A Test of Vehicle-to-Grid (V2G) for Energy Storage and Frequency Regulation in the PJM System

Results from an Industry-University Research Partnership

Willett Kempton,[*] Victor Udo,[†] Ken Huber,[§] Kevin Komara,[§] Steve Letendre,[¶]

Scott Baker,[*] Doug Brunner,[*] & Nat Pearre[*]

* University of Delaware
† Pepco Holdings, Inc
§ PJM Interconnect
¶ Green Mountain College

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Executive Summary

This report documents a practical demonstration of Vehicle-to-Grid power, providing real-time frequency regulation from an electric car. Vehicle-to-Grid (V2G) presents a mechanism to meet key requirements of the electric power system, using electric vehicles when they are parked and underutilized. While V2G is expected to have several applications, the most economic entry for this green innovation is the market for ancillary services (A/S). The highest value A/S is frequency regulation (in many ISOs, including PJM, this service is simply called "regulation" and we will use that term subsequently). In areas with deregulated electricity markets, regulation can have average values of \$30-\$45/MW per hour, with hourly rates fluctuating widely around that average.

A second market of interest is spinning reserves, or synchronous reserves, with values in the range of \$10/MW per hour, but much less frequent dispatch. The primary revenue in both of these markets is for capacity rather than energy, and both markets are well suited for batteries as a storage resource because they require quick response times yet low total energy demand. Additionally, V2G can provide distribution system support when there is a concentration of parked V2G cars, along overload elements in the distribution system.

A later application, when parked V2G-capable cars are connected and aggregated in large numbers, would be to use them as dispersed energy storage for intermittent but renewable resources such as wind and solar. The results of the study show that V2G, in addition to providing valuable grid servies, could also prove to be a prominent application in the global transition to the emerging green and sustainable energy economy.

A fully functional, freeway-capable electric vehicle was used in this study. Its power electronics are designed to both drive the vehicle and allow for high-power exchange with the electric grid. We modified this vehicle by adding controls and logic to make it respond to the PJM real-time signal for regulation.

The data and resulting graphs show the ability of the car to provide regulation in addition to zero emission local commute driving. This is a technology proof of concept with a single vehicle. Current work is directed toward developing dispatch of about a half-dozen vehicles. To move from a technology demonstration to commercial application, the next step would be a business model development at the scale of 100 to 300 vehicles.

The report is comprised of six sections. Section I provides an introduction of the research initiative. Section II covers the infrastructural background concepts involved in V2G application for regulation. Section III calculates the commercial value of V2G as demonstrated by the existing ancillary service markets. Section IV reviews distribution issues, including service drop and distribution transformer power capacity. Section V describes the methodology used in the study. In Section VI, we present the experimental results of the test. Finally, in Section VII, we provide concluding remarks and the proposed future work that will be needed to make this green, sustainable and energy security/independence innovation a reality.

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Section I: Introduction

With the increasing cost of petroleum and growing acceptance of global climate change as a critical environmental problem, policy makers, engineers and business leaders are searching for alternative energy solutions. Re-electrification of automobile transportation and enhancement of the existing power system grid is one such solution.

The electric power system is a complex and critical infrastructural system, yet it lacks energy storage capacity, so electricity must be simultaneously produced and consumed.[1] Automobiles contain distributed energy storage; today, that storage is in the form of liquid fuel but we, and much of the industry, anticipate a shift to electricity.[2] Both the power system and automobiles are designed to meet peak demands – peak electric use for the power system and the power to accelerate to full speed for the automobile. The actual level of utilization of both assets is far less than 100% most of the time, especially for local commute vehicles for individual urban families.

Although the electric power system industry has undergone restructuring, the fundamental engineering aspects of the system remain the same. The load and the generation in the system must be balanced at all times. To accomplish this real time balancing, several functions have been established to manage the system effectively.

With restructuring, some of the balancing functions, such as spinning reserve and regulation, have become marketed services. Other functions, such as voltage control and reactive power management, are at the distribution level and remain the responsibility of the local load-serving entity. Spinning reserve and regulation are termed ancillary services, abbreviated A/S, in well-established power markets such as PJM and other Regional Transmission Organizations (RTOs) or Independent System Operators (ISOs).

The biggest challenge with electric vehicles has been the battery that stores the energy needed to drive the vehicle, with challenges of both cost and lifetime. There has been significant research to improve both variables and it is anticipated that if adequate public policy is implemented, both costs will become competitive within four to seven years.[*] Now is the time to establish the business models for electric vehicle interaction with the grid, so that the business is developed and ready for rapid expansion as electric vehicles enter the market place in the coming years.

AC Propulsion of California has designed an electric drive system using mass-produced 18650 lithium-ion batteries and a patented power electronics unit that is ideally suited for Vehicle-to-Grid (V2G). They have also created electric and plug-in hybrid vehicles by converting existing gasoline vehicles. Other manufacturers, including global auto manufacturers such as Renault/Nissan, Mitsubishi Motors, and BMW, are producing all-electric vehicles for some markets and have announced full-scale production plans for all-electric vehicles.

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[*] This lifetime prediction is based on current production of Li cells that achieve 7,000 cycles at 100% DOD, much more at shallower DOD (e.g. A123's testing, reported on http://www.a123systems.com/technology/life). The cost prediction is based on the current wholesale cost of today's Li cells, $250/kWh. The time frame suggested is the timing by which several major auto manufacturers have announced production of tens or hundreds of thousands of vehicles requiring large batteries.

Based on the above background, Pepco Holdings Inc. (PHI) co-funded the theoretical analysis of the concept of V2G, and evaluation of V2G for PJM, at the University of Delaware in 2003. This effort was built on the seminal work at the University, published in 1997,[2] and a burst of activity in 2000-2001 funded jointly by the California Air Resource Board and the LA Department of Water and Power. The results of those analyses were published in international journals between 2002 – 2005.[3, 4, 5] We here use the term V2G to refer to provision of two-way electrical service from a vehicle to the electrical grid, under control of a grid operator's signal. In May 2007, the University of Delaware, PHI and other partners, established the Mid-Atlantic Grid Interactive Car Consortium (MAGICC) to prove the V2G concept. MAGICC activities are funded by awards of $200,000 of the Delaware Green Energy fund, $250,000 from PHI, and $150,000 from Google.org, for R&D and demonstration purposes.

At the University of Delaware, on October 18, 2007, a team of PHI, PJM and University engineers and officials successfully interconnected an AC Propulsion "eBox" (a converted Toyota Scion xB) to the PJM grid using a direct signal from the PJM control center to dispatch the vehicle as a regulation resource, like traditional generators. The set-up and key players on the research are captured in Figure 1. This technical breakthrough was demonstrated publicly for the first time on October 23, 2007 to FERC Commissioners and staff at their Washington offices. The next sections cover the engineering, market and experimental results of this proof of concept study.

Figure 1: The AC Propulsion eBox plugged in to a meter board built for the experiment, with standard meter and breakers. The open hood shows the AC-150 power electronics unit, which both drives the car and manages the bidirectional flow of electricity to the grid. The laptop in the foreground is a portal to the PJM control system. Photo taken during the first experiment controlling vehicle power by an ISO's regulation signal. Present were (L to R): Willett Kempton, Len Beck, Doug Brunner, Ken Huber, Victor Udo, Kevin Komara, and Mark Holman, as well as Jackie Piero (taking photograph).

Section II: Electric Power System Background

Power System and Regulation

The power system infrastructure is essentially a network of wires and sophisticated switches controlled by high-speed computers. Its basic function is to move power from where it is generated to where it is utilized. The power system must balance load and generation, or demand and supply while the energy flow is in the form of real and reactive power.

The system frequency must be kept at, or very near to, its nominal frequency – 60Hz in the United States, or 50Hz in many other countries. Any deviation from this requires action by the system operator. If the frequency is too high, that means there is too much power being generated in relation to load. Therefore, the load must be increased or the generation must be reduced to keep the system in balance. If the frequency is too low, then there is too much load in the system and the generation must be increased or the load reduced. As mentioned previously, these adjustments are called frequency regulation, or simply "regulation."

Regulation is performed at the local level but accomplishes the desired effect on frequency at the grid level. Sufficient accumulation of adjustments to local generators or loads will adjust the frequency of the entire interconnect. A more detailed description of this multi-layer and multi-level hierarchical nature of the power system and load and frequency control can be found elsewhere.[2, 6, 7]

The Value of Storage to the Grid

With the restructuring of the power system functions, the primary role of the system operator is to balance reliability and cost.[8] Most Americans take power availability for granted, but this must be designed in, at additional cost. Most power system design and operations are engineered with extra margin, to allow for certain loss probability. Large scale inexpensive storage would improve today's grid, by increasing reliability and reducing power system costs.

As the power system develops more renewable generation, the need for electrical storage is likely to increase. Today's predominant renewable power generation fluctuates with the input (for example, sunlight or wind). At today's levels, fluctuating renewable generation is adjusted for with existing mechanisms (for example, by adjusting today's fossil generators up and down to compensate). At higher levels of renewable generation, storage, transmission, and controllable loads all become useful resources to smooth fluctuating power. Electric vehicles have the ability to provide two of these functions – energy storage and controllable loads.

