehicle performing V2G regulation services under the direct, deterministic architecture.

this section exclude the annualized capital cost (c_{ac}) used in (5) as this cost will be evaluated in Section 5.3. The remaining parameters for this study are provided in Table 1.

Using these new, time resolved and probabilistic revenue and cost models (6), the costs and revenues were calculated for the average V2G vehicle owner under the direct, deterministic architecture. The average annual revenues and costs are presented in Table 2, with a graph of the cumulative average annual gross profit over the course of the year shown in Fig. 4. These calculations show an impressive average gross profit from V2G frequency regulation services of \$1374 per year for an average gross margin of 58%.

These economic results agree with previous studies in that the average annual gross profits for vehicles performing V2G services are indeed positive and substantial. It is notable that the magnitude of the average annual gross profits can vary by a factor of more than 2.5 depending on the year⁴. Fig. 4 shows that the revenue from V2G

⁴ The CAISO ancillary service market experienced much lower hour-ahead procurement pricing in 2007. This can be attributed to the fact that in both 2006 and 2008 there was an abundance of hydroelectric power in the spring and summer season which forced many thermal generation units offline due to the lower production cost of hydroelectric power. This resulted in bid insufficiencies in the ancillary service market and thus increasing the hour-ahead procurement prices for ancillary services particularly in the regulation sector. Additionally, the increase in ancillary service hour-ahead procurement pricing in 2008 was affected by high natural gas prices [23,24].

Table 2
Economic modeling results for the direct, deterministic architecture.

	2006	2007	2008
Average annual revenue ($r_{\text{Reg-Up}}^{\text{Yearly}} + r_{\text{Reg-Down}}^{\text{Yearly}}$)	\$2697	\$1709	\$2701
Regulation-up revenue ($r_{\text{Reg-Up}}^{\text{Yearly}}$)	\$1456	\$1150	\$1377
Regulation-down revenue ($r_{\text{Reg-Down}}^{\text{Yearly}}$)	\$1241	\$559	\$1324
Average annual cost ($c_{\text{Reg-Up}}^{\text{Yearly}} + c_{\text{Reg-Down}}^{\text{Yearly}}$)	\$1132	\$900	\$954
Average annual gross profit ($r_{\text{Reg-Up}}^{\text{Yearly}} + r_{\text{Reg-Down}}^{\text{Yearly}} - c_{\text{Reg-Up}}^{\text{Yearly}} - c_{\text{Reg-Down}}^{\text{Yearly}}$)	\$1565	\$809	\$1747

ancillary services is not accumulated gradually. Instead there are particular days and weeks of the year when it is very lucrative to perform V2G.

5.2. V2G compensation for ancillary services: aggregative architecture

To meet the assumptions of the aggregative architecture, the V2G contract revenues and costs (3–5) must be modified to take into account the varying contract price of ancillary services ($p_{\text{cap}}(k)$), the hourly average availability of the individual vehicle under study ($A_{\text{vehicle}}(k)$), the minimum reliability of the aggregator during the contract hour ($R(k)$), the increased fleet size required by the aggregative architecture to improve reliability (x_{fleet}), and the hourly average availability of the entire aggregated vehicle fleet ($A_{\text{fleet}}(k)$).

As before, the vehicle owner can only collect revenues or incur costs when they are connected to the V2G charger and it is assumed that the aggregator will not bid for regulation services if it is not cost-effective for the vehicles. The aggregator distributes the hourly revenue that is delivered to the aggregator to all the vehicles that have been connected to that aggregator's V2G charger network during the previous hour. The revenue delivered to the aggregator for each hour is

$$r_{\text{Reg-Up}}(k) = R(k)((p_{\text{cap}}(k)P) + (p_{\text{el}}(k)PR_{\text{d-c}})) \left[\frac{n_{\text{vehicles}}}{x_{\text{fleet}}} \right] \quad (7)$$

$$r_{\text{Reg-Down}}(k) = R(k)(p_{\text{cap}}(k)P) \left[\frac{n_{\text{vehicles}}}{x_{\text{fleet}}} \right]$$

This total revenue must be split among the vehicles that are connected to the aggregator during the previous hour. The ratio of the minutes that the subject vehicle is connected to the grid to the total number of minutes that the other aggregated vehicles are connected to the grid is

$$\frac{A_{\text{vehicle}}(k)}{n_{\text{vehicles}} A_{\text{fleet}}(k)} \quad (8)$$

Table 3
Economic modeling parameters for the study of the aggregative architecture.

