THESIS

EVALUATION OF DISTRIBUTED ENERGY STORAGE FOR ANCILLARY SERVICE PROVISION

Submitted by

Casey W. Quinn

Department of Mechanical Engineering

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Master's Committee:

Advisor: Thomas H. Bradley

Daniel Zimmerle
Peter M. Young

ABSTRACT

EVALUATION OF DISTRIBUTED ENERGY STORAGE FOR ANCILLARY SERVICE PROVISION

Researchers have proposed that distributed energy storage devices could be used to perform ancillary services for the electric grid. This work focuses on vehicle-to-grid and battery-to-grid distributed energy storage devices. In conceptual studies, distributed energy storage devices were shown to be able to accrue revenue for performing these grid stabilization services, and these revenues were used to show that the use of vehicle-to-grid and battery-to-grid can help to offset the initial increased capital cost of electric vehicles. These conceptual studies have assumed a command architecture that allows for a direct and deterministic communication between the grid system operator and the distributed energy storage devices.

The first part of this thesis compares this direct, deterministic command architecture to an aggregative command architecture on the basis of the availability, reliability and value of the vehicle-to-grid 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, 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.

The second part of this work investigates the effects of introducing battery state of charge and time series generation control signals. Results show that in order to integrate a vehicle-to-grid system into the existing markets and power grid the distributed energy storage system will require: 1) an aggregative architecture to meet current industry reliability standards, 2) the construction of low net energy automatic generation control signals, 3) a lower percent call for distributive energy storage systems even if the pool of contracted ancillary service resources gets smaller, 4) a consideration of vehicle performance degradation due to the potential loss of electrically driven miles, and 5) the incorporation of power-to-energy ratios.

The third part of this work adapts the vehicle-to-grid model to a battery-to-grid system. Results show that if the automatic generation control signals contain low energy content, battery-to-grid has higher revenue potential than vehicle-to-grid due not having to account for vehicle driving behavior. Additionally, the third portion of this work proposed and performed high level analyses of operational options for battery-to-grid systems receiving automatic generation control signals with high energy content.

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INTRODUCTION

Plug-in Hybrid Electric Vehicles

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].

The effectiveness with which PHEVs can achieve a balance between the benefits and the costs of their implementation is highly dependent on the detailed design, function, and conditions of use of the individual vehicle. At present, there exists no universally agreed upon or optimum design for PHEVs. Every PHEV design that has been proposed or constructed represents a distillation of the designer's philosophy for maximizing the benefits and minimizing the costs of the PHEV.

PHEV Charging

A fundamental characteristic of PHEVs is their ability to recharge their energy storage system (ESS) from the electric grid. The charging system of a PHEV is the set of controls, communication, power electronics, and power transfer equipment that makes PHEV recharging possible. 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 PHEV through a charge port. G2V is the traditional method for charging the batteries of PHEVs. 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.

Energy Storage System (ESS)

Electrochemical energy storage for PHEVs usually consists of batteries, although battery/ultracapacitor [2] and regenerative fuel cell [3-5] PHEVs have been proposed. The ESS for battery PHEVs consists of the battery modules and their support systems including thermal management, electrical management, and safety subsystems. The functions of the ESS for PHEVs is to store electric energy for propulsion and to meet some short-term power demands of the vehicle. These short-term power demands can be charging the ESS in the case of regenerative braking, or they can be discharging the ESS, in the case of vehicle accelerations. The batteries of PHEVs must perform these functions at a variety of states of charge. Depending on the characteristics of the vehicle, the electrical energy stored can commonly be as large as 19 kWh with power transients of >75 kW for a mid-sized sedan [6], or 30 kWh and >150 kW for a full-size sport utility vehicle (SUV) [7].

Charging Control

The design of charging systems for PHEVs consists of both the specification of the physical hardware for charging and the specification of the control system which controls the charging strategy for the vehicle. PHEV ESS charging can be constrained or unconstrained. Unconstrained charging is the simplest form of PHEV charging and allows the PHEV owner to plug in at any time of the day with no limitations [8]. Constrained charging is defined as any charging strategy in which the electric utility and vehicle are able to cooperatively implement charging strategies. These constrained charging strategies will aim to limit PHEV charging loads so that they are not coincident with the peak loads of the day. The first generation of PHEVs will use unconstrained opportunity charging due to the initial low volume of vehicles and low impact on the electric grid [9-11]. However, most research to date has shown that as PHEVs penetrate the market, unconstrained charging will need to be replaced with some level of constrained charging to reduce the possibility of exacerbating peak electric demands [12-14]. Constrained charging behavior can potentially permit up to 50% PHEV market penetration without an increase in generation capacity and also presents the possibility for the electric utility to regulate the system more effectively resulting in more uniform daily load profiles and reduced operational costs [12]. The most prevalent strategies currently being pursued to implement constrained charging are labeled as valley filling, demand response, vehicle-to-grid, real-time price charging, and delayed charging [11-18].

Charging Infrastructure Specifications

The SAE J1772 standard has been developed to provide design guidance for PHEV power transfer connections. The standard requires PHEV power transfer connections to be able to operate on single phase 120 V or 240 V and also support communication. The power transfer equipment can either be a separate component or be integrated into the power electronics of the traction motor and motor drive. In order for

PHEVs to be capable of V2G, either an inverter must be added to the PHEV's power electronics, or equipment capable of utilizing the on-board charger as both an inverter and a rectifier would need to be used [15]. Although various power levels of charging have been proposed, level 1 charging (110 V, 15 A) is the most common. Level 2 and level 3 quick chargers have increased power ratings, but the installation of level 2 and level 3 chargers can be a slow and costly process, especially for residential installations [16].

Charging Infrastructure Communication

All of the constrained charging strategies require some level of communication between the PHEV or PHEV owner and the electric utility or grid system operator. For demand response, real-time pricing, and delayed charging, the PHEV or PHEV owner must be able to receive and process pricing and/or power interrupt signals sent by the electric utility [12]. Valley filling and V2G charging require electronic two-way communication between the PHEV and the electric utility or the grid system operator [9, 17]. Two-way communication is required because the electric utility or the grid system operator needs to know the SOC of all the PHEVs connected in order to forecast the expected charging load for the valley-filling algorithm and the availability of PHEVs for providing V2G frequency control. Research has shown that the communication task can be achieved by integrating Broadband over Powerline and HomePlug™, Zigbee™, or cellular communication technologies into a stationary charger or into the PHEV's power electronics [18].

Electric Grid Impacts

Studies have stated that constrained charging can provide the electric utility an opportunity to improve resource utilization. As a result, the electric utilities may be able to provide reduced rates to PHEV owners who comply with the regulations of the constrained charging program [19]. These reduced rates help improve vehicle performance in terms of operating cost. However, constrained charging programs can lead to reductions in fuel economy and All Electric Range (AER) since the preferential charging times would decrease the number of hours PHEVs are able to charge each day. As the allowable charging hours are decreased, the PHEV has fewer opportunities to recharge. PHEVs utilizing level 1 charging can be significantly impacted since it takes approximately 8 hours to charge a vehicle with an ESS usable capacity similar to a Chevrolet Volt [16, 20]. If a PHEV is incapable of fully recharging the ESS, the AER of the vehicle will be reduced and could decrease the fuel economy of the vehicle if the PHEV is forced to operate in CS mode more frequently. Increased operation in CS mode reduces PHEV performance in terms of fuel economy, which is one of the major vehicle attributes being considered to justify the higher cost of PHEVs in comparison to conventional vehicles and HEVs.

The largest impact controlled charging will have on the electric grid is associated with the communication requirements needed between PHEVs and PHEV owners and the electric utility or grid system operator. The simplest communication method an electric utility can use to control charging behaviors is “time of use” (TOU) rates. TOU rates vary the cost of electricity to try and persuade vehicle owners to charge at off-peak demand times and can be relayed to PHEV owners through rate plans that only change based on time of day and year and require the installation of an electric meter capable of metering and logging energy usage at a fine granularity for billing purposes. However, it is yet to be determined if TOU rates are strong enough motivators to affect the charging habits of the majority of PHEV owners. The next level of complexity available for the electric utility is the use of real-time data communication. One of the problems associated with using real-time data transfer to centrally monitor and control a large number of PHEVs is that it is understood to be an overwhelming task [21]. Constrained charging of PHEVs will require a large investment in communication infrastructure – which may be somewhat mitigated by the increased adoption of advanced metering technologies – and will significantly increase the workload of the electric utility.

Another large concern currently being expressed by electric utilities is the expected increased loads on residential transformers and other electric grid components. Studies have shown that the acceptance of HEVs has typically occurred unevenly within a geographic area, and they are expecting the adoption of PHEVs to follow a similar pattern [22]. Uneven adoption may stress residential transformers because many residential transformers are already approaching their recommended capacity, due to electric load growth from other factors. Another concern is that although constrained charging of PHEVs will help the electric utility keep from exacerbating their peak demands, constrained charging may force transformers and other grid infrastructure to be fully utilized for the majority of the day. Increased use would reduce equipment rest and cooling time, which could shorten the operational life of the equipment [23, 24].

THESIS OVERVIEW

This thesis is divided into three parts: 1) The Effect of Communication Architecture on the Availability, Reliability and Economics of Plug-in Hybrid Electric Vehicle-Vehicle-to-Grid Ancillary Services, 2) An Evaluation of State-of-Charge Limitations and Actuation Signal Energy Content on Plug-in Hybrid Electric Vehicle, Vehicle-to-Grid Reliability and Economics, and 3) An Evaluation of State-of-Charge Limitations and Actuation Signal Energy Content on the Reliability and Economics of Grid-Connected Distributed Energy Storage Systems.

Part I focuses on vehicle-to-grid (V2G) system architecture and economic feasibility. 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 PHEVs. To date, all such studies have assumed a vehicle command architecture that allows direct and deterministic communication between the grid system operator and the vehicle. Part I compares this direct, deterministic vehicle command architecture to an aggregative vehicle command architecture on the basis 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.

Part II builds upon the work completed in Part I and incorporates time series area generation control signals and battery SOC into the model. This added detail allows for the evaluation of actual ancillary service call signals and how vehicle-to-grid devices respond to these signals. Additionally, the increased fidelity of the model allows for an analysis of how the percent call of V2G ancillary service providers affects the reliability of the provision of ancillary services.

Part III extends the work completed in Parts I and II to the evaluation of stationary distributive energy storage systems. Previous research has proposed to prolong the use of batteries that are no longer deemed fit for use in electric vehicles in order to provide additional revenue and help offset the initial increased capital cost of electric vehicles over convention vehicles. This part of the thesis applies the developed framework in Parts I and II in order to determine the economics and reliability of stationary battery-to-grid devices.

PART I:

THE EFFECT OF COMMUNICATION ARCHITECTURE ON THE AVAILABILITY, RELIABILITY AND ECONOMICS OF PLUG-IN HYBRID ELECTRIC VEHICLE-VEHICLE-TO-GRID ANCILLARY SERVICES

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 [9-11, 25]. 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 [12-14]. Fewer studies have considered the impacts of widespread 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 [15, 23]. 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 [15, 17, 23, 26-31].

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 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 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 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 (1.8kW [1] -17 kW[32]) are below the 1MW-h threshold that is required of many ancillary services contracts [27].

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 [21]. 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.

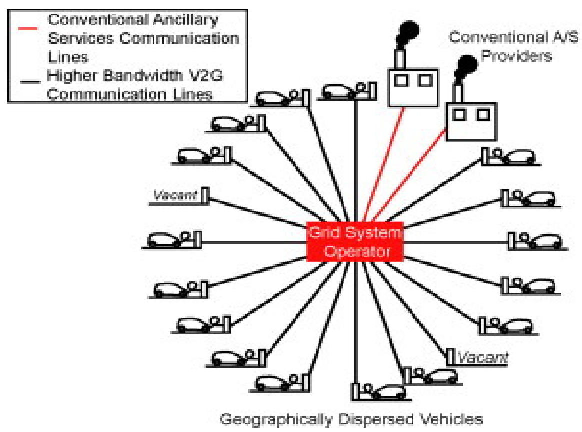

Fig. 1: Example plug-in vehicle-to-grid network showing geographically dispersed communications connections under the direct, deterministic architecture

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 parallel aggregated V2G resources 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 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 vehicles is of a more manageable scale than communication network required under the direct 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.

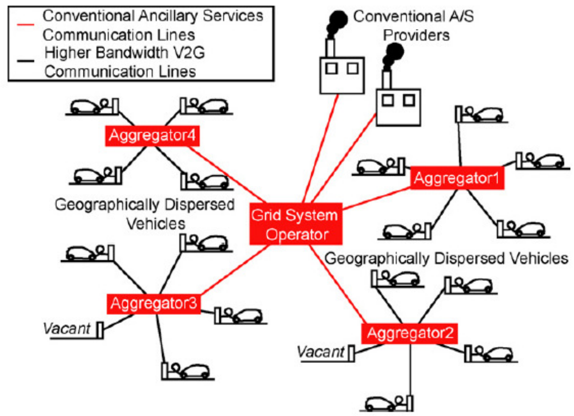

Fig. 2: Example plug-in vehicle-to-grid network showing geographically dispersed communications connections under the aggregative architecture

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 powerplant 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 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 compare to 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 2003-2007[33].

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) [34]. 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 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=10kW) was assumed for all vehicles, regardless of size, matching assumptions made in previous studies [23].

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 charger. 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 10:45am 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 daily averaged vehicle availability is equivalent to the long-term averaged AF of the resource, which equals 83.6%. For the home and work charging scenario, the availability of the V2G vehicles is improved because of increased charger penetration resulting in a minimum vehicle availability of 82.0% and a daily averaged vehicle availability equivalent to a long-term averaged AF 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 every vehicle always connects to V2G-capable charging stations at both home and work, could the direct, distributed architecture approach industry availability norms.