Electric Vehicles and Grid Interconnection

The average US car is driven only one hour a day (in 2001, the average US driver drove 62.3 minutes/day).[9] In other words, these cars are parked most of the time doing nothing. Suppose those cars were a source of energy storage the remaining 23 hours? Now, let's also suppose the car can be driven without gas and can store up the needed energy when the wind is blowing or the sunlight is at maximum. Such cars enable pollution free driving while also providing value, and thus potentially payments, for providing electric services to the electric grid.

The above scenario is not far-fetched. The pieces are available today but the cost of storing the energy in the car – through battery technology – is still high. Our hypothesis in this study is that, given the right market value, the above scenario can be realized in the next few years. As a transition, we postulated that the regulation market could provide the needed funds to jump-start the process if appropriate public policy is implemented.

To prove this, we demonstrate that an electric vehicle can provide regulation. An electric vehicle can be used as both a load and a generating source to balance the system frequency by charging the battery when there is too much generation in the grid and acting as a generator by discharging the battery when there is too much load in the system.

In addition to regulation, vehicles can provide other services including: spinning reserve, which contracts for the availability to provide power during unplanned outages of base load generators; back-up service, where one or more vehicles can be connected together to serve as a micro-grid during power outage in a given neighborhood; and peak management, when there are a significant number of V2G cars parked and connected to help reduce system peak. With enough V2G-capable electric vehicles, a truly dispersed storage for electric energy will emerge.

Section III: Commercial Value of V2G for Ancillary Services

Ancillary services (A/S) support the stable operation of the electric system. These ancillary service markets are managed by the Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) and may differ in their control method, response time, and duration of power dispatch, contract terms, price and terminology. Ancillary services account for 5-10% of electricity cost, or $12 billion per year in the US; 80% of these payments are for regulation and spinning reserve.[3] The two ancillary service markets specifically analyzed here are regulation and spinning reserve.

Regulation

Based on our prior analyses, the most valuable A/S market is the regulation market (also referred to as frequency regulation or, in parts of the E.U., called regulating power). Regulation is responsible for maintaining the frequency of the grid at 60 Hz. In the US, this is accomplished by using a real-time communication signal directly controlled by the grid operator. The regulation control signal can call for either a positive or negative correction, often referred to in the industry as "regulation up" and "regulation down", respectively. If load exceeds generation, frequency and voltage drop and the ISO/RTO relays a signal to generators requesting regulation up. When generation exceeds load and frequency increases, the ISO/RTO requests regulation down and asks generators to reduce generation. The timescales of the regulation signal are much smaller than the daily fluctuations in load associated with ramping up and down at the beginning and end of the day, respectively. Figure 2 shows the difference between the hour timescale of economic dispatch (for example, ramping up in the morning) and the minute-by-minute adjustments of regulation that take place at all hours of a given day.

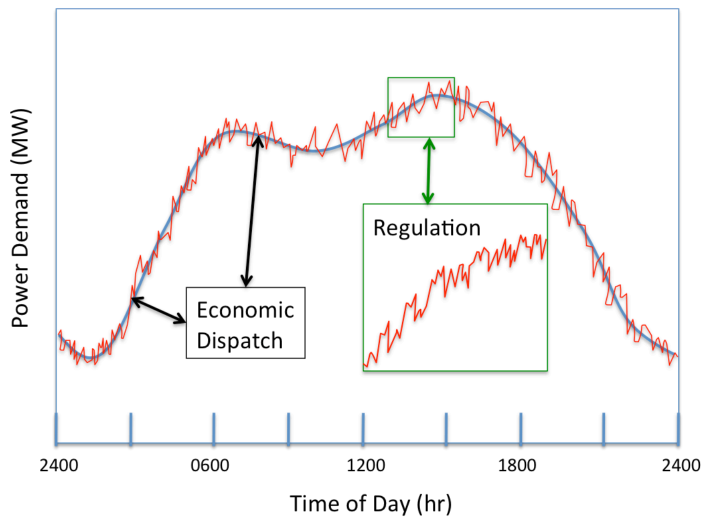

Figure 2: The rapid adjustments of regulation contrasted with the economic dispatch associated with slower load changes, such as ramping up in the beginning of the day (area between the black arrows). Regulation takes place during all hours of the day, unlike peak load, it does not necessarily increase during times of peak demand.

Regulation is contracted capacity on an hourly basis, and dispatched on intervals between four seconds and one minute, depending on jurisdiction. Figure 3 shows one day on the California ISO, with both the contracted amount and the Processed Area Control Error (Processed ACE) shown on the same scale[10]. Regulation is dispatched to correct for the ACE, but the generator-specific regulation signal will vary from ACE, for example, it may be tailored to the type and ramp rate of the generator. Nevertheless, ACE is a good measure of the actual system need for regulation, and figure is representative of the distinction between contracted regulation and dispatched regulation – typically the dispatched amount is much less than the contracted amount. Also, neither regulation up nor regulation down is dispatched for a long duration, typically it is dispatched only a few minutes at a time. This is a good application for a battery connected by a high power connection, as the battery charges or discharges slightly, thus incurring much less wear than deep cycles. If sized adequately, and if the signal is indeed balanced in the long run, the charge should only fluctuate around its initial charge state; it usually should neither completely drain nor fill. Sizing of both battery kWh and V2G contract are important, to ensure that the wear from regulation cycling is substantially less than the value of this service.

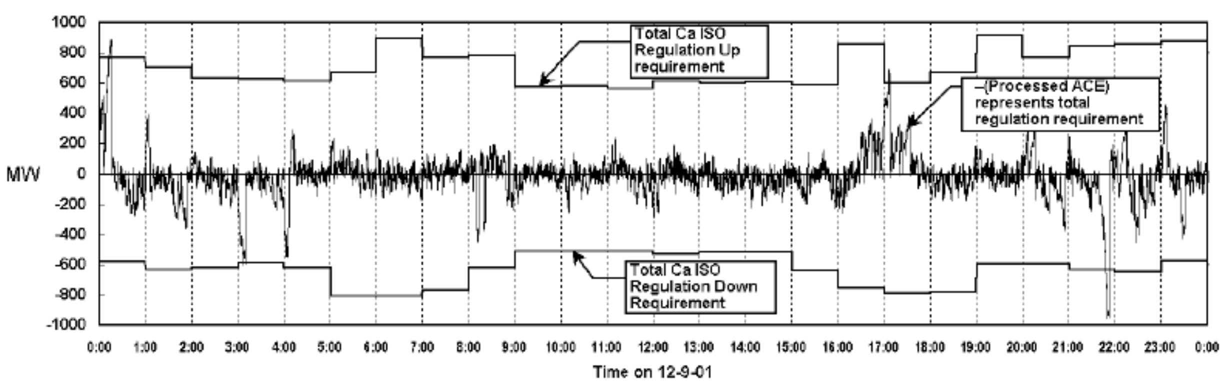

Figure 3: Hourly contracted regulation (solid, blocked line), and regulation dispatch requirement (jagged signal line, which is Processed Area Control Error, PACE) for the California ISO. (From Figure 10 in Brooks[10]).

In the PJM Interconnect RTO, regulation is controlled by PJM via an Automatic Generation Control signal (AGC, referred to hereafter as the regulation signal). PJM can call on generators for regulation control as often as hundreds of times per day and requires a response time of not more than five minutes. PJM has a minimum power capacity contract size of 1 MW and requires contracts to provide equal amounts of regulation up and regulation down. Other ISOs contract for regulation up and regulation down separately and/or for differing amounts. The market size for contracted regulation services in PJM is 1% of peak load, a maximum of 1,500 MW, with a typical amount of about 900 MW. Contracted amounts change hourly—dispatch is much more frequent, and usually smaller, than the contracted amount, as in Figure 3.

Regulation is contracted and paid for the available power capacity at any one hour, with a separate and typically much smaller payment for the amount of energy provided. This means a generator sitting idle with the ability to provide regulation is paid the same capacity payment as the generator that was called upon to provide regulation. There is also an additional payment for energy generated, typically based on the real-time locational-based marginal price (LBMP). Table 1 shows the average annual market clearing prices for regulation across five different grid operators in the US from 2004-2006.

Table 1. Average annual market clearing prices for regulation among five US grid operators from 2004-2006

	Regulation ($/MW-h)		
	2004	2005	2006
PJM	$42.75	$49.73	$32.69
RTO-NE	$28.92	$30.22	$24.02
NY ISO	$22.59	$39.21	$51.26
ERCOT	$22.66	$38.07	n/a
CAISO	$29.00	n/a	$36.04

Spinning Reserve

Spinning reserve is generation capability that can provide power to the grid immediately and reach full capacity within 10 minutes when called upon by the ISO/RTO. This power must be provided by equipment electrically synchronized with the grid. Typically requests for this generation to provide power are made around 20-50 times a year. They are paid for their ability to provide power during an unplanned event, such as a generator failure, and are also paid for the energy (MWh) generated during a call, based on the LMBP. For example, a 1 MW generator kept “spinning” for 24 hours would be sold as 1 MW-day. When called upon, spinning reserve events can vary greatly in duration. In 2007, PJM had 45 spinning reserve events with an average duration of 14 minutes. The minimum duration was five minutes and the maximum was 51 minutes. Table 2 shows the average annual market clearing prices for spinning reserves capacity across five different grid operators in the US.