Parameters	Description	Value	Units	Comments
P	Vehicle V2G power capacity	10	(kW)	As in [16]
$R_{\text{d-c}}$	Ratio of energy dispatched for regulation services as a proportion of contracted power and time	10	(%)	As in [16]
p_{cap}	Hourly ancillary service contract price	Varies	(\$MW h ⁻¹)	Taken from [22]
R	Probabilistic vehicle hourly reliability	Varies	(%)	Derived from [21]
A_{vehicle}	Probabilistic vehicle hourly availability	Varies	(%)	Derived from [21], refer to Fig. 3
A_{fleet}	Probabilistic V2G fleet hourly availability	Varies	(%)	Derived from [21], refer to Fig. 3
x_{fleet}	Fleet scaling factor	2.49		Calculated from (2)
c_{en}	Cost per unit of energy	0.21	(\$kW h ⁻¹)	Calculated from (5)
p_{el}	Market selling price of electricity	0.10	(\$kW h ⁻¹)	–
c_{pe}	Electricity purchase price	0.10	(\$kW h ⁻¹)	Equal to p_{el}
η_{conv}	Inverter energy conversion efficiency	0.73	(%)	As in [16]
c_{d}	Battery degradation cost	0.077	(\$kW h ⁻¹)	Calculated from (5)
E_{s}	Battery storage capacity	5	(kWh)	–
c_{b}	Battery cost	300	(\$kW h ⁻¹)	As in [16]
c_{l}	Battery replacement cost	240	(\$)	As in [16]
L_{c}	Battery life	1500	(cycles)	As in [16]
DoD	Battery depth of discharge	100	(%)	As in [16]

These conditions lead to a new set of equations for the hourly revenue and costs from V2G under the aggregative architecture.

$$r_{\text{Reg-Up}}(k) = \frac{A_{\text{vehicle}}(k)R(k)((p_{\text{cap}}(k)P) + (p_{\text{el}}(k)PR_{\text{d-c}}))}{x_{\text{fleet}}A_{\text{fleet}}(k)}$$

$$r_{\text{Reg-Down}}(k) = \frac{A_{\text{vehicle}}(k)R(k)(p_{\text{cap}}(k)P)}{x_{\text{fleet}}A_{\text{fleet}}(k)} \quad (9)$$

$$c_{\text{Reg-Up}}(k) = \frac{A_{\text{vehicle}}(k)R(k)(c_{\text{en}}(k)PR_{\text{d-c}})}{x_{\text{fleet}}A_{\text{fleet}}(k)}$$

$$c_{\text{Reg-Down}}(k) = 0$$

For this analysis, the driving habits of the subject are assumed to be equivalent to the driving habits of the NHTS average driver. This implies that the hourly availability of the subject vehicle ($A_{\text{vehicle}}(k)$) is equal to the hourly availability of the fleet ($A_{\text{fleet}}(k)$). As in the direct, deterministic architecture, we assume the home connection scenario and that each V2G vehicle is capable of providing $P=10$ kW of power. The vehicle owner is modeled as a selective bidder who will not bid on hourly contracts where the costs of providing ancillary services are greater than can be covered by revenues. The cost calculations for this section exclude the annualized capital cost (c_{ac}) used in (5), as this cost will be evaluated in Section 5.3. The remaining parameters for this study are provided in Table 3.

In this example, the aggregator would have to utilize a V2G fleet scaling factor (x_{fleet}) of 2.49 in order to provide ancillary services with 98.89% reliability throughout the day for the home connection scenario. Using (7), the annual revenues and costs were estimated for the average V2G vehicle owner in the aggregative architecture. These results are presented in Table 4 and Fig. 5, and the average gross profits from V2G frequency regulation services are \$662 per year for an average gross margin of 58%.

Table 4
Economic modeling results for the aggregative architecture.

	2006	2007	2008
Average annual revenue ($r_{Reg-Up}^{Yearly} + r_{Reg-Down}^{Yearly}$)	\$1303	\$855	\$1291
Regulation-up revenue (r_{Reg-Up}^{Yearly})	\$725	\$587	\$688
Regulation-down revenue ($r_{Reg-Down}^{Yearly}$)	\$578	\$268	\$603
Average annual cost ($c_{Reg-Up}^{Yearly} + c_{Reg-Down}^{Yearly}$)	\$558	\$440	\$465
Average annual gross profit ($r_{Reg-Up}^{Yearly} + r_{Reg-Down}^{Yearly} - c_{Reg-Up}^{Yearly} - c_{Reg-Down}^{Yearly}$)	\$745	\$415	\$826

5.3. Comparison of V2G compensation for ancillary services among architectures

Comparison of the aggregative architecture results in Table 4 to the direct, deterministic architecture results in Table 2 show that the increased fleet size that is required for the aggregative architecture has decreased the profits that are accrued by the average individual vehicle. To demonstrate how this decrease in profits for the aggregative architecture affects the viability of V2G to provide ancillary services we will determine what the return on investment for both the direct, deterministic and aggregative architectures should be based upon our analyses.