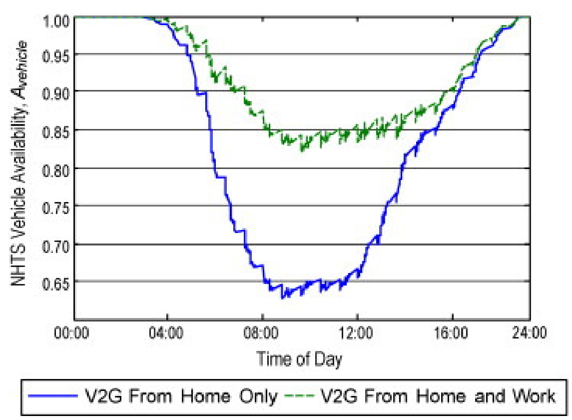

Fig. 3: Availability of vehicle-to-grid enabled vehicles as a function of time of day for two infrastructure infiltration scenarios

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 is simply 100%. Thus, the availability of V2G ancillary services under the aggregative 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 powerplant 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 NERC reported Service Hours (SH) [20]. The reliability (R) of a system to provide the contracted and commanded ancillary services is:

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

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 2003-2007, which result in a FDHR of 1.11% giving a reliability (R) of 98.89% [33].

4.1. Reliability of the Direct, Deterministic Architecture

To model the reliability of the direct, deterministic architecture we must understand 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 that 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 hour[1], 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 the NHTS fleet equals the FDHR for V2G ancillary services. The daily average reliability (R) of the direct, deterministic architecture is 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

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

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 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:

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

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 = (1-FDHR) = 98.89%) are x_{fleet}= 2.49 and x_{fleet}= 1.81 respectively . This fleet scaling factor (x_{fleet}) determines the amount of power $\frac{P \cdot n_{\text{vehicles}}}{x_{\text{fleet}}}$ 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 norms[2].

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 view point of the grid systems operator on the grounds of system reliability.

---

[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_{fleet}=2.5. If each vehicle can provide 10kW of ancillary services and the aggregator has contracted with n_{vehicles}=250 vehicles, the aggregator can contract to provide 1.0 MW of ancillary services with a daily average reliability of 98.89%. To provide a 10 MW contract with an industry standard equivalent reliability, the aggregator must enroll n_{vehicles}=2500 vehicles to improve the probability that the vehicles will be available to perform grid ancillary services.

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 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 OAISIS database [35].

Previous studies of the economics of V2G have shown that there exists a significant return on investment for the owners of V2G-capable vehicles [23, 27, 30]. 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 [30], 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, and 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 effective[3].

This study adopts the revenue and cost framework that has been defined by Tomić and Kempton [30]. Regulation-up service is broken into two terms: a contract payment ($p_{\mathrm{cap}} \cdot P$), and a payment for the delivery of energy to the grid ($p_{\mathrm{el}} \cdot P \cdot R_{\mathrm{d-c}}$). The revenue for a single regulation-up services contract is the sum of these two terms, multiplied by the time that the vehicle is under contract (t_{plug}):

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

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 includes only the contracted power term:

$$r_{\mathrm{Reg-Down}} = t_{\mathrm{plug}} \left(p_{\mathrm{cap}} \cdot P \right) \quad (4)$$

To define the costs associated with providing regulation services, we use the assumption made in [30] that if a PHEV is providing both regulation-up and regulation-down services then the cost of regulation-down is zero (again because of its functional

[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.

similarity to charging). The cost associated with a single regulation-up contract is defined over a period t_{plug}, as below:

$$
\begin{aligned}
c_{\mathrm{Reg-Up}} &= c_{\mathrm{en}} \cdot P \cdot R_{\mathrm{d-c}} \cdot t_{\mathrm{plug}} + c_{\mathrm{ac}} \\
c_{\mathrm{Reg-Down}} &= 0 \\
c_{\mathrm{en}} &= \frac{c_{\mathrm{pe}}}{\eta_{\mathrm{conv}}} + c_{\mathrm{d}} \\
c_{\mathrm{d}} &= \frac{E_{\mathrm{s}} \cdot c_{\mathrm{b}} + c_{\mathrm{L}}}{3 \cdot L_{\mathrm{C}} \cdot E_{\mathrm{s}} \cdot (DoD)}
\end{aligned}
\tag{5}
$$

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 ($A_{\mathrm{vehicle}}(k)$), the time varying reliability of the average vehicle over the course of each hour ($R(k)$), and the hourly pricing ($p_{\mathrm{cap}}(k)$ and $\mathrm{p}_{el}(k)$), we can calculate the expected values of the hourly revenues and costs to an average V2G vehicle owner under the direct, deterministic model.

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

For this study we assume the home only charger 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 the 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 I.

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 II, 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 $1,374 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 year[4]. Fig. 4 shows that the revenue from V2G ancillary

[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 [36, 37].

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

TABLE I
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 [30]
$R_{\text{d-c}}$	Ratio of energy dispatched for regulation services as a proportion of contracted power and time	10	(%)	As in [30]
p_{cap}	Hourly ancillary service contract price	varies	($/MW-h)	Taken from [35]
R	Probabilistic vehicle hourly reliability	varies	(%)	Derived from [34]
A_{vehicle}	Probabilistic vehicle hourly availability	varies	(%)	Derived from [34], Refer to Fig. 3
c_{en}	Cost per unit of energy	0.21	($/kWh)	Calculated from (5)
p_{el}	Market selling price of electricity	0.10	($/kWh)	----------
c_{pe}	Electricity purchase price	0.10	($/kWh)	Equal to p_{el}
η_{conv}	Inverter energy conversion efficiency	0.73	(%)	As in [30]
c_{d}	Battery degradation cost	0.077	($/kWh)	Calculated from (5)
E_{s}	Battery storage capacity	5	(kWh)	----------
c_{b}	Battery cost	300	($/kWh)	As in [30]
c_{L}	Battery replacement cost	240	($)	As in [30]
L_{c}	Battery life	1500	(cycles)	As in [30]
DoD	Battery depth of discharge	100	(%)	As in [30]

TABLE II
Economic modeling results for the direct, deterministic architecture

	2006	*2007*	*2008*
Average Annual Revenue ($r_{\text{Reg-Up}}^{Yearly} + r_{\text{Reg-Down}}^{Yearly}$)	\$2,697	\$1,709	\$2,701
Regulation Up Revenue ($r_{\text{Reg-Up}}^{Yearly}$)	\$1,456	\$1,150	\$1,377
Regulation Down Revenue ($r_{\text{Reg-Down}}^{Yearly}$)	\$1,241	\$559	\$1,324
Average Annual Cost[5] ($c_{\text{Reg-Up}}^{Yearly} + c_{\text{Reg-Down}}^{Yearly}$)	\$1,132	\$900	\$954
Average Annual Gross Profit ($r_{\text{Reg-Up}}^{Yearly} + r_{\text{Reg-Down}}^{Yearly} - c_{\text{Reg-Up}}^{Yearly} - c_{\text{Reg-Down}}^{Yearly}$)	\$1,565	\$809	\$1,747

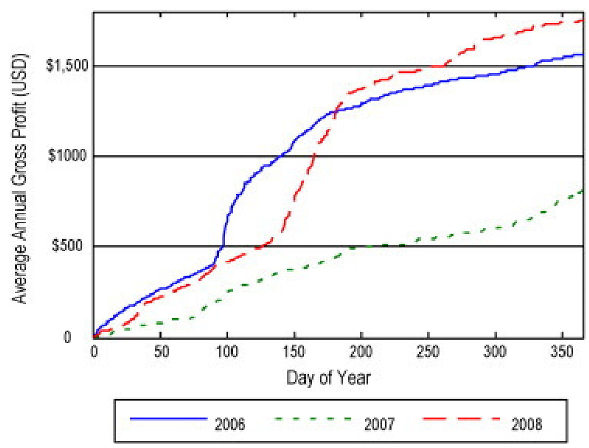

Fig. 4: Cumulative average annual gross profits for an average vehicle performing V2G regulation services under the direct, deterministic architecture

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

[5] The Average Annual Cost excludes the Annualized Capital Cost, (c_{ac}).

reliability (x_{fleet}), and the hourly average availability of the entire aggregated vehicle fleet (A_{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:

$$
\begin{aligned}
r_{\text{Reg-Up}}(k) &= R(k)\left(p_{\text{cap}}(k)\cdot P + p_{\text{el}}(k)\cdot P \cdot R_{\text{d-c}}\right)\frac{n_{\text{vehicles}}}{x_{\text{fleet}}} \\
r_{\text{Reg-Down}}(k) &= R(k)\left(p_{\text{cap}}(k)\cdot P\right)\frac{n_{vehicles}}{x_{\text{fleet}}}
\end{aligned}
\qquad (7)
$$

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:

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

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

$$
\begin{aligned}
r_{\text{Reg-Up}}(k) &= \frac{A_{\text{vehicle}}(k)\cdot R(k)\left(p_{\text{cap}}(k)\cdot P + p_{\text{el}}(k)\cdot P \cdot R_{\text{d-c}}\right)}{x_{\text{fleet}}\cdot A_{\text{fleet}}(k)} \\
r_{\text{Reg-Down}}(k) &= \frac{A_{\text{vehicle}}(k)\cdot R(k)\left(p_{\text{cap}}(k)\cdot P\right)}{x_{\text{fleet}}\cdot A_{\text{fleet}}(k)} \\
c_{\text{Reg-Up}}(k) &= \frac{A_{\text{vehicle}}(k)\cdot R(k)\left(c_{\text{en}}(k)\cdot P \cdot R_{\text{d-c}}\right)}{x_{\text{fleet}}\cdot A_{\text{fleet}}(k)} \\
c_{\text{Reg-Down}}(k) &= 0
\end{aligned}
\qquad (9)
$$

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 is equal to the hourly availability of the fleet. As in the direct, deterministic architecture, we assume the home only charger 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 the 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 III.

TABLE III
Economic modeling parameters for the study of the aggregative architecture

Parameters	Description	Value	Units	Comments
P	Vehicle V2G power capacity	10	(kW)	As in [30]
$R_{d\text{-}c}$	Ratio of energy dispatched for regulation services as a proportion of contracted power and time	10	(%)	As in [30]
p_{cap}	Hourly ancillary service contract price	varies	($/MW-h)	Taken from [35]
R	Probabilistic vehicle hourly reliability	varies	(%)	Derived from [34]
$A_{vehicle}$	Probabilistic vehicle hourly availability	varies	(%)	Derived from [34], Refer to Fig. 3
A_{fleet}	Probabilistic V2G fleet hourly availability	varies	(%)	Derived from [34], Refer to Fig. 3
x_{fleet}	Fleet scaling factor	2.49	(--)	Calculated from (2)
c_{en}	Cost per unit of energy	0.21	($/kWh)	Calculated from (5)
p_{el}	Market selling price of electricity	0.10	($/kWh)	----------
c_{pe}	Electricity purchase price	0.10	($/kWh)	Equal to p_{el}
η_{conv}	Inverter energy conversion efficiency	0.73	(%)	As in [30]
c_d	Battery degradation cost	0.077	($/kWh)	Calculated from (5)
E_s	Battery storage capacity	5	(kWh)	----------
c_b	Battery cost	300	($/kWh)	As in [30]
c_L	Battery replacement cost	240	($)	As in [30]
L_c	Battery life	1500	(cycles)	As in [30]
DoD	Battery depth of discharge	100	(%)	As in [30]

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 only 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 IV 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 IV
Economic modeling results for the aggregative architecture

	2006	*2007*	*2008*
Average Annual Revenue ($r_{\text{Reg-Up}}^{\textit{Yearly}} + r_{\text{Reg-Down}}^{\textit{Yearly}}$)	\$1,303	\$855	\$1,291
Regulation Up Revenue ($r_{\text{Reg-Up}}^{\textit{Yearly}}$)	\$725	\$587	\$688
Regulation Down Revenue ($r_{\text{Reg-Down}}^{\textit{Yearly}}$)	\$578	\$268	\$603
Average Annual Cost[6] ($c_{\text{Reg-Up}}^{\textit{Yearly}} + c_{\text{Reg-Down}}^{\textit{Yearly}}$)	\$558	\$440	\$465
Average Annual Gross Profit ($r_{\text{Reg-Up}}^{\textit{Yearly}} + r_{\text{Reg-Down}}^{\textit{Yearly}} - c_{\text{Reg-Up}}^{\textit{Yearly}} - c_{\text{Reg-Down}}^{\textit{Yearly}}$)	\$745	\$415	\$826

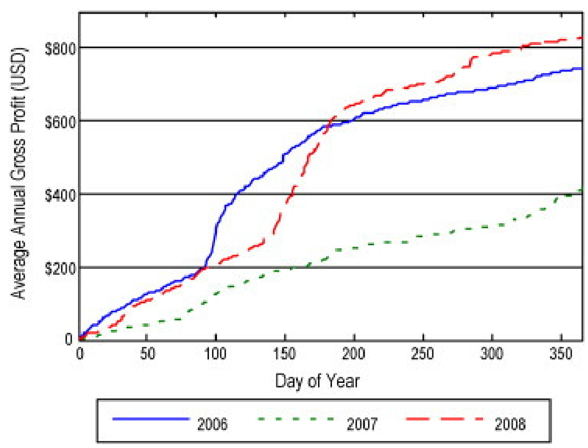

Fig. 5. Cumulative average annual gross profits for an average vehicle performing V2G regulation services under the aggregative architecture

5.3. Comparison of V2G Compensation for Ancillary Services Among Architectures

Comparison of the aggregative architecture results in Table IV to the direct, deterministic architecture results in Table II show that the increased fleet size that is

[6] The Average Annual Cost excludes the Annualized Capital Cost, (c_{ac}).

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 (10), and the assumptions made are summarized below in Table V.

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

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 \$8,443 for the direct, deterministic architecture and \$4,068 for the aggregative architecture.

TABLE V
Parameters for capital cost payback calculation

Parameters	***Value***	***Units***	***Comments***
$\overline{AAGP}$	1,374	(\$/year)	Direct, deterministic architecture average annual net revenue
$\overline{AAGP}$	662	(\$/year)	Aggregative architecture average annual net revenue
n	10	(years)	Investment payback period, As in [27]
i	10	(%)	Discount rate, As in [27]

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 [23, 16]. 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 a profit of \$7,643-\$7,943 for the direct deterministic architecture and \$3,268-\$3,568 for the aggregative architecture. This profit 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. 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 $1,020 and $2,108 for the two architectures, respectively. This scenario would eliminate many of the upfront costs associated with home connection and utility upgrades, leaving approximately $1,020 - $2,108 for the two architectures respectively, to be applied to the purchase cost of the V2G-capable PHEV.