Table 2. Average annual market clearing prices for spinning reserve among five US grid operators from 2004-2006

	Spinning Reserve ($/MW-h)		
	2004	2005	2006
PJM	$14.86	$14.41	$14.94
RTO-NE	n/a	n/a	n/a
NY ISO	$2.38	$7.57	$8.25
ERCOT	$8.32	$16.61	n/a
CAISO	n/a	n/a	$9.61

Ancillary Service Markets and the V2G Vehicle Value Proposition

Research by Willett Kempton and Jasna Tomic at the University of Delaware and Steven Letendre of Green Mountain College indicates that energy stored in batteries, particularly in V2G-enabled electric vehicles, is almost ideally suited to serve the regulation and spinning reserve markets.[2, 3, 4, 5] To summarize those articles, the inherent quick response time from a battery storage system was predicted to more than meet the response time requirements of PJM or any other system operator (this prediction is experimentally validated subsequently in the present report). However, contracts may require sustained output (e.g. an hour for spinning reserves), so, given limited kWh energy storage, that would lead to the capacity of storage resources like V2G being downrated below their maximum power capacity. Historic system operations demonstrate that hourlong dispatch is rarely required of a resource providing these services. Thus, some revisions to the criteria to qualify resources to provide grid regulation and spinning reserve may be in order to most effectively use storage resources in wholesale A/S markets. As shown in Tables 1 and 2, the potential value per vehicle is much greater when selling regulation as opposed to spinning reserve; in addition, the cycling of the storage device is much more frequent for regulation than spinning reserve.

In either A/S market, the maximum value potential is realized by having a high power connection to the vehicle with bidirectional capabilities. Since regulation is paid for in terms of power capacity, a vehicle able to provide 15 kW is much more valuable than a vehicle only able to provide 2 kW*. In addition, the ability to transmit that power bidirectionally means that the vehicle can 'sell' both regulation up and regulation down from a zero point. If only unidirectional power flow were possible, regulation down for example, the battery would quickly be filled, at which point the vehicle could be of no further service to the grid operator. (A similar limitation applies when only providing regulation up, in which case the battery would drain.) Although spinning reserve and regulation can, in principle, be provided by a charging vehicle through modulation or interruption of the charge, the value generated is much smaller because it

* More precisely, reliable V2G capacity is a function of the power connection, duration required by the power market, and the energy storage of the battery. Formulas to compute this are in the 2005 "Fundamentals" article by Kempton and Tomic[4].

is only an offset from an average charging rate (e.g. 1 kW) rather than from the maximum capacity (e.g. 15 kW).

Figure 4 shows the ten-year present value of revenues produced by one V2G vehicle given the following assumptions:

- The vehicle is plugged and providing V2G services 80% of the time, that is, 7,008 hours per year. The other 20% of the time the car could be unplugged, being driven, or the vehicle owner could choose not to provide V2G services.
- Average market-clearing price for regulation is $40/MW-h and spinning reserve is $10/MW-h.
- The vehicle is capable of bidirectional power flow.
- There exists a 7% discount rate.
- Only gross revenues from capacity payments are shown. For net, one would subtract battery life costs from increased cycling, round-trip energy losses, standby power draw, as analyzed elsewhere[4,5].

This figure shows the much higher value of a high power connection in both energy markets. The figure also illustrates the higher potential revenue in the regulation market, compared with spinning reserves. We do not analyze additional value streams that do not already exist as wholesale markets (e.g. reactive power management, peak load reduction for distribution support, micro-grid emergency power, etc).

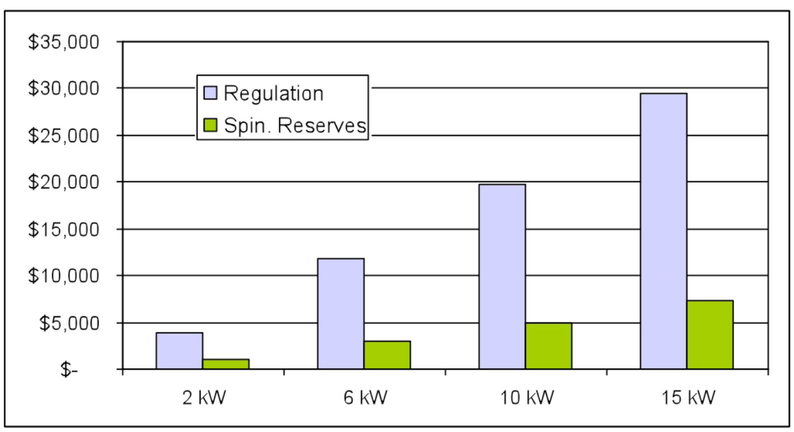

Figure 4: Discounted present value of gross revenues generated from selling regulation and spinning reserve, at varying power levels.

The incremental capital cost of high power (15 kW) charging is typically much less than the incremental value for either market shown in Figure 4. Onboard costs for high power may, paradoxically, be negative. That is, the design approach historically taken by vehicles with 6.2 kW grid connection and lower has been to build separate electronics for one-way charging. By contrast, for 10 kW and higher charging, the approach taken by AC Propulsion and companies buying or licensing their design (e.g. Tesla and BMW) has been to use the existing drive electronics for charging from (as well as discharging to) the grid. This results in complete elimination of one device, a separate charger, resulting in an overall reduction in vehicle cost. Offboard, there is the cost of plug and building circuit, plus there could be capital costs in the electric power system if upgrades are needed to the distribution system for higher power. The building or "customer side" costs are analyzed elsewhere[5]; the possibility of distribution system costs is evaluated in the next section.

Section IV: Distribution Infrastructure Considerations

The above revenue discussion only considers the existing value of regulation and spinning reserve. The cost and value for integrating the vehicle into the distribution system was not considered and neither were the environmental and storage values.

For each of the distribution systems in which the car has been tested, no distribution system problems were identified. However, given that V2G-based regulation implies that the car must be ready to function either as a generator or a load at any given time, the distribution system must have sufficient capacity to supply and accept power in and out of the car. Experienced distribution engineers who have reviewed the technology and the test sites see a V2G car no differently than a distributed generator and/or additional load. That is, the service drop (the last wire that connects the utility to the customer), the distribution transformer (on a pole or pad mount), the primary lateral and the three phase feeders, must all be checked to ensure that they are properly sized to accommodate the car's power capacity.

Of these four distribution system components, the service drop and the pole mount transformers will have the highest impact on the cost of integrating a 10 kW to 19 kW car into the distribution system. They are the components most likely to need upgrading. The existing inventory of these types of transformers in any distribution system may have many transformers with capacity smaller than the 16-19 kW capability of the car. Some transformers are rated as low as 5 kVA. However, for energy efficiency and conservation, many utilities are discontinuing the lower rated transformers and are standardizing on fewer sizes.

In the three PHI distribution utilities, for example, the existing pole mount or overhead transformers are standardized at 15, 25, 50, 100, up through 500 kVA for single-phase applications, with the 15 kVA now being phased out. Pole mount transformers might typically serve three single-family residences. Pad mount transformers, which can also serve underground power lines, are standardized at 25, 50, 100 and 167 kVA for single-phase applications. Three phase transformers are standardized at 75 through 2500 kVA.

For the first vehicle on a distribution transformer, if the 19 kW is treated as an additional load to an existing transformer with say three or more residential customers, it would require a rating of at least 50 kVA. This 50 kVA rating will assume that the total coincident peak of the exiting load is not more than 30 kW thus ensuring the accommodation of the 19 kW for the car. These load allocations will meet the standard of most distribution systems, which are designed to meet peak demand. However, it should be noted that under regulation the car can act as a load and as a generator at any time. When it acts as a generator, the loading of the transformer can be reduced by as much as the 19 kW the car supplies. (Anti-islanding is discussed subsequently.) When it acts as a load, the transformer would be fully loaded during the time of the assumed coincident peak.

As a 19 kW load addition, a typical V2G car installation might cost $2,000 to install including the service drop, and upgrade from say a 25 kVA pole mount transformer to 75 kVA. Service drop costs vary widely, and could increase the costs above this example figure. Bigger size transformer upgrades, which may also require feeder upgrades, are typically covered under a distribution system planning expansion. Workplace V2G infrastructure per vehicle costs could be lower if a single transformer were put near the parking lot for multiple vehicles; in any event, workplace system upgrade costs will be covered as commercial project using appropriate rate and revenue test process of a typical utility.