Previous studies have estimated the anticipated initial investment that would be required to become a V2G ancillary service provider and broken this initial investment up into an annualized capital cost (c_{ac}). Instead of estimating the expected initial investment required and including the annualized capital cost in our revenue and cost calculations, we utilize the average annual gross margins for both the direct, deterministic and aggregative architectures to estimate the maximum initial investment allowed, given an assumed discount rate and investment period.

In this section, we estimate gross profits as the mean of the average annual gross profits (\overline{AAGP}) for 2006, 2007, and 2008, for both architectures. Assuming an investment period of 10 years and a discount rate of 10%, we compute the maximum allowable initial investment ($c_{c\ max}$). Cash flows are discounted utilizing Eq. (10), and the assumptions made for the investment payback period (n) and the discount rate (i) are summarized in Table 5:

$$c_{c\ max} = \overline{AAGP} \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right] \tag{10}$$

The maximum allowable initial investment ($c_{c\ max}$) must cover the upfront costs of vehicle upgrades, utility-side infrastructure upgrades, communication system upgrades, and any other setup

costs. This calculation does not quantify communication costs, any costs or profits taken by the aggregators, or degradation of vehicle systems other than the battery. Since these administrative and operational costs are not included in this calculation, the computed investment represents a reasonable upper bound on the allowable initial investment for each architecture. Using these data, the maximum allowable initial investment ($c_{c\ max}$), was found to be \$8443 for the direct, deterministic architecture and \$4068 for the aggregative architecture.

This study has been based on a 10 kW power connection which would most likely require an upgrade to the home connection of \$500–800 and a possible need for utility infrastructure upgrade of roughly \$2000 [10,27]. The home connection upgrade costs will be borne by the vehicle owner, the utility upgrade costs are assumed to be borne by the utility. These scenarios show that the investment in V2G infrastructure has positive net present value with profits of \$7643–7943 for the direct, deterministic architecture and \$3268–3568 for the aggregative architecture. This financial return can be applied to the upfront purchase cost of the V2G-capable PHEV.

In the near-term, PHEVs are more likely to charge with a standard outlet in the home, which has a power throughput (P) of 2.4 kW. For this scenario, the resulting \overline{AAGP} is \$166 for the aggregative architecture and \$343 for the direct, deterministic architecture, which will result in a maximum allowable initial investment ($c_{c\ max}$) of \$1020 and 2108 for the two architectures, respectively. This scenario would eliminate many of the upfront costs associated with home connection and utility upgrades, leaving approximately \$1020–2108 for the two architectures, respectively, to be applied to the purchase cost of the V2G-capable PHEV.

From these analyses it can be seen in Fig. 6 that although the aggregative architecture provides a positive net present value, it substantially limits the profits that can be acquired from V2G regulation services which in turn limits the amount of initial investment that a V2G owner could payback over a reasonable period of time. However, it should be recalled that these calculations do not quantify communication costs, any costs or profits taken by the aggregators, or degradation of vehicle systems other than the battery. It is highly probable that once these costs are accounted for, the amount of initial investment that a V2G owner can payback will be significantly reduced and could possibly deem certain V2G scenarios not cost-effective in the near-term; especially the aggregative architecture.

Table 5
Parameters for capital cost payback calculation.

Parameters	Value	Units	Comments
\overline{AAGP}	1374	(\$year ⁻¹)	Direct, deterministic architecture annual average gross profit
\overline{AAGP}	662	(\$year ⁻¹)	Aggregative architecture annual average gross profit
n	10	(years)	Investment payback period, as in [12]
i	10	(%)	Discount rate, as in [12]

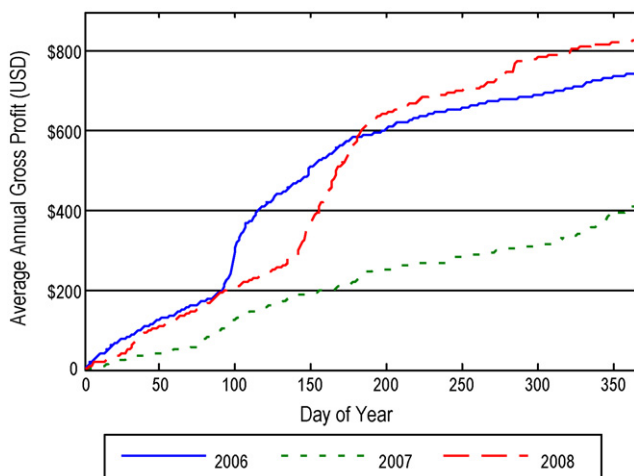


Fig. 5. Cumulative average annual gross profits for an average vehicle performing V2G regulation services under the aggregative architecture.