From these analyses it can be seen 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.

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 can 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 powerplants. 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.

PART II:

AN EVALUATION OF STATE-OF-CHARGE LIMITATIONS AND ACTUATION SIGNAL ENERGY CONTENT ON PLUG-IN HYBRID ELECTRIC VEHICLE VEHICLE-TO-GRID RELIABILITY AND ECONOMICS

1. INTRODUCTION

Researchers have developed analyses and demonstrations of vehicle charging behavior, but the fewer studies have considered the impacts of wide-spread vehicle-to-grid (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 [15, 23]. Conceptual V2G studies have investigated the economic feasibility of plug-in vehicles that can perform grid ancillary services (A/S), particularly frequency support [15, 17, 23, 26-31, 38].

These studies which have found V2G to have a significant return on investment have based their analyses on two critical assumptions regarding the A/S signal: 1)The automatic generation control (AGC) signal is assumed to be a power signal which contains little or no energy content, and 2) Independent System Operators (ISOs) and Balancing Authorities (BAs) procure excessive A/S capacity and therefore V2G vehicles would only be called upon to provide energy services approximately 10% [27] of the contracted period. Together, these assumptions ensure that the energy removed or added from the battery, will net to zero over both short and extended periods. These assumptions eliminate the finite energy capacity of batteries from consideration in V2G reliability evaluation.

This study presents a set of simulations relaxing these assumptions thereby showing the effects of battery state of charge (SOC) limitations on V2G reliability and economics. To perform these experiments, this work proposes a model of V2G reliability and availability under an aggregative architecture, including a novel SOC control model. Next, a synthetic and generalizeable AGC signal is constructed to understand in general the effect of battery SOC limitations on V2G reliability and economics. Finally, an AGC signal derived from the 2008 Western Area Power Administration (WAPA) area control error (ACE) signal is used to test the real-world effects of SOC limitations.[7]. The discussion section focuses on the implications of these results on the scalability of V2G as an economic enterprise.

[7] The ACE signal is the observed difference between power production and power demand on the grid; a negative ACE value corresponds to power demand exceeding power production and a positive ACE value signifies excess power production relative to power demand.

2. DESCRIPTION OF V2G MODEL

In order to enhance the analysis of V2G it was decided to develop a model which could account for battery SOC, incorporate automatic generation control signals, and evaluate the impact of V2G on vehicle performance. To accomplish this, a Matlab™/Simulink™ model was created to evaluate how vehicle driving behavior affects a PHEVs ability to perform A/S through V2G and is shown in Fig.6. Matlab™ was used to integrate the driver behavior (2009 National Housing Transportation Survey (NHTS) [34]) data, feed in the AGC signal used for A/S calls, and analyze the aggregated vehicle results. Simulink™ performed the time series simulations of driving, charging, and V2G A/S for each vehicle.

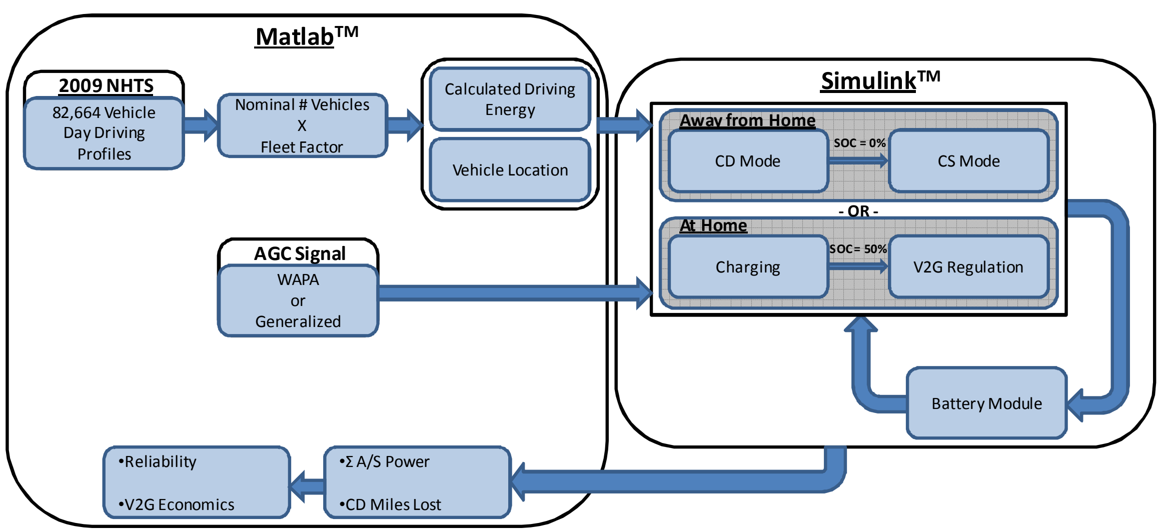

Fig. 6: MatlabTM/SimulinkTM V2G-CapableModel.

2.1. Vehicle Driving Behavior

The 2009 NHTS dataset was filtered to represent a fleet of new light duty vehicles (vehicle production year no older than 2002), which started and ended their reporting day at home, and made at least one trip during the reporting day. This filtered data set consists of a total of 82,664 vehicles (61,577 weekdays and 21,087 weekends). The vehicle day trips are chained together to create a day driving profile for each vehicle in the dataset. The day trips are characterized by the distance travelled and start and end time. The trips are analyzed to ensure that the average trip speeds are realistic (less than 90 mph), and an electric energy consumption value is calculated for each vehicle trip based on a charge depleting electric consumption rate of 282 AC $(Wh)(mi)^{-1}$ [39] for a PHEV35 with 10 kilowatt-hours (kWh) of usable energy in the battery pack. In this analysis the SOC represents the useable SOC of the vehicle relative to the usable capacity of the battery, rather than the nameplate capacity of the battery. For simplicity all analyses in this paper assume 100% charger and battery joule efficiencies for the V2G system. This assumption regarding efficiency produces upper bound results as the inclusion of round trip efficiency losses would require either a derating of the charger power or a more advanced SOC charge control to eliminate energy biasing in the vehicle battery SOC. The 82,664 vehicle day profiles are used to create thirty days of driving behavior by random sampling with replacement. The thirty days consist of ten weekend days and twenty weekdays and the respective weekend and weekday driving behaviors from the NHTS are used. At the start of each simulation the SOC of each vehicle is initialized at a randomly distributed value between 50% and 99% SOC.

2.2. *V2G-Capable PHEV Model*

The Simulink^{TM} model uses a finite state machine to model whether the vehicle is at or away from home and connected or disconnected to the grid as shown in Fig. 6. When the V2G vehicle arrives home it is assumed that the vehicle is immediately plugged in. If the vehicle SOC is below 50% the state machine restricts the vehicle from providing V2G A/S services and causes the vehicle to charge at its designated charge rate. When the vehicle reaches 50% SOC the state machine commands the vehicle to charge and discharge as needed to meet the requirements of the AGC A/S signal call, and thus contributes towards the fleet's aggregated power. If the vehicle battery reaches 0% or 100% SOC the V2G vehicle is not able to contribute toward the A/S calls in the saturated direction but is able to contribute toward A/S calls in the unsaturated direction. When the vehicle is away from home and driving the vehicle operates in one of two modes: charge depleting mode (CD) and charge sustaining mode (CS) as defined in [1]. The vehicle transitions from CD and CS modes when the usable SOC has reached 0%.

2.3. *Baseline Model*

As a baseline for comparison, the Simulink^{TM} model also includes a finite state machine which represents a standard PHEV which doesn't perform V2G. When the vehicle is away from home and driving, the baseline PHEV model is fed the same driving profiles and operates identically to the V2G model. However, when the baseline PHEV is at home, it is assumed to be plugged in immediately, and charges at the specified charge rate until the battery reaches 100% SOC. The charger then shuts off and there are no changes to the vehicle SOC until the next vehicle trip. This baseline model allows for a comparison of a vehicle providing V2G A/S provision to the behavior of an unmodified PHEV utilized for exactly the same travel profile.

3. RESULTS

Using this novel simulation framework which includes AGC signals with energy content and varying percent calls for A/S provision, we can now understand the effects these parameters have on V2G's ability to provide ancillary services. The following sections show how this simulation framework affects V2G reliability, vehicle performance, and financial compensation for A/S provision.

3.1. Evaluation of the Effects of Driving Behavior on V2G Reliability

Previous studies have generalized the affect of driving behavior on V2G by assuming that vehicles are stationary and available 96% of the day [27]. By doing so they disregard the impact that stochastic driving patterns have on V2G A/S reliability. To model this effect, the 2009 NHTS dataset was used to define the driving behavior of vehicles and determine how vehicle driving profiles influence the reliability of V2G A/S provision.

For this analysis we assume (a) an aggregative architecture as in [40], (b) 100% reliable communication connection between the grid system operator and the aggregator, (c) 100% reliable communication between the aggregator and the vehicle, and (d) a one megawatt (MW) A/S contract[8]. Reliability is defined as the number of ten minute contract periods the aggregated fleet is able meet 100% of the contracted power for every call during each contract period. A contract period is considered to have failed when the

[8] The minimum A/S contract size for California [27].

aggregated fleet is unable to meet every four second A/S call in a ten minute contract period.

Contrary to the assumptions common in V2G evaluations, actual AGC signals have significant net energy content. To meet the power calls of the AGC signal, a generation unit will source or sink significant energy over an extended period. This behavior of existing A/S calls quickly saturates most V2G battery systems, obscuring the interaction between driving behavior, charge rate and SOC. To isolate these effects, a generic AGC signal was designed to have less energy content than the aggregated vehicle fleet, regardless of the power-to-energy ratio (P/E)[9].

A Markov transition matrix was utilized to create a synthetic, thirty day, AGC signal consisting of 648,000 calls[10] The synthetic signal consists of three call states, +1MW, -1MW, or 0 MW. A Markov matrix defines the probability of the call for period (*i+1*), based upon the call selected for period *i*. As is in [41], the probabilities are represented as in Table VI. The call for period *i* is identified by one row, the call for period (*i+1*) by a column, and the matrix cells represent the probability of transition from row *i* to any column. By definition, the probabilities in each row sum to 100%. A random number generator is utilized to select the next signal call state. The matrix is sampled without replacement to assure that the designed net-zero energy characteristics are met by the end of the one-month period. Thus, the probabilities change with time. An example Markov matrix is shown in Table VII. Note that if $a_{1,3} = a_{3,1} = 324{,}000$ and all other cells are zero, the resulting AGC signal would oscillate between up and down calls, would have no energy content, and thus would have no impact on SOC. This is

[9] Power-to-Energy ratio is the ratio of the vehicle charger power and vehicle battery capacity. A larger P/E ratio requires a shorter charging time. Ex) If a vehicle charger power is 5 kw and the vehicle battery capacity is 10 kwh the P/E ratio is 0.5 h^{-1}.
[10] Calls have a 4 second period with a value of either 1 MW or -1MW.

equivalent to the assumption made in previous studies that the A/S call signal has no net impact on battery SOC.

TABLE VI
Example Markov Matrix

Call for period i (MW)	Call for period $i+1$ (MW): 1	0	-1
1	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$
0	$a_{2,1}$	$a_{2,2}$	$a_{2,3}$
-1	$a_{3,1}$	$a_{3,2}$	$a_{3,3}$

To produce an AGC signal with more realistic behavior but still constrained to have less energy content that the V2G fleet, the matrix shown in Table VII was utilized. The resulting integrated energy content of the synthetic AGC signal is shown in Fig. 7. Shifting approximately 9.3% of the probability from $a_{1,3}$ to $a_{1,1}$ and from $a_{3,1}$ to $a_{3,3}$ forces 9.3% of consecutive AGC signal calls to occur in the same state. This produces an AGC signal with non-zero, but controllable energy content impacting SOC. Increasing the weights of cells $a_{1,1}$ or $a_{3,3}$ increases the energy content in the resulting generated signals.

TABLE VII
Generated AGC Markov Matrix

Call for period i (MW)	Call for period $i+1$ (MW): 1	0	-1
1	30,000	0	294,000
0	0	0	0
-1	294,000	0	30,000

While synthetic, the AGC signal generated in this fashion compares favorably to ACE signal data provided by the WAPA Rocky Mountain control area once the ACE signal was filtered to remove the low-frequency content with a period in excess of two hours (see Section 4). A synthetic signal allows experimentation with an engineered A/S call signal. In practice such an AGC signal can be generated within the balancing authority's control system, using a combination of filtering and feedback control techniques.

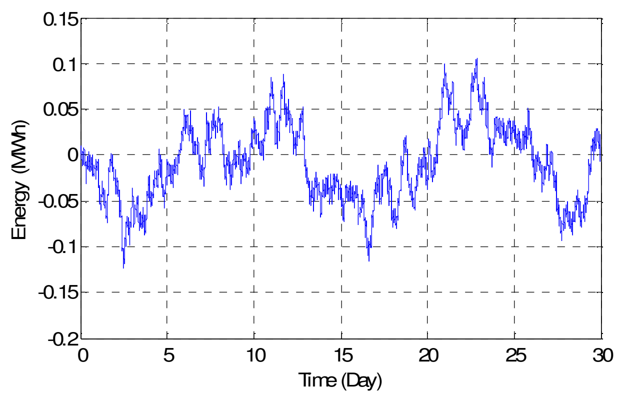

Fig. 7: Energy content of generated AGC signal after integration.

Table VIII compares the maximum and minimum energy excursion of the generated AGC signal to the maximum allowable energy excursion of the aggregated vehicle fleet. As described above, the analysis assumes a 10 kwh usable battery, three charge rates, ranging of 5-15 kw, and a maximum allowable energy excursion equal to 50% of SOC for an aggregated fleet with a fleet scaling factor (x_{fleet})[11] of 1. This last assumption is based upon the V2G control methodology described earlier, where all vehicles are charged to 50% SOC before engaging in V2G. This methodology maximizes

[11] Fleet factor (xfleet) is the fleet scaling factor above the nominal number of vehicles required to reliably meet the contracted power, based on the vehicles' charging rate. Ex) a xfleet of 1for a fleet of vehicles with a charger connection of 10 kw would require a 100 vehicles to meet a 1MW A/S contract; a xfleet of 2.5 for the same fleet would require 250 vehicles.

the range of usable SOC for V2G, and minimizes the impact of AGC signals containing energy content.