On the customer side of the meter, paid by the customer or aggregator, our small sample of test residential locations is in the $500 to $800 range for a complete installation by a licensed electrician, with parts and inspection. Adding the "charging station" envisioned for some cars* may cost up to $800 additional. This could be higher in a commercial building or location where the parking is far from electrical service, or on the other hand it could be lower if multiple plugs are installed together along a single line. Some or all of these costs could arguably be attributed to the base vehicle cost, or the convenience cost of fast recharge, rather than a cost addition for V2G.

The above analysis takes the approach of treating high-power electric vehicles as potential coincident load. This is a safe initial approach, consistent with existing electric industry procedures to accommodate new customer loads. In the longer term, as the market develops, the intelligence and control required for ancillary services provision could also be used to reduce costs for distribution system or service upgrades. As an illustrative example, suppose that a vehicle capable of 19 kW bidirectional power (and sufficient battery size) is proposed for a residence with a 25 kVA transformer and potentially 20 kW of coincident loads from three residences on that transformer. The vehicle could be authorized only for a lower charging level (up to 5 kW), but allow its full 19 kW of discharge. Therefore, this vehicle could participate in a symmetrical A/S regulation market at only 5 kW, but could participate in the A/S spinning reserve market at 19 kW. Such limits would have to be enforced by non-overridable software controls to securely prevent overload. The same vehicle might participate at higher power levels while parked at work.

Distribution system considerations could be modified, potentially reducing costs, if the signaling is smart about the distribution constraints. For example, the power limits could be dynamic, based on current loads, transformer temperature, and vehicle authorizations at the other residences on the same distribution transformer and feeder. A potential problem might be that if many cars are on the same distribution feeder and are switched at once, step voltage limits could be exceeded, a problem that could be solved by upgrading distribution system regulators or by phased switching of vehicles on the same feeder. Such controls are technically straightforward and may be consistent with the emerging smart grid approach, but they would require thorough

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* For example, a charging station might not activate the 240 V power until a pilot circuit is closed. Charge station costs discussed here assume on-board charging electronics, as noted earlier.

fault analysis as well as company and regulatory review, then establishing a registration and approval process. Our point is not that such control and authorization are needed, rather that in the long term they represent an alternative to making distribution system upgrades for every case.

Other infrastructure considerations include the addition of communications, transmission system, and parking lots enhancements. Communications can be provided via building internet router and power-line carrier (as we have done) or by a cell phone service. Since part of the goal of electric vehicles with V2G is to reduce the load on, and pollution from, electrical generation, intelligently-designed electric vehicles should increase electric energy use but do so off-peak, thus minimizing need to increase capacity for either generation or transmission. If large numbers of plug-in cars create significant new load, transmission enhancements will need to be analyzed as part of larger scale system planning or regional transmission planning. Existing parking lots for participating organizations or multi-family residences may have to be re-arranged to provide power to V2G parking spots near electrical service. These challenges are not different from typical residential and commercial customer adjustments for other market trends such as previous increases in vehicle size, or new loads from facility expansion or equipment upgrades.

Section V: Testing Methodology and Process

Testing Components Description and Set-up

To test electric vehicles as potential energy storage for regulation in the PJM System, five main components were required: an electric vehicle with V2G capability, a communication protocol and the equipment (laptop) to connect with PJM SCADA system, an adequate electrical outlet with metering panel, and data storage (server). The major components of the methodology and the needed setup for testing and data collection are described below:

1. V2G-Capable Car
    - The eBox started as a stock, manual transmission, 2006 Scion xB. At AC Propulsion in San Dimas, CA, the gas tank, fuel lines, engine, transmission, emissions controls and exhaust system were removed.
    - AC Propulsion then installed an AC Induction motor, AC-150 power electronics unit, and custom built battery. Battery installation required removal of much of the belly-pan of the vehicle to fit a 'T'-shaped battery down the central tunnel and a separate battery pack under the rear seats. A plug was added to the vehicle for charging and discharging.
    - The vehicle was equipped with a 355 volt, 35 kWh battery.
    - The electric drive train has the ability to accelerate from 0 to 60 mph in less than eight seconds and a tested "real world" range of 120-150 miles on a charge.
    - With the AC-150 power electronics unit built by AC Propulsion, which controls the conversion of high-voltage DC into an AC current to power the electric motor the vehicle also has the ability to: a) operate as a DC-AC inverter from the battery to the grid, and b) to match voltage and precisely synchronize the resulting AC signal to the line phase.
    - The onboard power electronics are thus intrinsically capable of supplying power to the grid in phase with an existing AC signal. To supply A/S therefore requires taking the line

phase from the grid connection, rather than from the motor controller, taking the power signal from the regulation signal instead of from the throttle, and shunting the resulting power not to the electric motor but to the grid.

2. Communication Protocol and Equipment
   - At the University of Delaware an Arcom Director (an industrial communications gateway also used by conventional generators providing ancillary services) was installed in the vehicle to receive the PJM signal and to control charging and discharging.
   - The test vehicle, currently responding in real-time to PJM's regulation signal, is capable of providing 19 kW and of responding on sub-second timescales. To make this useful, the University had added communications from PJM to the vehicle via a powerline-carrier ethernet bridge connected to the charging line circuit (this could alternatively be set up with a cell-phone or other signal medium).
   - The command signal is lifted from the power line and decoded onboard the car by the Arcom Director. Additionally, the Arcom Director has been programmed to automatically send data to the University of Delaware's server whenever it is connected to the internet.
   - The University of Delaware designed a software protocol for device communication, and coordinated software modifications by software engineers from AC Propulsion (of the vehicle management system), Arcom (of the communications gateway) and PJM (of the A/S dispatch system).
   - A new generator was added to the queue for ancillary services called 'V2Gcar1'. See Figure 5.

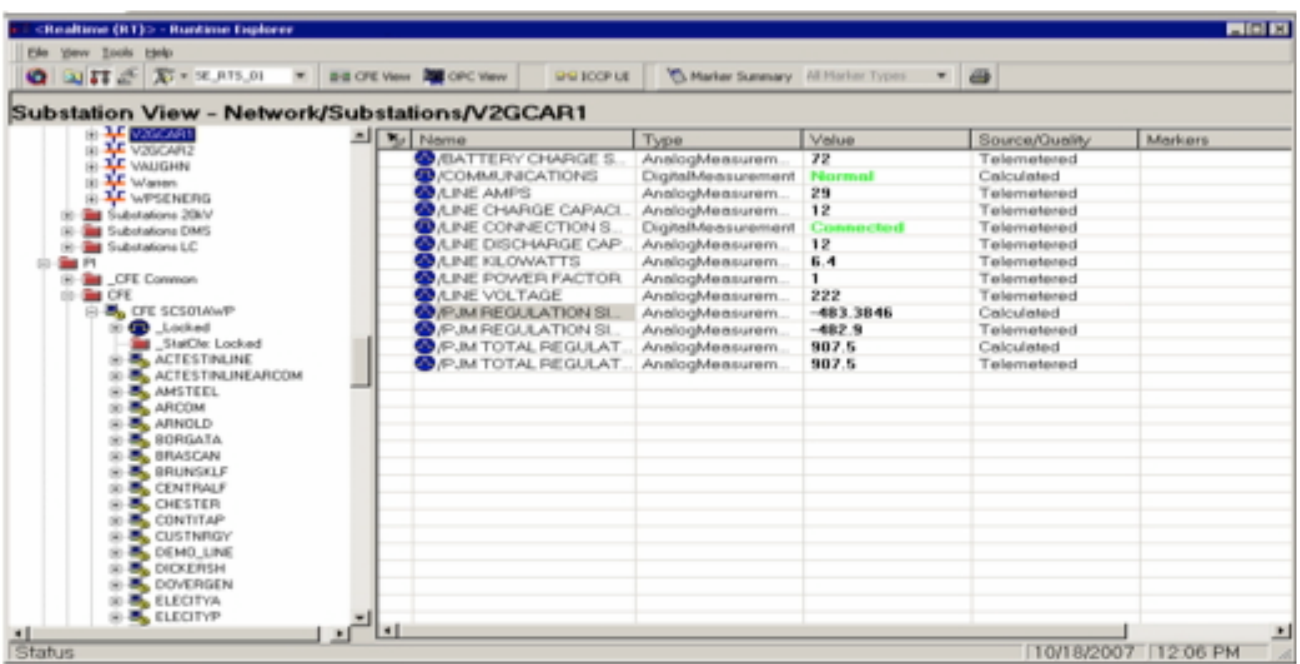

Figure 5: On PJM's SCADA, V2GCAR1 is shown as a generator, which is plugged in and responding to the encrypted signal used by PJM to control generators' output.

3. Metering Panel
    - For demonstrations, providing a visual display of the bidirectional flow of power into and out of the car, a meter board (Figures 1 and 6) was constructed by PHI electricians at their Delmarva Power facility in Newark, Delaware. The meter board provides a standard utility revenue meter, as well as a compact working display with a residential main breaker, circuit breakers, and both 110 volt and 208/240 volt outlets. Figure 6 shows the set-up that was demonstrated to FERC in Washington, D.C.