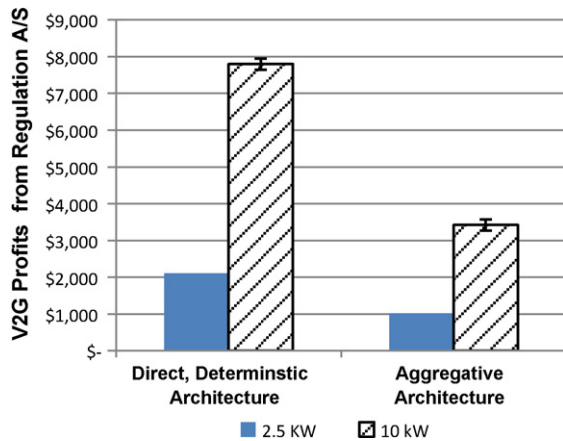


Fig. 6. Comparison of the V2G profits for the direct, deterministic and aggregative architectures for the 2.4 and 10 kW power connection scenarios. The 10 kW scenario shows the estimated variance of V2G profits based on the expected costs that will be assumed by vehicle owner.

6. Discussion

In order to realize a V2G ancillary services system in the near future, the architecture of the command and contracting system must satisfy the requirements of both the grid system operator and the vehicle owners. The grid system operator requires that V2G be a resource that is compatible with its current command and contracting system. The vehicle owners require a command and contracting architecture that maximizes a robust return on their investment in V2G-capable vehicles and hardware. There exist fundamental disagreements among these V2G stakeholders as to which V2G architectures are acceptable and feasible. Only architectures that are acceptable to all V2G stakeholders are worthy of near-term consideration and development.

From the perspective of the grid system operator, the aggregative architecture represents a more feasible and extensible architecture for implementing V2G ancillary services. For the system operator, the aggregative architecture is an improvement relative to the direct, deterministic architecture because it allows V2G to make use of the current market, command and control architectures for ancillary services. This study has shown that V2G aggregators can control their reliability and contractible power to meet industry standards by controlling the size of their aggregated vehicle fleet, thereby providing the grid system operator with a buffer against the stochastic availability of individual vehicles. This allows V2G to maintain a reliability equivalent to conventional ancillary services providers including conventional power plants. Because the payments from the grid system operator for ancillary services are equal for both architectures, the direct, deterministic architecture offers no apparent advantages from the perspective of the grid system operator.

From the perspective of the vehicle owner, the direct, deterministic architecture is preferred relative to the aggregative architecture. This study has shown that the initial allowable investment for the aggregative architecture is approximately 40% of the initial allowable investment for the direct, deterministic architecture. The substantially higher initial investments allowed by the direct, deterministic architecture suggests that the average vehicle owner will prefer the direct, deterministic architecture. Still the aggregative architecture should be able to provide a positive net present value for the investment in V2G infrastructure.

These divergent preferences of the vehicle owners and the system operator highlight a fundamental problem that must be overcome before V2G can be successfully implemented. The differing requirements of the stakeholders make only the aggregative

architecture acceptable to both parties. The direct, deterministic architecture is unacceptably complex, unreliable and unscalable to utilities and grid system operators. The aggregative architecture more than halves the revenue that can be accrued by the vehicle owners but still allows for a positive revenue stream. Only the aggregative architecture is mutually acceptable to all stakeholders and can provide a more feasible pathway for realization of a near-term V2G ancillary services system.

This study suggests that an aggregator is required to meet the reliability requirements of V2G as an ancillary services provider. This aggregator can be an entity that is external to the grid system operator, or the aggregator function can be performed by the grid system operator itself. In either case, the reliability requirement forces the aggregator to aggregate larger fleets of vehicles than would be required under the direct, deterministic architecture for equivalent power contracts. This has the inevitable effect of reducing the revenues to the vehicle owner. Based on these analyses, it is required that future studies of V2G take into account either the reduced value to the system operator of low-reliability ancillary services from direct, deterministic V2G, or the reduced revenues available to the vehicle owners under the high reliability aggregative architecture.

7. Conclusions

This study has introduced and compared two architectures of V2G ancillary services with the goal of directing the development of a near-term feasible and economically viable V2G infrastructure. This work has proposed models of V2G availability, reliability and compensation that are novel in that they incorporate travel survey data, utility reliability survey data, and time series ancillary services pricing. The results of these analyses show that a V2G architecture that aggregates vehicles can improve compatibility of V2G with the current ancillary services system by improving the reliability of V2G ancillary services and meeting the minimum contractible power requirements. The improvements that are realizable in the aggregative architecture have the detrimental effect of reducing the revenue collected by the vehicle owner. The results of this work suggest that the aggregative architecture provides the concept of V2G-provided ancillary services with a more feasible pathway to near-term realization.

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