TABLE VIII
Generated AGC and Vehicle Fleet Energy Comparison

30 Day Markov AGC Energy		**Fleet 50% Max. Allowable Energy Content**		
Max. Energy	**Min. Energy**	**5 kw 0.5 P/E**	**10 kw 1.0 P/E**	**15 kw 1.5 P/E**
0.1 MWh	-0.1 MWh	1.0 MWh	0.5 MWh	0.3 MWh

Results for this analysis are compared to a baseline fleet factor of 2.5 previously calculated by Quinn, et. al in [40]. Fig. 8 displays the aggregated fleets' averaged reliability for 5 simulations with percent call[12] ranging from 10%-100% and a fleet factor of 2.5 for P/E ratios of 0.5, 1, and 1.5 respectively. The dashed line in Fig. 8 represents a reliability of 98.89%, a reliability value representative of gas-turbine systems as reported by NERC [33]. While reliabilities meet industry expectations at 10% call, reliabilities decrease rapidly at higher call rates. Therefore, the previously calculated fleet factor of 2.5 is insufficient to meet industry reliability expectations, given the impact of driving and SOC modeled here,[13] even with a battery-specific AGC signal engineered to minimize net energy content.

Assuming the A/S provider would be held to industry standard reliabilities regardless of the percent call, multiple simulations were run to determine the fleet factor required to perform A/S with a minimum reliability of 98.89% for all percent calls. A fleet factor of 3.25 is required for P/E ratios greater than one, provided the energy content of the A/S signal never exceeds the energy capacity of the V2G fleet. Fig. 9 shows the reliabilities for the three different P/E ratios for percent calls ranging from 10-100%

[12] Percent call is a random selection of a percentage of contract periods. For the thirty day signal a 10% call only requires the V2G fleet to provide energy services for 432 randomly selected contract periods out of the 4320 contract periods in this study.
[13] Direct comparisons to previous work are complicated by the use of the 2009 NHTS data instead of the 2001 data, the restrictions requiring the vehicle to be charged to 50% SOC prior to providing A/S, or a combination of the two.

for a fleet factor of 3.25. V2G fleets with a P/E ratio of less than one would require a higher fleet factor in order to meet industry standard reliability for all percent call scenarios. The lower aggregated performance is likely attributed to the slower rate of charge and thus longer period of time required to reach 50% SOC.

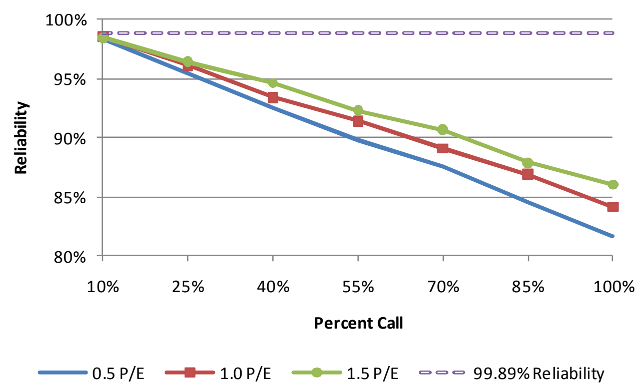

Fig. 8:V2G Reliabilities for a 2.5 Fleet Factor

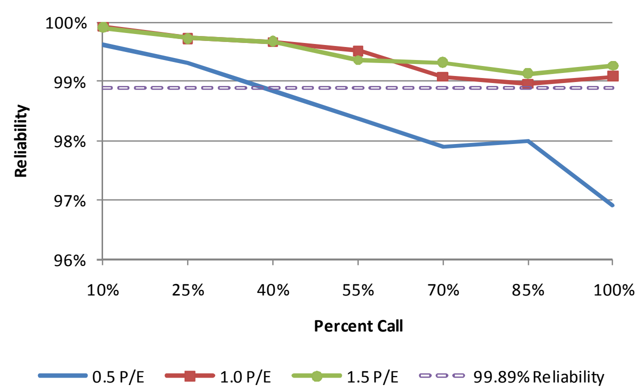

Fig. 9: V2G Reliabilities for a 3.25 Fleet Factor

3.2. V2G Effects on Vehicle Performance

Previous studies have assumed that V2G A/S will have little or no effect on vehicle driving performance in terms of lost CD driving range [27]. In order to test this hypothesis the simulations compared the CD distance of the V2G capable PHEV model to the CD distance of the baseline PHEV model. The simulations found that there exist a series of tradeoffs between V2G participation and PHEV function which can decrease CD range, thus showing that V2G provision by vehicles would be another factor impacting vehicle performance. Fig. 10 displays the CD miles lost over a 30 day period. Plot (a) in Fig. 10 shows the CD miles lost for a fleet factor of 2.5 and plot (b) shows the CD miles lost for a fleet factor of 3.25. These plots show that the CD miles lost for a thirty day period is approximately 210 miles and is relatively insensitive to fleet factor, percent call, and P/E ratio.

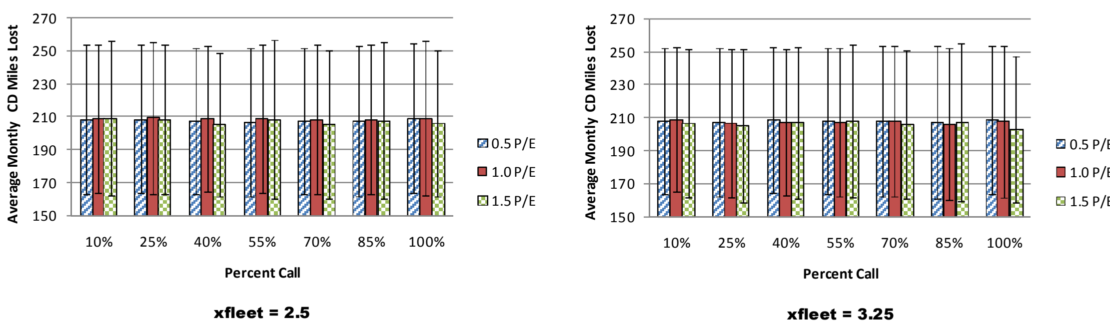

Fig. 10: a)CD Miles Lost for fleet factor of 2.5 b)CD Miles Lost for fleet factor of 3.25.

The estimated cost associated with V2G performance loss (C_{V2G}) is calculated using (11), and determines the financial loss due to reduced CD miles driven. This financial loss is estimated based on the increased use of the internal combustion engine and thus increased gasoline consumption and reduced electric energy consumption. This calculation uses the estimated average cost of gasoline and electricity for 2011 posted by U.S. Energy Information Administration (EIA)[42], the average fuel economy based on the Chevrolet Volt [43], and the same charge depleting electric consumption value used in the simulations. The estimated financial cost of V2G performance loss for a thirty day period for the three P/E ratios and percent calls are shown in Fig. 11 for a fleet factor of

3.25. For all scenarios the estimated cost of V2G due to CD miles lost is approximately $11 for a thirty day period or approximately $130 for a year.

$$c_{V2G} = \left[\frac{(CD_{loss} * c_{fuel})}{mpg}\right] - \left[CD_{loss} * EC_{CD} * c_{energy}\right] \quad (11)$$

Advanced charging algorithms for V2G vehicles such as adaptive controllers with foresight and vehicle user feedback might be able to reduce V2G's affect on CD range. However, the goal of these algorithms is to ensure that the vehicle is fully charged prior to departure. In doing so these algorithms will reduce the V2G operational time and increase the required fleet factors in order to provide reliable A/S. Alternatively, it is possible to maintain the fleet factor, but this may limit the aggregators' ability to provide A/S. Either scenario will likely reduce the income received from V2G provision. This demonstrates that a tradeoff exists between maximizing V2G revenues and reducing negative effects on vehicle performance, and these issues must be considered in the development of V2G architectures.

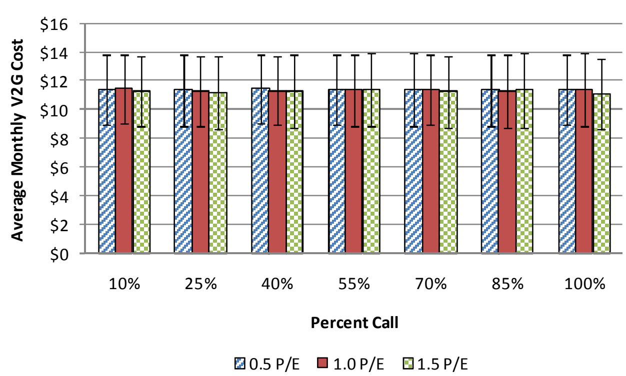

Fig. 11: V2G Monthly Cost due to CD Miles Lost for a 3.25 fleet factor.

Loss of CD range also impacts other stakeholders participating actively or implicitly in V2G. Vehicle OEMs are unlikely to welcome deleterious effects of V2G on CD range, as it directly impacts the owner's perception of vehicle quality. Loss of CD range could also be unacceptable to the vehicle owner, unless the CD range loss was financially compensated. The next section will evaluate how vehicle performance loss impacts V2G finances.

3.3. V2G Compensation for Ancillary Services

The following analysis utilizes previous work based upon 2006-2008 CAISO regulation market data [35, 40], to look at the economic potential of V2G, including SOC and the effects of charging control.

The estimated cost associated with V2G performance loss discussed in the previous section is used in calculating an adjusted average annual gross profit ($\overline{AAGP}$) in order to calculate the maximum potential revenue ($r_{\max}$) from V2G using (12).

$$r_{\max} = (\overline{AAGP} - C_{V2G})\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \quad (12)$$

The annual gross profits are estimated as the mean of the average annual gross profits for 2006, 2007, and 2008, less the estimated cost of vehicle performance loss (C_{V2G}). To compare to previous work, this study considers a 10 kw vehicle and also an estimated value for a 2.5 kw vehicle. The values used in the computations are shown in Table IX and are based upon a percent call rate of 10%. The maximum potential revenue must cover the upfront costs of adding V2G capability to a PHEV, utility, communication and other infrastructure upgrades, and other setup costs. Offsetting costs is the estimated V2G revenue earned by the vehicle owner. This calculation does not reduce V2G revenue by communication cost or aggregator profit, nor does it account for degradation of vehicle systems other than the battery. Since operational costs are not included in this calculation, the resulting value represents an upper bound on the potential V2G revenue.

Fig. 12 displays a comparison of the potential V2G revenues between the results found in this study and previous work which excluded the effects of SOC [40]. The revenues from the previous study were based on a fleet factor of 2.5 whereas this study which does include the affects of SOC is based on a fleet factor of 3.25. Most likely a charger power greater than 3.3kw (level 2 charger) will require an upgrade to the home connection at a cost of $500-$800 and a possible need for utility infrastructure upgrade of roughly $2000 [16, 23]. The home connection upgrade costs will be borne by the vehicle owner, the utility upgrade costs are assumed to be borne by the utility.

TABLE IX
Economic Modeling Parameters

Parameters	***Value***	***Units***	***Comments***
CD_{loss}	2485	(miles)	Annual charge depleting miles lost; estimated from Fig. 10.
c_{fuel}	3.17	$(\$)(gal)^{-1}$	Projected 2011 USA avg electricity rate [42]
Mpg	37	$(miles)(gal)^{-1}$	Chevy Volt est. EPA avg mpg [43]
EC_{CD}	0.282	$(kwh)(mi)^{-1}$	Charge depleting electric consumption[39]
c_{energy}	0.11	$(\$)(kwh)^{-1}$	Projected 2011 USA avg. gasoline price [42]
N	10	(years)	Investment payback period, As in [27]
I	10	(%)	Discount rate, As in [27]

When not accounting for SOC, the 2.5kw charger provides $1020 over a ten year period for V2G A/S provision, however, when the effects of SOC are included, V2G A/S provision is no longer economically viable. For higher P/E ratios the economic incentives are $3,270 and $2,320 if the $800 infrastructure upgrade cost is removed from the expected ten year V2G revenues. The error bars display the maximum ten year V2G revenues if the $800 infrastructure upgrade cost is unnecessary. This shows that SOC effects in this model produce a 30% economic loss in comparison to the previous study.

This economic loss is attributed to required increased fleet factors and the cost associated with V2G performance loss.

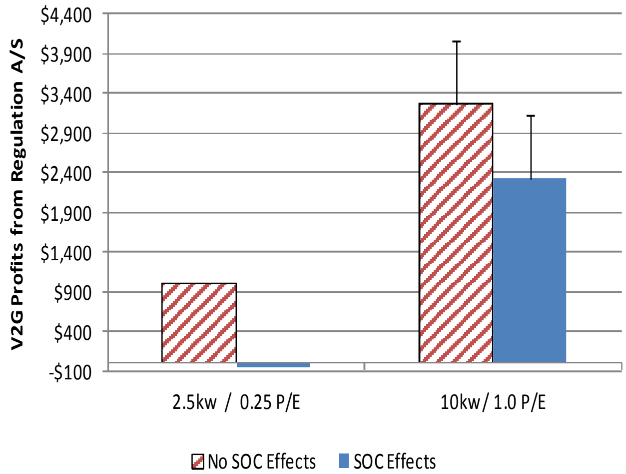

Fig.12: Comparison Estimated 10 Year V2G Profits

4. V2G RELIABILITY FOR AGC SIGNALS WITH LARGE ENERGY CONTENT

Up to this point this study has commanded V2G with a generated signal having low energy content so as to isolate the driving behavior effects on PHEVs ability to provide A/S through V2G. However, recent studies of A/S signals [44] have shown that the signal contains significant energy content. To evaluate and determine the affects high energy content signals have on V2G fleets' ability to provide A/S, CSU worked with WAPA to obtain historical ACE data.

4.1. Processing of the WAPA ACE

The WAPA ACE signal was analyzed to determine which months of data contained the fewest number of data recording errors and filling algorithms were used to patch the data. Where the data contained recording errors the values were set to zero – i.e. no AGC call. In addition, segments containing more than seven consecutive, identical, non-zero values were also considered to be data errors and set to zero. Ultimately, data from April, May, September, and February had the fewest errors, and were utilized in this analysis.