4. Adequate Outlet
    - High-power charging points with powerline ethernet connectivity were installed on the University of Delaware campus (80 amp, 208 volt, or 16.6 kW), and at a private residence (50 amp, 240 volt, or 12.0 kW), both values below the maximum 19.2 kW capacity of the AC-150. See Figures 1 and 6.

5. Data Storage on Server
    - The University of Delaware set up data transmission from the car over the internet and created automated programs running on a dedicated server to receive and catalog that data. When the vehicle is plugged into a powerline ethernet equipped plug, vehicle data is transmitted to the University of Delaware in real time approximately every ten seconds. Battery state of charge (SOC), plug capacity, battery voltage, line current, regulation signal, and some additional variables are transmitted to and stored in a University server. This server data is the basis of the graphics in the next section.

Figure 6: Typical set-up for demonstrations. Here, a Vehicle-to-Grid demonstration at FERC in Washington, D.C. Operating off of the PJM regulation control signal (monitored by the laptop computer), the vehicle showed bidirectional flow of electricity using standard residential electric meter and breaker boxes shown at right.

Using the set-up described above, a prototype eBox electric vehicle was loaned to the partnership by AC Propulsion. After very successful initial tests with the loaned vehicle (including integration into the PJM SCADA system shown in Figure 5), the University of Delaware, with the support of the Delaware Green Energy Fund, subsequently purchased an eBox. Plans for additional vehicles have been made that will be used to test a fleet aggregation business IT platform in the next phase of the study.

Safety First: Anti-Islanding Test

"Anti-islanding" is the ability of a generator to avoid supplying power to the grid if a circuit is opened. It is a necessary feature of distributed generation capacity for two reasons. Without it, excessive current could be drawn from the device, potentially damaging power electronics. More importantly, line workers may assume that circuits on the load side of an open line or open switch will not be energized – if there is an active "island" of energized lines, this poses a hazard to line workers. For distributed generation, anti-islanding requirements and test criteria are defined by IEEE draft standard 1547. The eBox has been tested by the US DOE's National Renewable Energy Laboratory and passed all IEEE 1547 tests for anti-islanding. This section describes additional testing we did with partners as an extra step to insure anti-islanding under our installed field conditions.

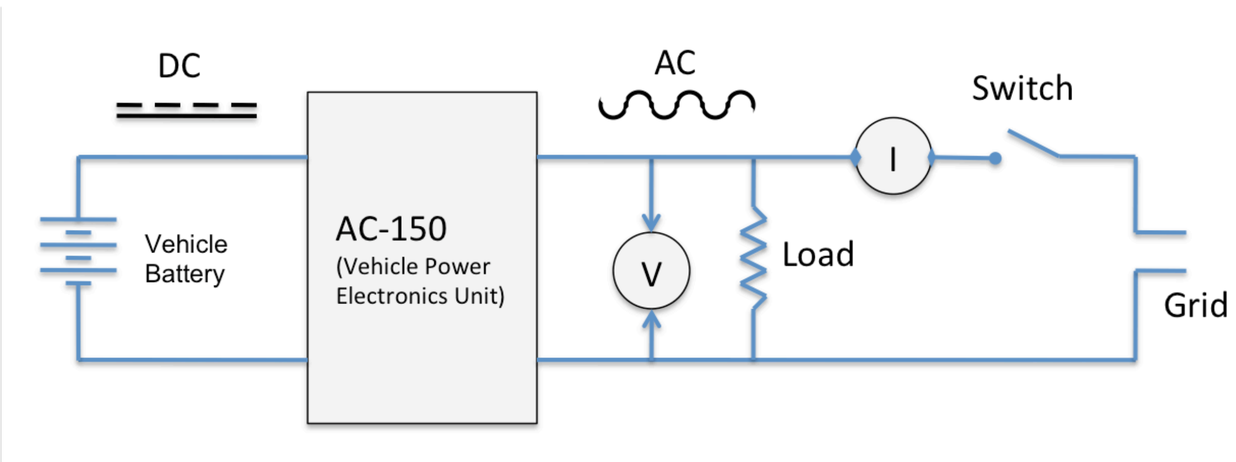

Figure 7: Simple electrical circuit representation of the methodology including the anti-islanding test. The AC elements include the voltage meter (V), the current meter (I), load (a hairdryer), and a switch.

We tested anti-islanding using a simple setup with the vehicle, voltage and current meters, and switch, with a load on the vehicle side of the switch (Figure 7). This test setup allowed the vehicle to power the load while also providing grid power, or to provide part of the load with the grid providing the rest.

The following four specific tests were conducted to evaluate the anti-islanding capability of the AC-150 power electronics used in the AC Propulsion eBox electric vehicle using this experimental setup:

Test 1: Set the AC-150 output to zero, so the load is powered by grid only.

Test 2: Set the AC-150 output at roughly half the load.

Test 3: Set the AC-150 output equal to the load, so current through I is zero.

Test 4: Set the AC-150 output greater than the load.

In each of the four tests, voltage and current meters were monitored, as was the operation of the resistive load. Under all combinations, loss of the line 60 Hz grid source (by opening the switch) resulted in shutdown of the AC-150 vehicle power source. This was confirmed by visual observation of the current and voltage meters, which shut down after an imperceptible delay (under one second delay).

This simple setup confirmed the very important safety tests of anti-islanding carried out previously by AC Propulsion, and which is now also verified by the National Renewable Energy Laboratory. With this safety assurance, the vehicle can be, and has been on a number of occasions, plugged-in in six different distribution systems in the PJM grid. There nevertheless remains the need discussed previously to ensure sufficient capacity at the distribution transformer, service drop, and the customer charging station.

Section VI: Test Results and Discussion

Simple Charging – Load (No Regulation)

When the vehicle is set to the charge mode instead of the V2G mode, “simple charging” will take place wherein the energy transfer is from the grid to the vehicle. No use is made of the regulation signal, and in a typical situation, charging begins at the maximum power level permitted by the charging infrastructure. This is illustrated in Figure 8.

In Figure 8, the battery state of charge (SOC) is indicated by the green line with the scale shown on the right-hand axis. State of charge is imprecisely measured by voltage and the upper and lower battery limits are truncated to preserve battery life. Here we use the percentage SOC as an approximate measure. In this time period show in Figure 8, the battery begins at ~78% SOC just after 10:00 and progresses to ~89% SOC at this particular outlet maximum charge power at 10 kW. The charge rate is indicated by the red line, with numeric labels on the left-hand axis. Once the battery reaches ~90% SOC the charging rate is gradually reduced by the battery management system to preserve battery life. For the same reason, charging stops at 97% SOC, so once that point is reached just before 11:15, the charging power goes to zero.

No regulation is provided during the time-span shown in Figure 8, so the recorded Regulation signal, indicated by the blue line and evaluated on the left-hand axis, is at 0 kW. Note that in Figure 8 and subsequent graphs, the battery SOC appears to fluctuate rather than increasing smoothly, even during simple charging. This is an artifact of the measurement instrument precision for battery SOC being only to the nearest 1%.

Figure 8: Simple charging, with power flowing from the grid to the vehicle. As the battery reaches full charge, about 10:25, charging current slows and eventually stops at 11:15.

Also note that the sign convention is set to be consistent with that of the grid operator rather than the vehicle. Generators are logically a positive value for generation, negative for a load, and we follow that convention here. That is, the regulation signal and the power supplied by the vehicle use negative values for flow out of the grid (regulation down or charging), positive values for flow into the grid (regulation up, discharging to grid).

Simple Discharging – Generation (No Regulation)

We manually discharged the vehicle battery, putting power into the local grid, in order to test this capability, as shown in Figure 9. The vehicle began with about 11% SOC, and was instructed to put 10 kW continuously on to the grid. This is an experimental procedure – in normal operation, the vehicle battery would not be manually discharged to the grid, especially down to zero state of charge as we have done here.