From discussions with WAPA, it was determined that, if high-speed regulation resources such as batteries or V2G were available, the highest value would be to call these resources first, prior to slower conventional resources. Therefore the ACE signal was pre-processed in two methods to generate raw AGC and filtered AGC signals for four months of equivalent A/S call signal. For the raw AGC signal, the ACE data were clipped at ± 1 MW. Fig. 13 shows two plots; the upper plot a) shows ten minutes of the unclipped raw ACE signal and the lower plot b) shows the same signal but clipped at ±1 MW. For the filtered AGC signal, the data was first filtered to remove DC content, by high-pass filtering with a cutoff period of two hours. The cutoff frequency was selected as a measure that could be readily implemented within the capabilities of a balancing area's control system. The filtered ACE signal was then clipped at ± 1 MW to produce the filtered AGC signal. The filtered AGC signal has significantly lower energy content than the raw AGC signal, and represents a signal that is at least minimally engineered to support storage devices with limited SOC range.

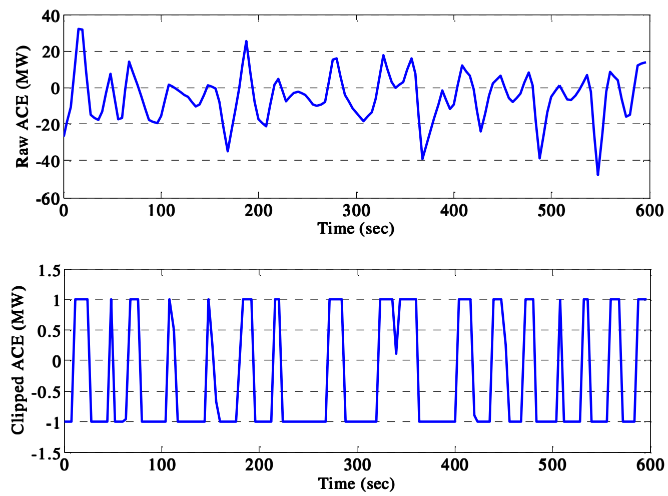

Fig. 13: a) Raw ACE signal b) Clipped ACE signal.

Table X summarizes key maximum and minimum energy excursions for the A/S signals. The raw AGC signal exhibits characteristics similar to the PJM data [44]; both contain significant energy content. The filtered AGC signal displays significantly reduced energy content, but more than the synthetic signal utilized in Section 3.

TABLE X
WAPA ACE Energy Content

	Raw AGC Energy (MWh)		Filtered AGC Energy (MWh)	
	Max	**Min**	**Max**	**Min**
April	24.5	-24.6	2.2	-0.7
May	62.8	-12.8	1.3	-1.2
September	185.0	-1.2	0.6	-4.5
February	136.2	-2.4	1.9	-0.9

4.2. Evaluation of V2G Reliability for WAPA Data

Fig. 14 displays the results from the simulations ran utilizing both the raw and filtered AGC call signals using a fleet factor of 3.25. As expected, the raw AGC signal produces very low reliability at high percentage call rates. The filtered AGC signal, which has energy content similar to the vehicle fleet, has less impact, but still reduces the reliability somewhat relative to the synthetic signal discussed earlier. It also reverses the optimum choice of P/E ratio, slightly favoring P/E ratio of 1.0 over a P/E ratio of 1.5. At low percent call rates, the existing balancing area control signals could potentially be utilized for V2G operation. However, for high call rates – a likely scenario for utilizing high-speed regulation resources – a specialized signal which meets the needs of V2G would be required to meet normal reliability metrics.

An additional interesting difference is that these A/S signals tend to decrease the difference in reliability between high and low P/E ratios. In fact, for the unfiltered signal, low P/E ratios tend to produce higher reliabilities, whereas they produced lower reliabilities for the synthesized signal. For the filtered AGC signal, the change is less pronounced, with most months similar to results from the synthesized signal. The underlying cause of this behavior is that the low P/E ratio chargers take longer to saturate the battery, allowing the vehicle to meet more A/S contract periods. This result indicates that an A/S signal tuned for V2G operations must be carefully crafted and optimized for the expected P/E ratios of the involved vehicles.

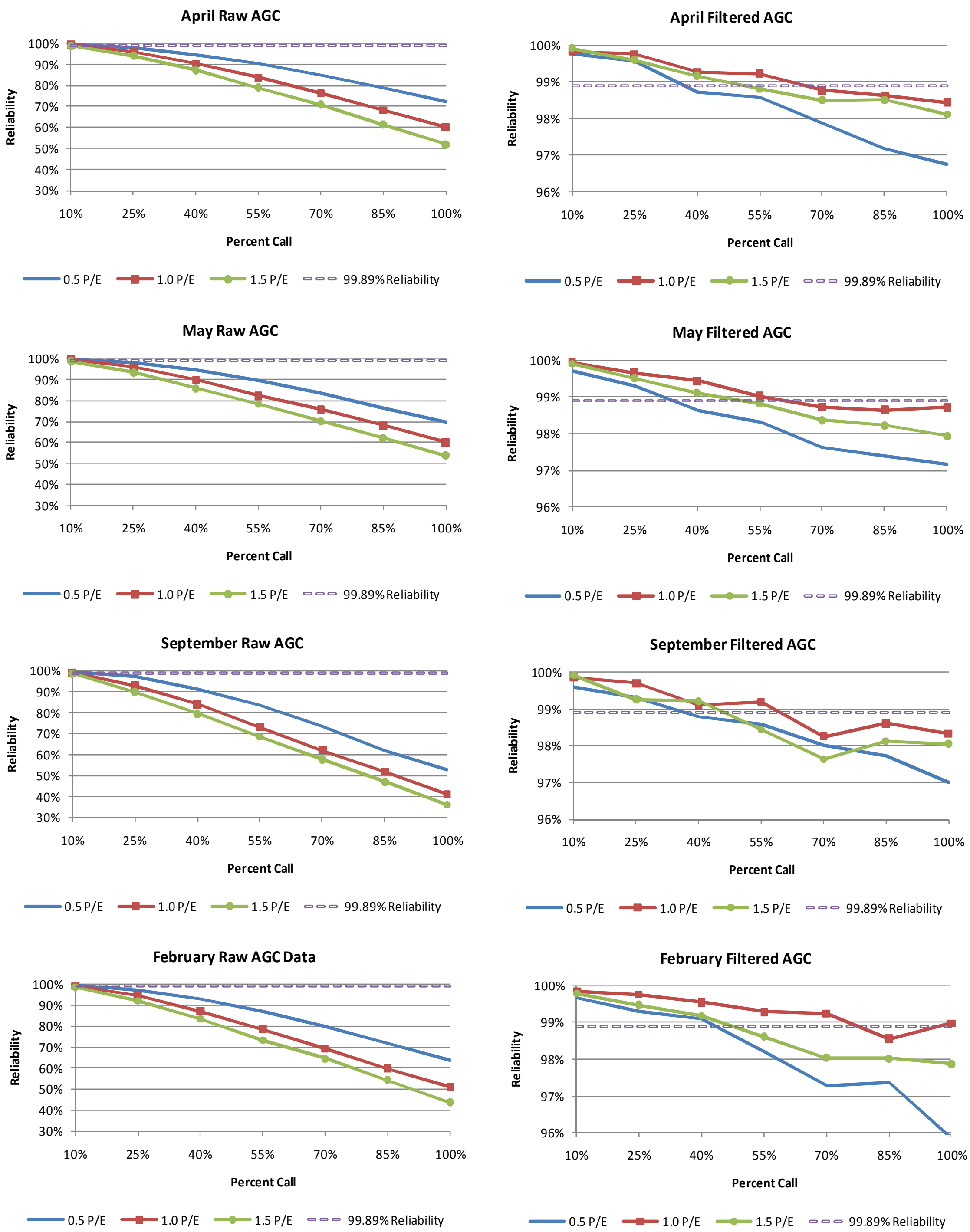

Fig. 14: a) Reliability results for raw AGC data b) Reliability results for filtered AGC data.

5. CONCLUSIONS

To realize a V2G A/S system in the near future, the requirements of both the grid system operator and the vehicle owner must be satisfied. The grid system operator requires V2G resources be compatible with both its command and contracting systems. Simultaneously, vehicle owners require a command and contracting architecture that maximizes a robust return on their investment in V2G capability.

In order to satisfy the requirements of all V2G stakeholders and allow near future adoption of V2G for A/S provision, there are some important issues which must be addressed. This study has shown that, to integrate a V2G system into the existing market and power grid, any practical V2G system will require: 1) the utilization of an aggregative architecture to meet current industry standard reliability requirements [40], 2) the construction of low energy A/S call signals from existing ACE signals, 3) a lower percent call for V2G even if the pool of contracted A/S resources gets smaller, 4) compensation for decrease in vehicle value due to the loss of electrically driven miles, and 5) consideration of P/E ratios in the design of the V2G A/S call signal.

V2G has been proposed as a mechanism to provide distributed storage to improve grid stability and assist integration of renewable energy, while simultaneously providing income to offset the higher initial cost of PHEVs relative to HEVs [15, 17, 23, 26-31]. However, results from this study indicate that integration requirements of V2G negatively impact both the grid system operator and vehicle owner, and must be addressed before V2G can be widely adopted.

The analysis framework developed for this study can provide a framework for a comprehensive evaluation of V2G and other distributed storage technologies, including important system interactions normally neglected in such studies. This analysis has shown that future V2G viability and economic studies require more detailed models and must take into consideration the five key requirements stated here.

PART III:

AN EVALUATION OF STATE-OF-CHARGE LIMITATIONS AND ACTUATION SIGNAL ENERGY CONTENT ON THE RELIABILITY AND ECONOMICS OF GRID-CONNECTED DISTRIBUTED ENERGY STORAGE SYSTEMS

1. INTRODUCTION

Compared to conventional grid service providers, battery-based distributed energy storage units have advantages in terms of faster response times to command signals and the ability to answer bidirectional power commands with very low opportunity cost [45]. Providing the electric grid with a network of distributed energy storage (DES) devices has been identified as a way of substantially improving the stability and robustness of the existing electric grid [12-15, 17, 23, 26-31, 45]. Recent work has proposed that the introduction of electric and plug-in hybrid electric vehicles can help provide the electric grid with a large and inexpensive energy storage resource [17, 23, 26, 27, 30]. In addition, batteries for these vehicles will be determined unfit for vehicle performance after a certain period of time; however these batteries may still function sufficiently to provide stationary grid energy storage grid services before being disposed or recycled. This study focuses on the use of home energy storage appliance (HESA) scale distributed battery-to-grid (B2G) resource systems for ancillary service (A/S) provision particularly electric grid frequency regulation.

Economic studies of DES resources [38, 45, 46] have based their analyses on two critical assumptions regarding the A/S signal: 1)The automatic generation control (AGC) signal is assumed to be a power signal which contains little or no energy content, and 2) Independent System Operators (ISOs) and Balancing Authorities (BAs) procure excessive A/S capacity and therefore DES resources would only be called upon to provide energy services approximately 10% [27] of the contracted period. Together, these assumptions ensure that the energy removed or added from the DES resource, will net to zero over both short and extended periods. These assumptions eliminate the finite energy capacity of distributed energy resources from consideration.

This study presents a set of simulations relaxing these assumptions thereby showing the effects of battery state of charge (SOC) limitations on B2G reliability and economics. To perform these experiments, this work proposes a model of B2G reliability and availability under an aggregative architecture, including a novel SOC control model. Next, a synthetic and generalizeable AGC signal is constructed to understand in general the effect of battery SOC limitations on B2G reliability and economics. Finally, an AGC signal derived from the 2008 Western Area Power Administration (WAPA) area control error (ACE) signal is used to test the real-world effects of SOC limitations.[14]. The discussion section focuses on the implications of these results on the scalability of B2G as an economic enterprise.

[14] The ACE signal is the observed difference between power production and power demand on the grid; a negative ACE value corresponds to power demand exceeding power production and a positive ACE value signifies excess power production relative to power demand.

2. DESCRIPTION OF DISTRIBUTED B2G MODEL

This work is based on a Matlab™/Simulink™ model which was created to evaluate the impacts of battery state of charge (SOC) limitations on B2G reliability and economics for providing ancillary services. Matlab™ was used to feed in the AGC signal used for A/S calls, and analyze the aggregated results. Simulink™ performed the time series simulations of B2G A/S for each battery.

For this analysis we assume (a) an aggregative architecture[15], (b) 100% reliable communication connection between the grid system operator and the aggregator, (c) 100% reliable communication between the aggregator and the DES, and (d) a one megawatt (MW) A/S contract[16]. Reliability is defined as the fraction of contracts that the aggregated DES is able to meet 100% of the contracted power. This study utilizes ten minute contract periods, and a contract period is considered to have failed when the aggregated DES is unable to meet every four second A/S call in a ten minute contract period.

In this analysis the SOC represents the useable SOC of the individual battery relative to the usable capacity, rather than the nameplate capacity. The usable energy capacity of each battery is ten kilowatt-hours (kWh). For simplicity all analyses in this paper assume 100% charger and battery joule efficiencies for the B2G system. This assumption regarding efficiency produces upper bound results as the inclusion of round

[15] An aggregative architecture was deemed necessary in [40] for low energy and power resources.
[16] The minimum A/S contract size for California [27].

trip efficiency losses would require either a derating of the charger power[17] or a more advanced SOC charge control to eliminate energy biasing in the battery SOC[18]. All of the aggregated distributed B2G resources are initiated at 50% SOC and they charge and discharge as needed to meet the requirements of the AGC A/S signal call, contributing towards the aggregated power. If the battery reaches 0% or 100% SOC the battery is not able to contribute toward the A/S calls in the saturated direction but is able to contribute toward A/S calls in the unsaturated direction.

[17] For a 10kw charger connection and a round trip efficiency of 0.73, a regulation-up and –down the derated power provision of 7.3kw would be the maximum allowable bid for the B2G resource. The remaining charging capability would be used to maintain SOC but would not provide any A/S revenue.

[18] One solution is (if asymmetric bidding if allowed), for a 10kw charger connection and a round trip efficiency of 0.73, to remove SOC creep it would require a regulation-up power provision of 7.3kw and a regulation-down power provision of 10kw provided that the regulations markets allow for asymmetric bidding.