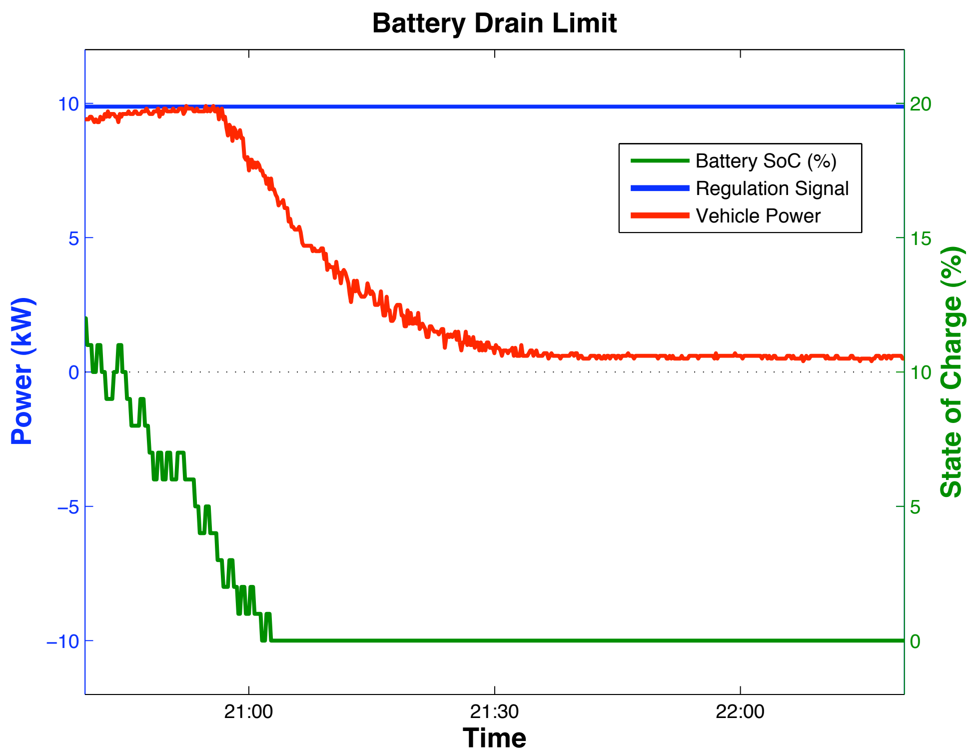

Figure 9: Manual discharge of the battery to the grid.

This experiment illustrates two mechanisms of battery protection built in to the vehicle. The first battery protection seen in Figure 9 is a user interface convention—the reporting of the state of charge. The display (and the reported value in the graph) shows as "zero" when there is actually still a small amount of charge in the battery. This is proven by noting that, even though the SOC in Figure 9 appears to be zero, a small amount of power continues to be provided, e.g. at 21:15. This is analogous to having the low fuel warning light come on when there is still a gallon or two of gas in the tank.

The other battery protection mechanism is at the battery management system level and has already been discussed in association with Figure 8. At very low states of charge (as at very high states of charge) the rate at which power is withdrawn from (or charged into) the battery is slowed. This is following our general design principle that battery protection takes priority over V2G requests. In Figure 9 this becomes apparent at approximately 20:55, about 5% SOC, when the vehicle power output ceases to follow the artificial V2G command for 10 kW discharge. Even an hour after the indicated SOC has reached 0%, a trickle of power is still flowing from the battery, eventually reaching zero after four hours (beyond the times shown in Figure 9).

Regulation – Normal Regulation Up and Down

The simple charging and discharging tested in the preceding two sub-sections, represents the pure use of the vehicle as a load and as a generator, respectively, without regulation. When the vehicle is set to respond to the regulation signal, that signal modifies the power flow into and out of the battery. This can be seen, for example, in Figure 10.

In Figure 10, regulation service is being provided by the vehicle. The PJM signal is indicated in blue, showing the short-term fluctuations of regulation. (In this case we are actually using a regulation signal based on overall system need, scaled to the particular vehicle's power capacity – this signal changes more rapidly than does the signal to a typical generator.) The power response of the vehicle (red) shows that the power drawn by the vehicle tracks the regulation signal (blue) very closely. The battery SOC is again in green, and fluctuates between about 60% and 70% in the two hours from 12:30 to ~14:30. After about 13:45 the SOC falls slightly because, during that time, more regulation up than regulation down was requested. The high time resolution of Figure 10 shows that the vehicle power electronics and battery respond very well to the regulation signal.

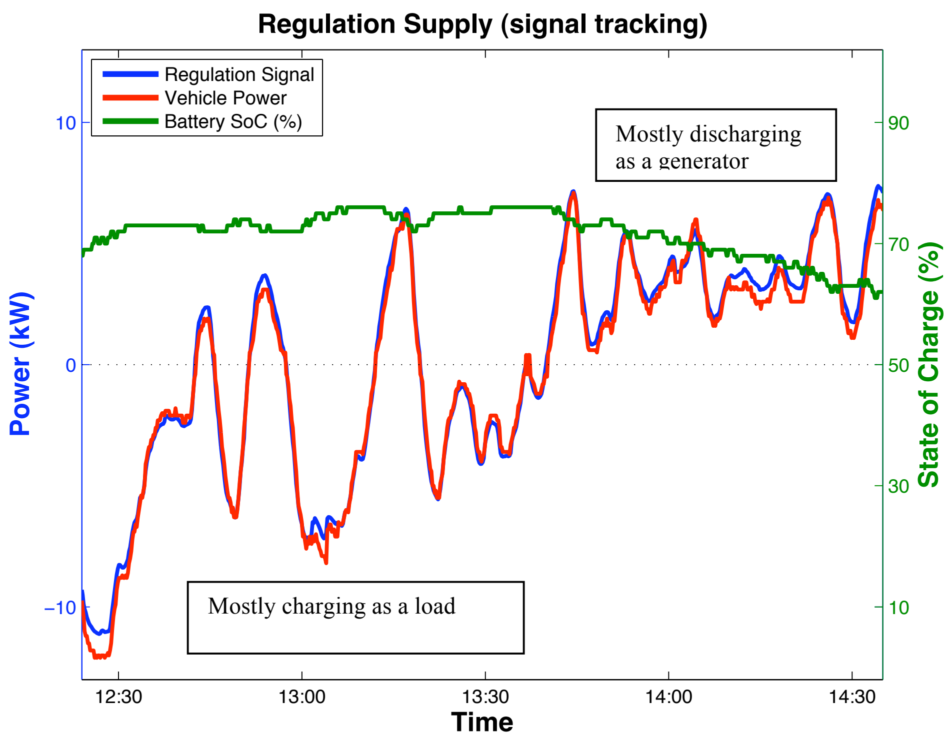

Figure 10: A test of providing two hours of regulation service.

A Day in the Life of a V2G Vehicle – 2.5 Hours Driving, 21.5 Hours Regulation

In a typical day, a vehicle that can be plugged in at home and at work can provide V2G regulation services for the majority of the day. Or, a vehicle used at home can provide V2G regulation services when not in use. In Figure 11 below, a 24-hour period of driving and V2G is shown. This is a sporadically used vehicle, and on this day, the vehicle is driven three times: between 14:48 and 15:16, when the battery SOC drops from 97% (full charge) to 91%; between 18:54 and 20:30 the vehicle is again off-grid, and the SOC drops from 97% to 88%; and again between 8:35 and 9:13 the next morning the vehicle drives further and the battery SOC drops from 70% to 49%. In this example V2G revenues would be earned for ~21.5 hours of the day. From the total battery depletion during the three drive events of 36%, we calculate that the vehicle was driven roughly 45 miles. Note that on this day, regulation was provided at all hours that the vehicle was not driving, yet it was never necessary to explicitly charge the vehicle. The charge available after extended periods of regulation was sufficient for subsequent driving. This is because more regulation down was needed than regulation up, as we discuss in the next section. We also note that the amount of energy (kWh) moved through the battery for V2G is comparable to the amount for driving, but SOC shift is usually moderate, even over many hours. To minimize battery wear, these SOC excursions due to V2G should be limited in size.

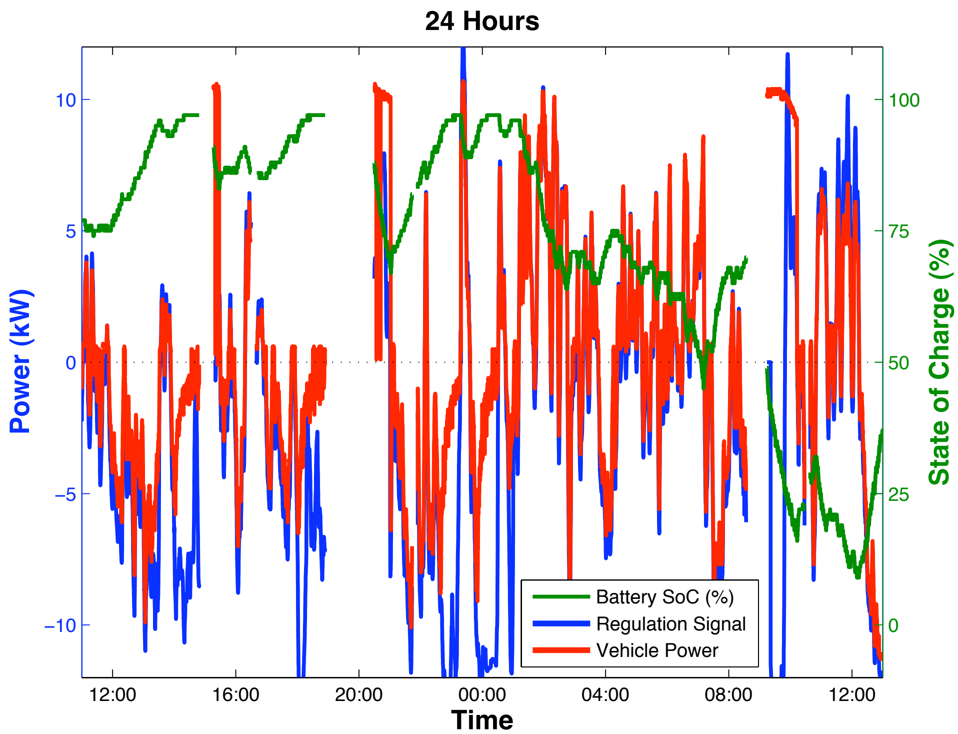

Figure 11: Regulation and driving during a 24-hour span. The vehicle is used three times for a total of ~2.5 hours, while providing V2G regulation for the remaining 21.5 hours.

Excessive Charging from Regulation – Reaching Over Charge Limit

In the following two examples there is a greater need for regulation down (removing power from the grid) than there is for regulation up. While this is a coincidence, it causes a net increase in the battery SOC over time. This is useful to illustrate potential limits to providing continuous regulation.

During the time-span covered in Figure 12 more regulation down than regulation up was requested, which has the net effect of charging the battery. By 02:00, the battery was almost full, and we begin to see failure to respond fully to regulation down requests – indicated by the red power line failing to track the blue signal line all the way down.

After 02:20, a long burst of regulation up drops battery SOC back down near 80%, and power resumes tracking signal until about 03:15. After 03:15, the full battery progressively degrades the ability of the vehicle to respond to continued regulation down requests – seen by the red power line being progressively separated further from the blue control signal. (Figure 13 will show that this reduced ability to provide regulation continues until 07:00 when the car is driven.)

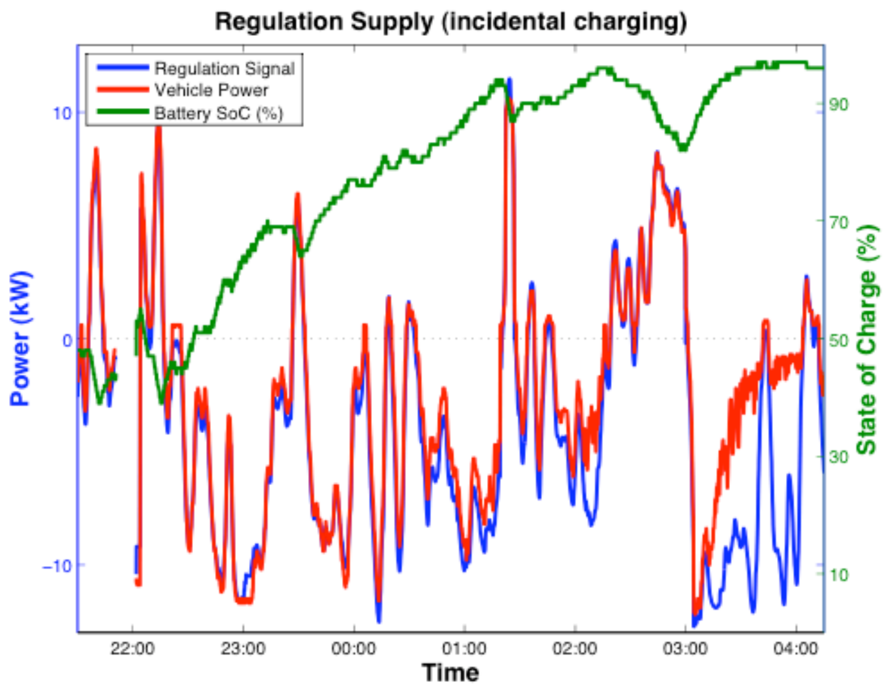

Figure 12: Overnight regulation with regulation down requests predominating; high state of charge after 03:00 precludes providing more regulation down.

As seen previously in Figure 8 for simple charging, when the battery gets close to full, the battery management system takes over from the regulation signal to prevent damage to the battery. For this vehicle, when the battery is above ~90% SOC it cannot be charged at 12 kW without undue wear on the battery, and charging stops completely above 96% SOC.

The progressively reduced ability to provide regulation is seen in greater detail in Figure 13, the time period subsequent to Figure 12. We saw in Figure 12 that the ability to respond to the demand for regulation down becomes sporadic after 02:00 and rare after 03:15. In Figure 13, we see further that the vehicle become even less responsive to regulation down, approaching zero power in response to the signal after 03:30, and the non-response problem persists until the car is driven after 07:00.

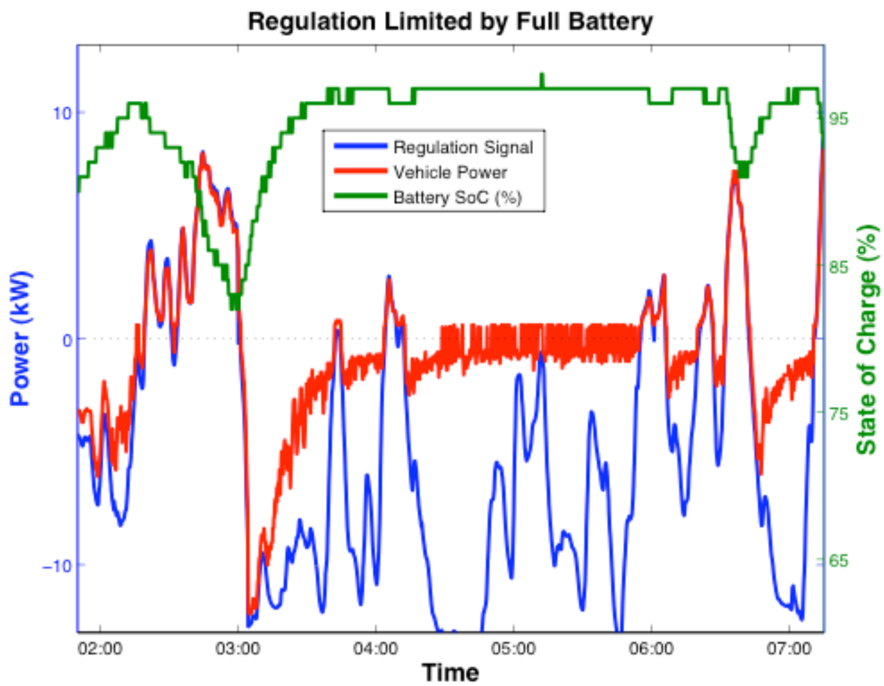

Figure 13: Regulation services limited by a full battery. This figure is an extension of Figure 12.

The reverse case, that excessive regulation down would empty the battery, is also possible and the discussion is similar. This is approximated in the previous Figure 9, showing simple discharge to the grid. If the battery is emptied by excessive calls for regulation up, that would mean that no more regulation up could be provided. Unlike the case with an inadvertently filled battery, if the battery is emptied, time must be allocated in order to charge prior to driving.

Demonstrations in Multiple Electric Distribution Systems

Demonstrations have been conducted at a variety of sites since October 2007. Most have included V2G provided by the vehicle under control of the PJM regulation signal. These have been at installations varying in size from small commercial up through large office buildings, hotels and a conference center, and in at least eight distinct utility service territories. The list below includes most of these demonstrations.

- September 28, 2007; NJ Board of Public Utilities Clean Energy Conference; New Brunswick, NJ; PSE&G
- October 7, 2007; UD Coast Day; Lewes, DE; City of Lewes Board of Public Works
- October 5 and 22, 2007; Test at Delmarva Power Northern Division General Office; Newark, DE; Delmarva Power
- October 24, 2007; FERC Offices; Washington, D.C.; Pepco
- November 14, 2007; PJM Interconnect V2G Symposium; PJM Headquarters, Norristown, PA; PECO

- November 30 – December 1, 2007; Ramapo College; Mahwah, NJ; PSE&G
- March 4-6, 2008; Washington International Renewable Energy Conference (WIREC); Washington, D.C.; Pepco
- End of March; Comverge Users Conference; Scottsdale, AZ; (LSE)
- April 27, 2008; Atlantic County Utilities Authority's Earth Day Festival; Egg Harbor Township, NJ; Atlantic City Electric
- June 11-12, 2008; Brookings Institute/Google.org Plug-In Electric Vehicle Conference; Washington, D.C.; Pepco
- June 12, 2008; Senator Harry Reid Energy Security Press Conference; Washington, D.C.; Pepco
- July 16, 2008; 2020 Vision National Summit on Energy Security; Washington, D.C.; Pepco
- January – Present, 2008; Normal charging and testing; UD Motor Pool; Newark, DE; City of Newark Electric Company

Implications and Limitations

While this test has demonstrated V2G as a provider of regulation and a means of storage, the cars used in the tests are prototypes and thus expensive on a per-vehicle basis. Thus far, fewer than 20 of these cars have been made at a cost of $70,000 each, about a $55,000 premium over an economy car. The two main costs are the components, notably the batteries and power electronics unit, and the labor for the conversion from gasoline to electric. High costs for both are predominantly due to low production volumes. Different components have cost reductions thresholds at different points, but one can roughly think of cost reductions occurring at yearly volumes of thousands, tens of thousands, and hundreds of thousands. Therefore, if there is little supply of cars, the costs are high, thus there may be no demand, and if there is no demand there is no supply–a classic "chicken and egg" situation.