3. EVALUATION OF DISTRIBUTED B2G A/S PROVISION WITH LOW ENERGY AGC SIGNALS

Actual AGC signals have significant net energy content [44]. To meet the power calls of the AGC signal, a generation unit will source or sink significant energy over an extended period. This behavior of existing A/S calls quickly saturates most energy storage systems. To eliminate this affect, a generic AGC signal was designed to have less energy content than the aggregated distributed B2G resource, regardless of the power-to-energy ratio (P/E)[19].

3.1. Synthetic AGC Signal Development

A Markov transition matrix was utilized to create a synthetic, thirty day, AGC signal consisting of 648,000 calls[20] The synthetic signal consists of three call states, +1MW, -1MW, or 0 MW. A Markov matrix defines the probability of the call for period (*i+1*), based upon the call selected for period *i*. As is in [41], the probabilities are represented as in Table XI. The call for period *i* is identified by one row, the call for period (*i+1*) by a column, and the matrix cells represent the probability of transition from row *i* to any column. By definition, the probabilities in each row sum to 100%. A random number generator is utilized to select the next signal call state. The matrix is sampled without replacement to assure that the designed net-zero energy characteristics are met by

[19] Power-to-Energy ratio is the ratio of the battery charger power and battery capacity. A larger P/E ratio requires a shorter charging time. Ex) If a charger power is 5 kw and the battery capacity is 10 kwh the P/E ratio is 0.5 h^{-1}.
[20] Calls have a 4 second period with a value of either 1 MW or -1MW.

the end of the one-month period. Thus, the probabilities change with time. An example Markov matrix is shown in Table XII. Note that if $a_{1,3} = a_{3,1} = 324{,}000$ and all other cells are zero, the resulting AGC signal would oscillate between up and down calls, would have no energy content, and thus would have no impact on SOC. This is equivalent to the assumption made in previous studies that the A/S call signal has no net impact on battery SOC.

TABLE XI
EXAMPLE MARKOV MATRIX

Call for period i (MW)	Call for period $i+1$ (MW): **1**	**0**	**-1**
1	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$
0	$a_{2,1}$	$a_{2,2}$	$a_{2,3}$
-1	$a_{3,1}$	$a_{3,2}$	$a_{3,3}$

To produce an AGC signal with more realistic behavior but still constrained to have less energy content than the distributed energy resource, the matrix shown in Table XII was utilized. The resulting integrated energy content of the synthetic AGC signal is shown in Fig. 15. Shifting approximately 9.3% of the probability from $a_{1,3}$ to $a_{1,1}$ and from $a_{3,1}$ to $a_{3,3}$ forces 9.3% of consecutive AGC signal calls to occur in the same state. This produces an AGC signal with non-zero, but controllable energy content impacting SOC. Increasing the weights of cells $a_{1,1}$ or $a_{3,3}$ increases the energy content in the resulting generated signals.

While synthetic, the AGC signal generated in this fashion compares favorably to AGC signal data provided by the WAPA Rocky Mountain control area once the AGC signal was filtered to remove the low-frequency content with a period in excess of two hours (see Section 4). A synthetic signal allows experimentation with an engineered A/S call signal. In practice such an AGC signal can be generated within the balancing authority's control system, using a combination of filtering and feedback control techniques.

TABLE XII
GENERATED AGC MARKOV MATRIX

Call for period i (MW) \ Call for period $i+1$ (MW)	1	0	-1
1	30,000	0	294,000
0	0	0	0
-1	294,000	0	30,000

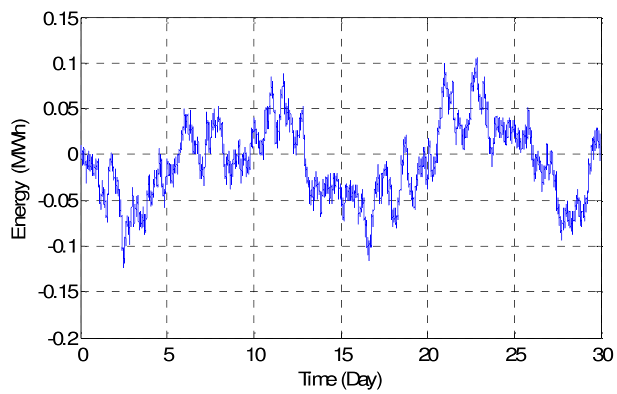

Fig. 15: Energy content of generated AGC signal after integration.

Table XIII compares the maximum and minimum energy excursion of the generated AGC signal to the maximum allowable energy excursion of the aggregated B2G resource. As described above, this analysis assumes a 10 kWh usable battery, three charge rates ranging from 5-15 kW, and a maximum allowable energy excursion equal to 50% of SOC for an aggregated B2G resource with a fleet factor (x_{fleet})[21] of 1. Defining the maximum allowable energy excursion of the distributed energy resource based on

[21] Fleet factor (xfleet) is the fleet scaling factor above the nominal number of distributed energy resources required to reliably meet the contracted power, based on the energy resources' charging rate. Ex) a xfleet of 1for energy resources with a charger connection of 10 kw would require a 100 distributed B2G resources to meet a 1MW A/S contract; a xfleet of 2.5 for the same aggregated B2G resource would require 250 distributed B2G resource.

50% SOC maximizes the symmetric range of usable SOC and minimizes the impact of AGC signals containing energy content.

TABLE XIII
GENERATED AGC AND DES RESOURCE ENERGY CONTENT COMPARISON

30 Day Markov AGC Energy		**Fleet 50% Max. Allowable Energy Content**		
Max. Energy	**Min. Energy**	**5 kw 0.5 P/E**	**10 kw 1.0 P/E**	**15 kw 1.5 P/E**
0.1 MWh	-0.1 MWh	1.0 MWh	0.5 MWh	0.3 MWh

Using this novel simulation framework which includes AGC signals with energy content and varying percent calls for A/S provision, we can now understand the effects these parameters have on B2G's ability to provide ancillary services. The following sections show how this simulation framework affects distributed energy resource reliability and financial compensation for A/S provision.

3.2. Evaluation of B2G Reliability

In order to determine the expected reliability of B2G resources, five simulations were ran for varying percent calls[22] from 10%-100% for a fleet factor of 1 and P/E ratios of 0.5, 1, and 1.5 respectively. Since, the aggregated DES resource is considered to be available 100% of the time, and the energy content of the A/S signal is less than the maximum allowable energy excursion of the aggregated distribute energy resource, at 100% call the aggregated DES resource will always have a 100% reliability. However, as P/E ratio increases and percent call is less than 100% there is a possibility of reduced reliability as the energy content associated with the percent call A/S signal will differ from the 100% call signal energy and could exceed the energy storage capacity of the DES resource. The probability of this reduced reliability occurring is dependent upon the length of the contract period and the energy content of each contract period. If all contract

[22] Percent call is a random selection of a percentage of contract periods. For the thirty day signal a 10% call only requires the V2G fleet to provide energy services for 432 randomly selected contract periods out of the 4320 contract periods in this study.

periods have net energy content close to zero the probability of the phenomenon is extremely low, however, if there is a large number of contract periods with positive or negative energy bias the chance of reliability loss is increased. All scenarios ran in this study with the synthetic A/S signal all exceeded a reliability of 98.89%; a reliability value representative of gas-turbine systems as reported by NERC [33]. This shows that provided the maximum energy excursion of the A/S signal doesn't exceed the maximum energy excursion of the distributed energy resource, it can be used as a primary (100% call) A/S provider.

3.3. B2G Compensation for Ancillary Services

The following analysis utilizes previous work [40] to determine the economic potential for B2G based upon 2006-2008 CAISO regulation market data [35]. Although this study has looked at ten minute contract periods for the simulations, the CAISO data used is based on hourly contracts. It is assumed that the aggregator will not bid for regulation services if it is not cost effective The aggregator distributes the hourly revenue to all of the distributed energy storage owners that have been connected to that aggregator's network during the previous hour. The revenue delivered to the aggregator for each hour is calculated using the values in Table XIV, equations (13), and (14) taken from [40] for aggregative architectures. However, for DES resources, we utilize a fleet factor of 1 and assume a the fleet availability (A_{fleet}) and vehicle/distributed energy resource availability ($A_{battery}$) of 100%, and an hourly reliability R(*k*) of 98.89%[23].

$$c_{en} = {p_{el}}/{\eta_{conv}} \quad (13)$$

[23] The simulations for this study showed reliabilities greater than 98.89% but this value was used to provide slightly conservative results.

TABLE XIV
ECONOMIC MODELING PARAMETERS FOR A/S REVENUES

Parameters	Description	Value	Units	Comments
P	B2G power capacity	10	(kW)	As in [27]
$R_{d\text{-}c}$	Ratio of energy dispatched for regulation services as a proportion of contracted power and time	10	(%)	As in [27]
p_{cap}	Hourly ancillary service contract price	varies	($/MW-h)	Taken from [35]
R	Probabilistic vehicle hourly reliability	98.89	(%)	----------
$A_{battery}$	Probabilistic battery hourly availability	100	(%)	----------
A_{fleet}	Probabilistic B2G fleet hourly availability	100	(%)	----------
x_{fleet}	Fleet scaling factor	1	(--)	----------
c_{en}	Cost per unit of energy	0.21	($/kWh)	Calculated from (13)
p_{el}	Market selling price of electricity	0.10	($/kWh)	----------
η_{conv}	Inverter energy conversion efficiency	0.73	(%)	As in [27]

$$
\begin{aligned}
r_{\text{Reg-Up}}(k) &= \frac{A_{\text{battery}}(k) \cdot R(k)\left(p_{\text{cap}}(k) \cdot P + p_{\text{el}}(k) \cdot P \cdot R_{\text{d-c}}\right)}{x_{\text{fleet}} \cdot A_{\text{fleet}}(k)} \\
r_{\text{Reg-Down}}(k) &= \frac{A_{\text{battery}}(k) \cdot R(k)\left(p_{\text{cap}}(k) \cdot P\right)}{x_{\text{fleet}} \cdot A_{\text{fleet}}(k)} \\
c_{\text{Reg}}(k) &= \frac{A_{\text{battery}}(k) \cdot R(k)\left(c_{\text{en}}(k) \cdot P \cdot R_{\text{d-c}}\right)}{x_{\text{fleet}} \cdot A_{\text{fleet}}(k)}
\end{aligned}
\tag{14}
$$

A mean of the average annual gross profits for 2006, 2007, and 2008 is taken, and this result is defined as the adjusted average annual gross profit ($\overline{AAGP}$). The ($\overline{AAGP}$) is used to calculate the maximum potential revenue ($r_{\max}$) for an individual HESA-scale resource using (15) and the values in Table XV.

$$
r_{\max} = \overline{AAGP} * \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right] \tag{15}
$$

TABLE XV
ECONOMIC MODELING PARAMETERS FOR B2G REVENUE

Parameters	*Value*	*Units*	*Comments*
$\overline{AAGP}$	1662	($/year)	10kw Aggregative architecture average annual net revenue
n	10	(years)	Investment payback period, As in [27]
i	10	(%)	Discount rate, As in [27]

Assuming an investment period of 10 years and a discount rate of 10%, we compute the maximum allowable potential revenue that must cover the upfront costs of purchasing the DES unit, adding communication and other infrastructure upgrades and setup costs. Offsetting costs is the estimated revenue earned by the distributed energy storage owner. This calculation does not reduce B2G revenue by communication cost or aggregator profit. Since operational costs are not included in this calculation, the resulting value represents an upper bound on the potential for B2G A/S revenue. Additionally, a charger power greater than 3.3kw (level 2 charger) will require an upgrade to the home connection at a cost of $500-$800 and a possible need for utility infrastructure upgrade of roughly $2000 [16, 23]. The home connection upgrade costs will be borne by the DES resource owner, the utility upgrade costs are assumed to be borne by the utility.

Using the values displayed in Table XIV for a 10kw charger, 10% percent call rate, and a fleet factor of 1, this study found the estimated maximum potential revenue for low energy content AGC signals is $10,200 and $9,400 if home upgrades of $800 are required. To calculate the maximum potential revenue for other charger powers the relationship is linear provided the reliability of the system remains above 98.89%. For example, a 5kw DES resource would expect to have a maximum potential net revenue of $5,100 if home upgrades are disregarded.

4. B2G RELIABILITY FOR AGC SIGNALS WITH LARGE ENERGY CONTENT

Up to this point this study has utilized a synthetic signal with low energy content. The following section will use WAPA ACE historical data which has significant energy content in order to provide insight on the affects high energy content signals has on B2G systems.

4.1. Processing of the WAPA ACE

The WAPA ACE signal was analyzed to determine which months of data contained the fewest number of data recording errors and filling algorithms were used to patch the data. Where the data contained recording errors the values were set to zero – i.e. no AGC call. In addition, segments containing more than seven consecutive, identical, non-zero values were also considered to be data errors and set to zero. Ultimately, data from April, May, September, and February had the fewest errors, and were utilized in this analysis.

From discussions with WAPA, it was determined that, if high-speed DES resources were available, the highest value would be to call these resources first, prior to slower conventional resources. Therefore the ACE signal was pre-processed in two methods to generate raw AGC and filtered AGC signals for four months of equivalent A/S call signal. For the raw AGC signal, the ACE data were clipped at ± 1 MW. Fig. 16 shows two plots; the upper plot a) shows ten minutes of the unclipped raw ACE signal and the lower plot b) shows the same signal but clipped at ±1 MW. For the filtered AGC signal, the data was first filtered to remove DC content, by high-pass filtering with a cutoff period of two hours. The cutoff frequency was selected as a measure that could be readily implemented within the capabilities of a balancing area's control system. The filtered ACE signal was then clipped at ± 1 MW to produce the filtered AGC signal. The filtered AGC signal has significantly lower energy content than the raw AGC signal, and represents a signal that is at least minimally engineered to support DES with limited SOC range.