As shown in the tests, V2G can provide very fast regulation and unlike traditional generation resources, the energy is stored and released during the provision of regulation service. This clean power function, in addition to oil-free personal transportation and the future potential to support intermittent renewables all provide environmental, system reliability, oil independence, and energy security benefits. Thus, there is a case for finding policy mechanisms to support initial fleets of V2G-capable vehicles. Policy mechanisms might include tax credits for purchase of such vehicles, and a vehicle-specific (and possibly temporary) special pricing model for V2G regulation.

As was illustrated in Figures 8 and 9, the unpredictable nature of regulation may at times fully charge or discharge the vehicle's battery. When this occurs, the ability to provide bidirectional regulation is lost. This limitation could be addressed in four ways:

1. On an individual car basis, provision of both regulation up and down could defer to a user-defined full or empty limit, and thus would cut short a single long dispatch but could

extend the time that one could sell a contract for regulation (whether or not this is a good tradeoff will depend on the rates and penalties in a particular ancillary service market).

2. At the aggregator level, the aggregator would be able to dispatch cars to match regulation needs; for example, a vehicle with full battery could be allocated to provide regulation up only, and a vehicle with insufficient charge for the next anticipated drive would be used by the aggregator only for regulation down.

3. The discussion in this paper assumes that vehicles have only two modes. They are either being dispatched by the aggregator up or down from a "normal" zero current, or they are not serving the aggregator and they are just charging as loads to serve driving. A different approach is suggested by generators providing ancillary services—generators providing regulation have a non-zero "preferred operating point", with regulation up or down from that. Similarly, generators providing spinning reserves are kept at a low but non-zero generation state (thus the name "spinning") and offer the amount between just spinning and their maximum output. It may be appropriate for a V2G aggregator to similarly operate at a non-zero "preferred operating point" (POP). The V2G aggregator's POP might normally correspond to the average rate to charge vehicles plus compensate for two-way losses. If the POP could be adjusted dynamically, say, hourly, that would give the aggregator more flexibility to deal with the situation of many vehicles being too high or too low in charge. This approach will need to be studied more carefully to avoid two potential problems: a. If the aggregator's POP is adjusted too frequently, or without prior notice to the ISO, it reduces or negates the value of regulation, and b. With a simple metering arrangement, the bulk power metering is done at the parking location, so cost or revenue of a non-zero POP is metered (and paid for) by the individual building at which the car is parked. Thus a non-zero POP may require more complex payment reconciliation.

4. At the ISO level, as storage becomes a larger fraction of regulation up, it may make sense to have a separate signal for storage resources. This would be useful not only for V2G but also for centralized batteries or flywheels used for regulation. Such a storage-specific regulation signal could require that the vehicle provide fast response and, in exchange, that the grid operator request equal quantities of regulation up and regulation down in a time period relevant to battery or flywheel storage capacity, say, within each half hour.

Our research is now shifting effort into the IT aggregation platform that will use proper algorithms to best match the driving pattern of each car driver with the historical regulation signal to ensure effective dispatch of V2G and minimize times that any battery is either fully charged or fully discharged. These and other issues need to be fully developed between the ISO, the aggregator and the market regulators.

Section VII: Conclusion and Future Work

Conclusion

Participation in ancillary service markets appears to be an appropriate use of electric vehicles. We have demonstrated this use at the single-vehicle level, operating under real-time dispatch by PJM. Data presented in this report demonstrate that electric vehicles are capable of providing ancillary services and storage.

The highest value ancillary service is regulation. In areas with deregulated electricity markets, regulation can have average values of $30-$45/MW per hour, with hourly rates fluctuating widely around that average. A second market of interest is spinning reserves, or synchronous reserves, with values in the range of $10/MW per hour, but much less frequent dispatch. The primary revenue in both of these markets is for capacity rather than energy, and both markets are well suited for batteries as a storage resource because they require quick response times yet low total energy demand. Additionally, V2G can provide distribution system support when there is a concentration of parked V2G cars, along overload elements in the distribution system.

Regarding storage, when parked V2G-capable cars are connected and aggregated in large numbers, they could be used as dispersed energy storage for intermittent but renewable resources such as wind and solar. The results of the study show that V2G, in addition to providing valuable grid servies, could also prove to be a prominent application in the global transition to the emerging green and sustainable energy economy.

Planned Expansion

By the end of 2009, we expect to add four V2G-capable cars to our trial fleet, funded by the US DOE, the Delaware State Fleet, and PHI. Regulation signal control will be shifted from the vehicle to a central server at the University. This will allow us to develop and test centralized regulation dispatch, though it will not yet provide sufficient total power for a regulation contract with PJM. The next steps needed are to develop multi-vehicle dispatch by an intermediary or aggregator. Then a full business model demonstration can be conducted, using 1 MW of vehicles in order to obtain a valid A/S contract with an ISO. This will allow us to evaluate and refine the aggregation algorithms currently under development.

The next step will be to develop a business model to justify a larger scale demonstration (1 MW) for regulation purposes. This will require a demonstration fleet of 100-300 vehicles on a "V2G service contract" with an aggregator. In such a trial fleet, as in the fleet of five vehicles, the regulation signal will only be directly visible to the aggregator, who will then broadcast vehicle specific regulation requests to each vehicle in the fleet. The power demanded of each vehicle will be based on: a) the regulation signal, b) the number of vehicles plugged in, c) the connection size to each vehicle, d) each vehicle's state of charge and e) the anticipated energy requirement of each vehicle as determined by onboard logic. To segue the concept demonstrated in this study into a business opportunity, the following are the public policy, engineering, infrastructure and operational activities that remain:

- Vehicle designer:
    - New vehicle design
    - Crash testing

  - Certifications
- Public awareness:
  - Attract federal, state and local funding to jump start adoption of plug-in vehicles
  - Continue V2G demonstrations to raise awareness and customers willingness to buy
- Technology needed – accelerate R&D with UD and MAGICC participants by:
  - Making the eBox and other MAGICC participating cars truly plug/play and drive
  - Developing a V2G aggregation business IT platform
  - Establishing V2G conversion and/or distribution shop(s) in the region
- Infrastructure – identify parking lots and distribution feeders that will:
  - Present the least cost for attracting customers and businesses to participate
  - Ensure win-win for utility operations
  - Allow expansion for future customers
- Operations – develop business processes and user-friendly procedures for:
  - Safe driving and connection of cars at home and workplace parking lots
  - Car maintenance and operations
  - Customer participation guidelines
  - Utility integration and aggregator responsibilities
  - Convenient plug and drive connections at homes and workplaces

Possible Future Research

This first step in the project shows that a battery powered car can be tied to the grid, power flow in each direction can be controlled, and the output can respond to the PJM Frequency Regulation signal. Several additional questions can be answered with research time but without requiring additional vehicle purchases.

1. Using databases of driving patterns, one could compare V2G resources based on actual patterns of people's vehicle use. This information would give an better insight into limits to charge/discharge which, in turn, would allow an understanding of how many times in a historical year those limits would likely be hit and whether that variability would effect the desirability of providing regulation at certain times (vehicle owners might spend less time plugged in on the weekend or a significant number of people may be traveling between 7-9 am, etc.).

2. Another study that could be performed is to analyze alternative parking scenarios. For example, how would the cost for a large parking lot electrical interface compare with the distributed costs discussed here? Will plug-in parking along streets, or roadways be conducive to V2G participation, or is time parked too short? Given the driving patterns mentioned in question 1 above, is the cost of secondary plug-in locations outside of the residence justified, either in owner convenience and range or in added V2G hours?

3. Modeling a number of typical service drops for thermal capacity as well as for flicker. This could compare one household hooked into a 25 KVA transformer with one car,

several sizes of service cable and a typical load mix; two or three households with vehicles on one transformer; different size transformers, and different typical load mixes.

4. Modeling distribution feeder saturation levels and show when multiple installs may affect the feeder. Perhaps a "good" ramp rate could be established – although the rapid response is beneficial to the load balancing exercise, there may be a practical limit so that voltage regulation devices in the distribution system can maintain proper feeder voltage. All the issues mentioned above should be studied in a good feeder model. It would probably be optimal to select several feeders – a very high impedance, low fault current feeder and a very stiff, high fault current feeder and then look at several different configurations and several paradigms with different delays set for different device switching. The study would need to cover protection, coordination, loading, voltage regulation, reliability, power quality. An extension of such a study would include how a Smart Grid could use V2G resources to actively reduce problems and increase efficiency.

5. To avoid non-participation when a battery is charged and the signal requires import of power to the battery, it might be worth triggering the vehicle heater with a bypass that will blow heat outside the vehicle (in warm weather). In this case it would be important to analyze the cost of electricity consumption not saved into storage versus the benefit of meeting a regulation down contract requirement even when the battery is full.

Acknowledgements

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