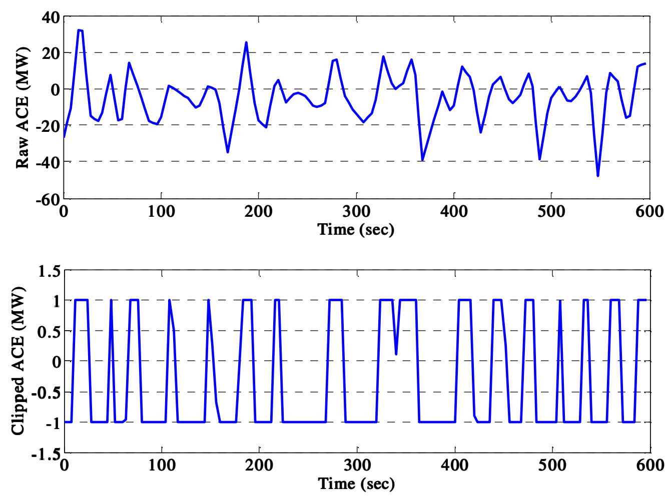

Fig. 16: a) Raw ACE signal b) Clipped ACE signal.

Table XVI summarizes key maximum and minimum energy excursions for the A/S signals. The raw AGC signal exhibits characteristics similar to the PJM data [44]; both contain significant energy content. The filtered AGC signal displays significantly reduced energy content, but more than the synthetic signal utilized in Section 3.

TABLE XVI
WAPA ACE ENERGY CONTENT

	Raw AGC Energy (MWh)		Filtered AGC Energy (MWh)	
	Max	**Min**	**Max**	**Min**
April	24.5	-24.6	2.2	-0.7
May	62.8	-12.8	1.3	-1.2
September	185.0	-1.2	0.6	-4.5
February	136.2	-2.4	1.9	-0.9

4.2. Evaluation of B2G Reliability for WAPA Data

Fig. 17 displays the results from the simulations run utilizing both the raw and filtered AGC signals, assuming a fleet factor of 1. As expected, the raw AGC signal produces very low reliability at high percentage call rates. The filtered AGC signal, which has energy content similar to that of the aggregated DES resource, has less impact, but still reduces the reliability somewhat relative to the synthetic signal discussed earlier. At low percent call rates, the existing balancing area control signals could potentially be utilized for DES A/S calls. However, for high percent A/S call rates – a likely scenario for utilizing DES resources – a specialized signal which meets the needs of limited energy ancillary service providers would be required.

An additional interesting difference is that these A/S signals tend to decrease the difference in reliability between high and low P/E ratios. In fact, low P/E ratios tend to produce higher reliabilities. The underlying cause of this behavior is that the low P/E ratio chargers take longer to saturate the battery, allowing it to meet more A/S contract periods. This result indicates that an A/S signal tuned for DES resources must be carefully crafted and optimized for the expected P/E ratios.

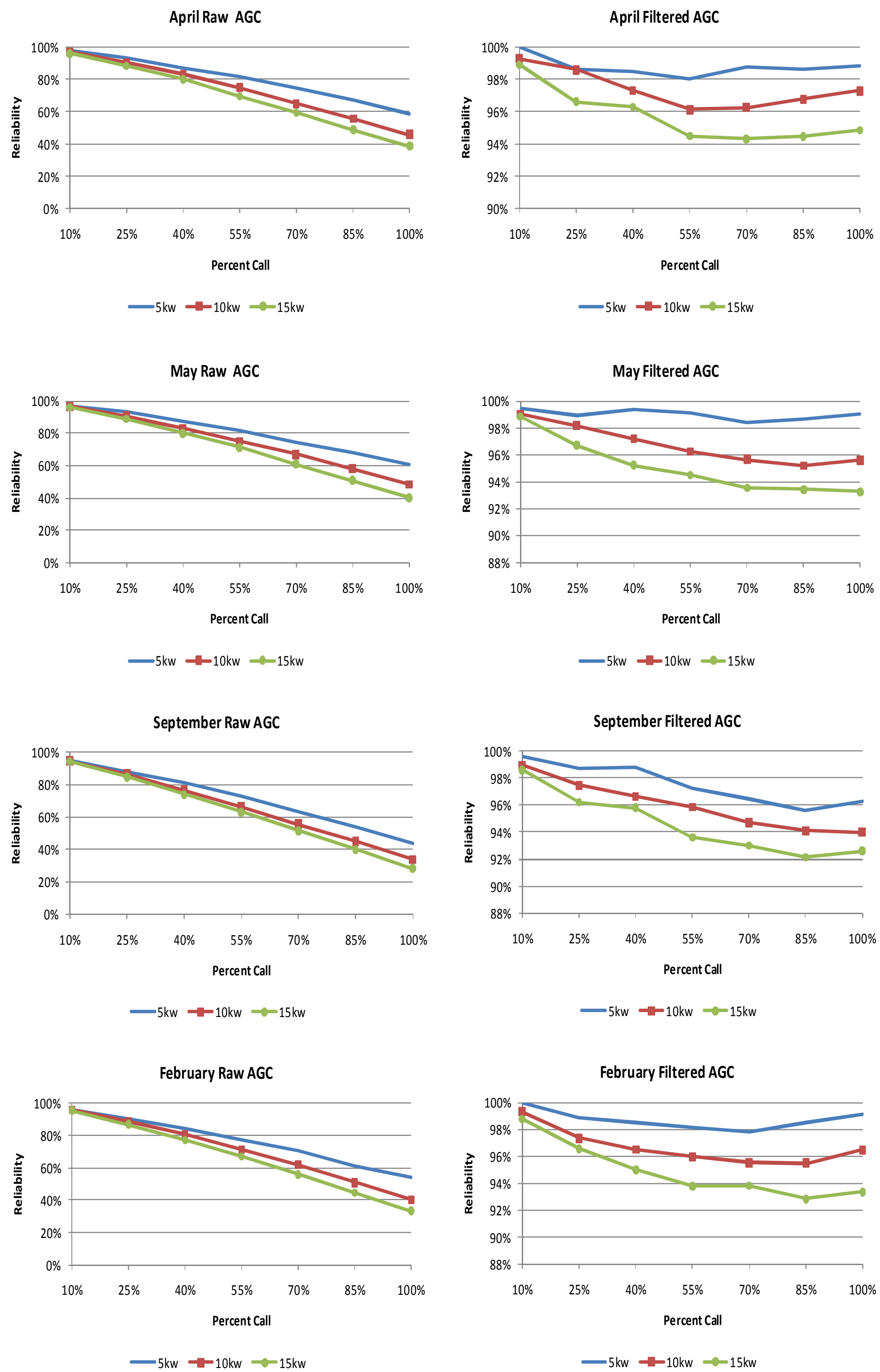

Fig. 17: a) Reliability results for raw AGC data b) Reliability results for filtered AGC data

5. DISCUSSION

This study has evaluated the ability of aggregated DES devices to provide ancillary services using A/S call signals with varying energy contents with respect to the energy capacity of the aggregated DES systems. Fig. 18 shows the three scenarios which were evaluated: 1) A/S call signals with less energy content than the aggregated DES devices, 2) A/S call signals with energy content greater than the aggregated DES devices, and 3) A/S call signals with significantly greater energy content than the aggregated DES devices.

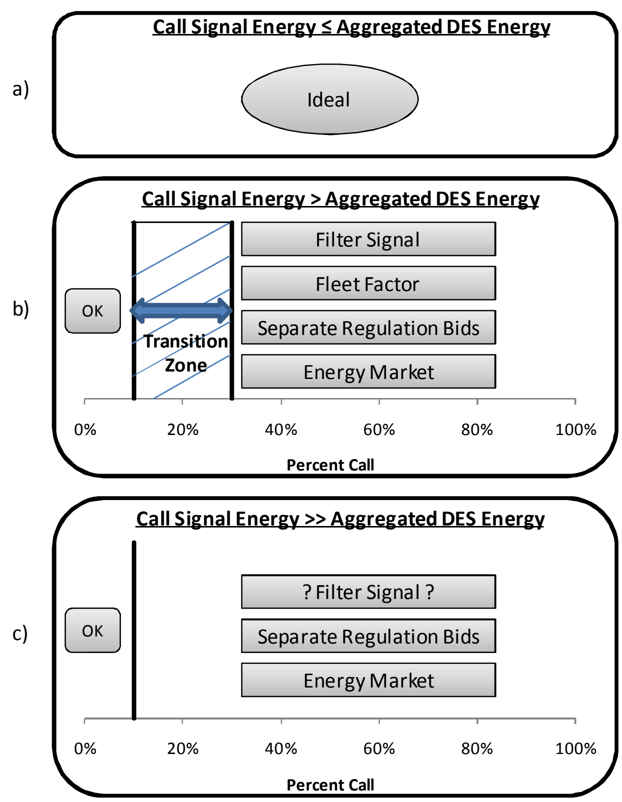

Figure 18 A/S Operational Options

5.1. Call Signal Energy ≤ Aggregated DES Energy

It has been found in this study that the ideal scenario for DES A/S provision is when the A/S call signal contains less energy content than that of the aggregated DES device. In this scenario the aggregated DES device can maintain high reliabilities regardless of the call rate of the device.

5.2. Call Signal Energy > Aggregated DES Energy

Since actual A/S call signals tend to contain significant energy content, evaluation of several approaches must be considered to incorporate aggregative DES devices into the A/S market. Fig. 18 b) represents the scenario where the A/S call signal energy is slightly greater than the energy capacity of the aggregated DES devices and displays the regions of percent call for A/S service provision. It has been shown in this study for all scenarios that if percent call for the aggregated DES devices remains below 10% the units can maintain an industry standard reliability. However, as depicted in Fig. 18 b) there is a transition zone where DES A/S provision remains effective. This zone expands from 10% towards 100% as the A/S call signal energy content approaches the energy capacity of the aggregated DES devices. In order to expand the transition zone towards the 100% call range four options are presented here: 1) increase the fleet factor to increase energy capacity, 2) filter the A/S call signal to remove DC content and reduce energy content, 3) allow separate bidding for regulation up and regulation down contracts, and 4) allow the aggregated DES devices to utilize the real time energy markets to return the aggregative DES devices back to a preferred operating SOC. Further description of these four options will now be presented.

5.2.1. Fleet Factor to Improve Reliability

The use of fleet factor to increase the aggregated DES energy capacity and improve the effectiveness of aggregated DES devices should only be considered when the energy difference between the A/S call signal and the aggregated DES devices is small. The reasoning for this is shown in Fig. 19 where increases in fleet factor significantly impacts the estimated ten year profits for each DES device owner.

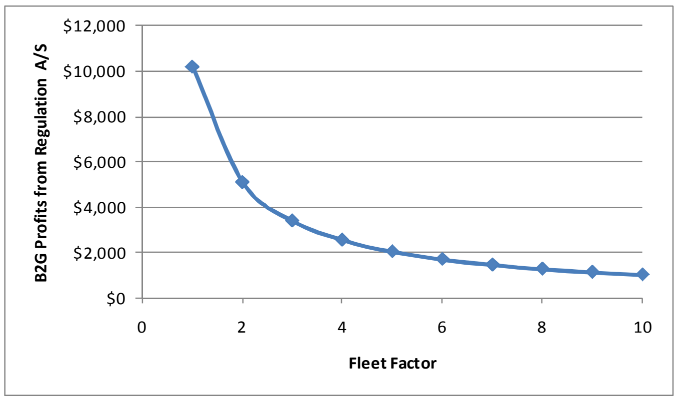

Fig.19: Estimated 10 Year B2G Profits for a 10kw Charger and 10% call rate.

5.2.2. Filter A/S Call Signal to Improve Reliability

Another option for consideration is to filter out the DC content of the A/S call signal. By doing this a separate signal can be created to contain energy content that is appropriate for the aggregated DES devices. However, if the original A/S call signal has significant amount of DC content, the DC portion of the original signal will still need to be accounted for and sent to conventional A/S providers. If filtering the original A/S call signal doesn't significantly reduce the amount of conventional A/S generation required, there is little benefit for the grid system operator and would be deemed an ineffective solution and would be reflected in the monetary value provided to aggregated DES devices.

5.2.3. Separate Regulation Bids to Improve Reliability

Allowing A/S providers to bid separately for regulation up and regulation down contracts would provide another way for limited energy aggregated DES devices to improve their reliabilities at higher percent call rates. As the aggregated SOC of the DES devices approach a set point the aggregator would then only bid in the appropriate regulation up or regulation down market to ensure a call doesn't occur which causes a failure to meet the call but this would also drive the aggregate SOC back to the desired operating point. For example if the aggregated SOC was approaching a fully depleted state the aggregator would only place bids in the regulation down market which would only allow perform regulation down calls and thus charge the DES device. Upon reaching a preferred operating point the aggregator would then resume bidding in both the regulation up and regulation down markets to increase revenues. However, this method is very sensitive to the energy content of the signal as signals with higher energy content will require more frequent bidding in only regulation up or regulation down markets instead of both. The more time that is spent only bidding in one market instead of both will result in decreased revenues. The relationship between percent time bidding in the regulation market has been evaluated for three years CAISO frequency regulation market data and simulated 50,000 times to determine the averaged expected revenues at different percent bids. Fig. 20 shows the results of the maximum and minimum expected revenues for different levels of percent bidding in the regulation up and regulation down markets. It can be seen this is essentially a linear relationship meaning with decreased number of bids in these markets leads to a proportional loss in revenues.

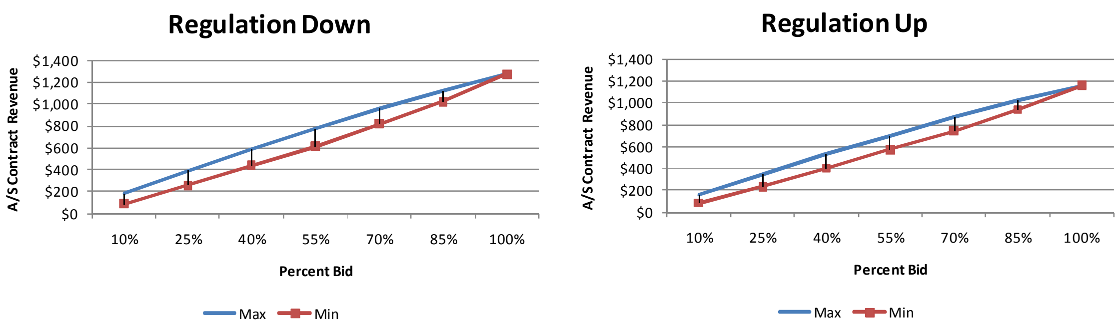

Fig. 20: Estimated A/S Contract Revenue for a) Regulation Down and b) Regulation Up

5.2.4. Participating in the Real Time Energy Market to Improve Reliability

A final solution that will be considered is to utilize the real time energy market to improve the reliability of the aggregated DES devices at higher percent call rates. As the aggregate SOC of the DES devices approach a set point the aggregator would then buy or sell energy on the real time energy market to drive the aggregate SOC back to a desired operating point. The downsides to this approach is that it will require the DES devices to remove itself temporally from the A/S market and thus forgoing the revenue of the A/S contracts and receive a lower revenue for the energy being sold on the energy market or worse yet have to pay for the energy required to return the aggregative DES devices back to a desired operating point. However, since the DES device will be absorbing or delivering energy continuously, this may prove to be a faster route to returning the DES device to the desired operating point and return to bidding in both the regulation up and regulation down markets than separate bidding in the regulation up or regulation down markets to drive the SOC back to the desired set point.

5.3. Call Signal Energy ≫ Aggregated DES Energy

A/S call signals which have significantly more energy content than the aggregated DES devices will be limited in regards to the solutions which would improve reliabilities at higher percent calls. Since the energy content of the A/S call signal is much greater than that of the aggregated DES device, using a fleet factor improvement will not be an economically feasible solution. As discussed in the previous section, filtering out the DC content of the A/S call signal will be feasible but it would need to ensure that this filtering process would decrease the use of conventional regulation devices to ensure that this method would be beneficial to the grid system operator. The remaining options to improve reliability is to allow aggregative DES devices to bid separately into regulation up and regulation down markets or allow the DES devices to utilize the real time energy market. The same caveats exist in this scenario as explained in the previous sections. However, with increasing difference between the DES devices energy capacity and the A/S call signal energy content, the economic feasibility will decrease due to reduced time of being able to bid in both regulation up and regulation down markets.

6. CONCLUSIONS

To realize B2G A/S system in the near future, the requirements of both the grid system operator and the DES owner must be satisfied. The grid system operator requires DES resources be compatible with both its command and contracting systems. Simultaneously, DES owners require a command and contracting architecture that maximizes a robust return on their investment in DES resources.

In order to satisfy the requirements of all DES stakeholders and allow near future adoption of B2G for A/S provision, there are some important issues which must be addressed. This study has shown that, to integrate an economically feasible B2G system into the existing market and power grid, any practical DES system will require: 1) the utilization of an aggregative architecture to meet current industry standard reliability requirements [40], 2) the construction of low energy A/S call signals from existing ACE signals, 3) a lower percent call for B2G even if the pool of contracted A/S resources gets smaller, and 4) consideration of P/E ratios in the design of the B2G A/S call signal. If however, the grid operator would require higher percent calls from the DES devices this study has outlined a few potential possible mechanisms to improve reliabilities at higher percent calls. However, further analysis of these possible scenarios is required to determine their financial viability.

B2G has been proposed as a mechanism to improve grid stability and provide additional financial compensation to help offset the cost of electrifying transportation [45]. However, results from this study indicate that issues with B2G integration negatively impact both the grid system operator and DES owner, and must be addressed before B2G can be widely adopted.

The analysis framework developed for this study can provide a framework for a comprehensive evaluation of DES technologies, including important system interactions normally neglected in such studies. This analysis has shown that future B2G viability and economic studies require more detailed models and must take into consideration the four key requirements stated here.

CONCLUSIONS AND CONTRIBUTIONS

To realize a DES A/S system in the near future, the requirements of both the grid system operator and the vehicle owner must be satisfied. The grid system operator requires DES resources be compatible with both its command and contracting systems. Simultaneously, DES owners require a command and contracting architecture that maximizes a robust return on their investment. Previous studies [17, 45] have proposed the use of DES systems to provide A/S provision to improve grid stability and assist integration of renewable energy, while simultaneously providing income to offset the higher initial cost of PHEVs relative to HEVs. However, these studies to date have been based on assumptions which 1) aren't compatible with current A/S market procedures and regulations 2) disregard the stochastic availability of vehicles, and 3) use annual averaged market pricing rather than time series data.

This study has built upon the foundational framework of the previous vehicle-to-grid studies conducted and created a higher fidelity evaluation and model by:

- Accounting for current A/S market regulations and procedures required for A/S providers.
- Including time series stochastic vehicle driving models using the National Housing Transportation Survey (NHTS) data.

- Using time series A/S market pricing data.
- Incorporating battery SOC.
- Evaluating affects of non net zero energy A/S signals.

Results from this research show that in order to integrate a DES system into the existing market and power grid the DES system will require:

- An aggregative architecture to meet current industry standard reliability requirements.
- The construction of low energy automatic generation control signals.
- A lower percent call even if the pool of contracted ancillary service resources gets smaller.
- A consideration of vehicle performance degradation due to the potential loss of electrically driven miles (V2G only).
- The incorporation of power-to-energy ratios.

The analysis framework developed for this study provides a framework and high fidelity model allowing for a comprehensive evaluation of DES technologies, including important system interactions normally neglected in such studies. This analysis has shown that future DES viability and economic studies require more detailed models and must take into consideration the key requirements stated here. This study has used both publically available and confidential data for this analysis, however the model created in this study readily accepts different datasets which allows for easy evaluation of individual markets if the appropriate data is available.

V2G and B2G have been proposed as a mechanism to provide distributed storage to improve grid stability and assist integration of renewable energy, while simultaneously providing income to offset the higher initial cost of PHEVs relative to HEVs. However, results from this study indicate that integration requirements of V2G negatively impact both the grid system operator and vehicle owner, and must be addressed before V2G and B2G can be widely adopted.

REFERENCES

[1] T.H. Bradley, A.A. Frank, “Design, demonstrations and sustainability impact assessments for plug-in hybrid electric vehicles.” Sustainable and Renewable Energy Reviews, Volume 13, Issue 1, Pages 115-128, January 2009.

[2] EPRI, Analysis of Ultracapacitors for Use in a Grid-Connected Electric Vehicle, Palo Alto, USA, 2002.

[3] F. Kalhammer, Plug-in Hybrid Electric Vehicle Workshop at 20th International Electric Vehicle Symposium, Long Beach, USA, November 2003.

[4] N. Schofield, H.T. Yap, C.M. Bingham, IEEE (Institute of Electrical and Electronics Engineers) International Conference on Electric Machines and Drives, San Antonio, USA, 2005.

[5] G.J. Suppes, S. Lopes, C.W. Chiu, Int. J. Hydrogen Energy 29 (2004) 369.

[6] W.R. Warf, M.S. Duvall, B.D. Moran, A.A. Frank, 16th Annual Battery Conference on Applications and Advances, Long Beach, USA, January 2001.

[7] M. Duvall, N. Meyer, B.R. Huff, C. Carde, J. Parks, R. Schurhoff, Design and Development of the UC Davis Future Truck, SAE, Warrendale, PA, USA, 2002.

[8] L. Gaines, A. Burnham, A. Rousseau, D. Santini, Sorting Through the Many Total-Energy-Cycle Pathways Possible with Early Plug-in Hybrids, Center for Transportation Research, Argonne National Laboratory, Argonne, USA, 2007.

[9] M. Kintner-Meyer, K. Schneider, R. Pratt, “Impacts assessment of plug-in hybrid vehicles on electric utilities and regional US power grids, Part 1: Technical Analysis,” Pacific Northwest National Laboratory, 2006.

[10] Electric Power Research Institute, “Environmental Assessment of Plug-In Hybrid Electric Vehicles. Volume 1: Nationwide Greenhouse Gas Emissions.” EPRI Report, 1015325, 2007.

[11] S. Hadley, A. Tsvetkova, “Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation,” Oak Ridge National Laboratory Report, ORNL/TM-2007/150, January 2008..

[12] P. Denholm, W. Short, "An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles", National Renewable Energy Laboratory Report, NREL/TP-620-40293, October 2006.

[13] K. Parks, P. Denholm, T. Markel, "Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory", National Renewable Energy Labortory Report, NREL/TP-640-41410, May 2007.

[14] W. Short, P. Denholm, "A preliminary assessment of plug-in hybrid electric vehicles on wind energy markets," National Renewable Energy Laboratory Report, NREL/TP-620-39729, April 2006.

[15] A.Brooks, "Vehicle-to-grid demonstration project: grid regulation ancillary service with a battery electric vehicle," Report prepared by AC Propulsion for the California Air Resources Board and the California Environmental Protection Agency. Available at www.udel.edu/v2g, December 2002.

[16] K. Morrow, D. Karner, J. Francfort, "Plug-In Hybrid Electric Vehicle Charging Infrastructure Review," Idaho National Laboratory Report, INL/EXT-08-15058, November 2008.

[17] W. Kempton, J. Tomić, "Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy," Journal of Power Sources, Volume 144, Issue 1, Pages 280–294, June 2005.

[18] T. Markel, Communication and Control of Electric Vehicles Supporting Renewables, National Renewable Energy Laboratory (NREL), Golden, CO, USA, 2009.

[19] M.J. Scott, M. Kintner-Meyer, D.B. Elliot, W.M. Warwick, Impacts Assessment of Plug-in Hybrid Vehicles on Electrical Utilities and Regional US Power Grids. Part 2: Economic Assessment, Pacific Northwest National Laboratory, Richland, WA, USA, 2006.

[20] M.S. Duvall, Battery Evaluation for Plug-in Hybrid Electric Vehicles, Electric Power Research Institute EPRI, Palo Alto, USA, 2005.

[21] B. Kirby, E. Hirst , "Customer-Specific Metrics for the Regulation and Load-Following Ancillary Services," Oak Ridge National Laboratory Report, ORNL/CON-474, January 2000.

[22] M. Rowand, Plug-in 2009 Conference and Exposition, Long Beach, USA, 2009.

[23] W. Kempton, V. Udo, K. Huber, K. Komara, S. Letendre, S. Baker, D. Brunner, N. Pearre, "A Test of Vehicle-To-Grid (V2G) for Energy Storage and Frequency Regulation in the PJM System," Mid-Atlantic Grid Interactive Cars Consortium (MAGICC), November 2008.

[24] J. Taylor, A. Maitra, M. Alexander, D. Brooks, M. Duvall, Evaluation of the Impact of PEV Loading on Distribution System Operations, IEEE Power Engineering Society, Calgary, Canada, July 2009.
[25] M. Duvall, “How many plug in hybrids can a smart grid handle?” Plug-In 2008 Conference & Exposition, San Jose, CA, July 2008.

[26] W. Kempton, J. Tomić, S. Letendre, A. Brooks, T. Lipman, “Vehicle to grid power: Battery, hybrid and fuel cell vehicles as resources for distributed electric power in California,” University of California, Davis Institute for Transportation Studies, UCD-ITS-RR-01-03, June 2001.

[27] W. Kempton, J. Tomić, “Vehicle-to-grid power fundamentals: Calculating capacity and net revenue,” Journal of Power Sources, Volume 144, Issue 1, Pages 268–79, June 2005.

[28] F. Moura, “Driving Energy System Transformation With “Vehicle-to-Grid” Power,” IIASA Interim Report IR-06-025, International Institute for Applied Systems Analysis, June 2006.

[29] H. Turton, F. Moura, “Vehicle-to-grid systems for sustainable development: An integrated energy analysis,” Technological Forecasting and Social Change, Volume 75, Issue 8, Pages 1091-1108, October 2008.

[30] J. Tomić, W. Kempton, “Using fleets of electric-drive vehicles for grid support,” Journal of Power Sources, Volume 168, Issue 2, Pages 459-468, June 2007.

[31] R. Sioshansi and P. Denholm, "The Value of Plug-In Hybrid Electric Vehicles as Grid Resources," *The Energy Journal*, Vol 31, No 3, pp 1-22, 2010.

[32] T.B. Gage, “Development and Evaluation of a Plug-in HEV with Vehicle-to-Grid Power Flow,” CARB Grant Number ICAT 01-2, www.smartgridnews.com/artman/uploads/1/sgnr_2007_12032.pdf, December 2003.

[33] North American Electric Reliability Corporation, “Generation Availability Report,” http://www.nerc.com, March 2009.

[34] National Household Transportation Survey, http://nhts.ornl.gov/.

[35] California Independent System Operator (ISO) Open Access Same-Time Information System (OASIS, http://oasishis.caiso.com/.

[36] California Independent System Operator Corporation, “Market Issues & Performance, 2007 Annual Report”.

[37] California Independent System Operator Corporation, “Market Issues & Performance, 2008 Annual Report”.

[38] B.D. Williams and K.S. Kurani, “Commercializing light-duty plug-in/plug-out hydrogen fuel cell vehicles: “Mobile Electricity” technologies and opportunities,” *Journal of Power Sources* ***166***, pp. 549–566, 2007.

[39] R. Carlson, et al,. “Testing and Analysis of Three Plug-in Hybrid Electric Vehicles.” SAE 2007-01-0283, SAE World Congress, Detroit, MI, April 2007.

[40] C. Quinn, D. Zimmerle, and T.H. Bradley, "The effect of communication architecture on the availability, reliability, and economics of plug-in hybrid electric vehicle-to-grid ancillary services," Journal of Power Sources, vol. 195, no. 5, pp. 1500-1509, March. 2010.

[41] T.W. Anderson, L.A. Goodman,m “Statistical Inference About Markov Chains,” Annals of Mathematical Statistics, Vol. 28, No.1, pp. 89-110, 1957.

[42] U.S. Energy Information Administration (EIA), “Short Term Energy Outlook”, http://www.eia.doe.gov/emeu/steo/pub/contents.html, Accessed March 2011.

[43] Chevrolet, “2010 Chevrolet Volt Features and Specs”, http://www.chevrolet.com/volt/features-specs/, Accessed March 2011.

[44] R. Entriken, D. Hawkins, K. Yagnik, N. Taheri, “Prototype Method for Analyzing Regulation by Limited Energy Storage,” EPRI Webcast, April 2010.

[45] B. Williams and T. Lipman, “Strategy for Overcoming Cost Hurdles of Plug-in Hybrid Vehicles in California,” Transportation Research Record, Vol. 2191 / 2010, pp. 59-66, 2010.

[46] Eyer, J., Corey, G., “Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide,” Sandia National Laboratory, SAND2010-0815, http://prod.sandia.gov/sand_doc/2010/100815.pdf.