

Final Report

Vehicle-to-Grid Demonstration Project: Grid Regulation Ancillary Service with a Battery Electric Vehicle

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1. Abstract

Electric vehicles could potentially provide valued services to the power grid when not being driven, reducing ownership costs. This project evaluated the feasibility and practicality of vehicles providing a grid ancillary service called regulation. Regulation is especially well suited to battery electric vehicles: it involves fast-response changes in power above and below a baseline. With the baseline set at zero power, the power fluctuations above and below zero average out to approximately zero net energy over time. Hence, a vehicle's battery state of charge would vary in the short term, but would not become discharged over time. A test vehicle was fitted with a bidirectional grid power interface and wireless internet connectivity, allowing power flow to or from the vehicle to be dispatched remotely. An 'aggregator' function was developed to represent a commercial middleman between a grid operator and multiple vehicles. Power dispatch commands were sent wirelessly to the vehicle at 4-second intervals, and the vehicle response was monitored and recorded. Results showed that wireless data transmission times were within ISO system requirements, and that the energy throughput through the battery due to regulation is similar to that of typical daily driving. The value created by the service exceeds the battery wear out costs under most operating assumptions. The long term effects on battery life were beyond the scope of the study; however it was noted that battery capacity increased by about 10 percent during the testing.

2. Executive Summary

2.1 Background

The zero-emission vehicle (ZEV) program is an integral part of CARB's strategy to reduce mobile source emissions. As part of the Low Emission Vehicle program, in 1990 CARB adopted a production mandate for zero emission vehicles, to begin in 1998. After producing and placing a limited number of electric vehicles as part of the negotiated Memorandum of Agreement, automakers have opposed further requirements to produce electric vehicles by claiming that these vehicles were too expensive to produce. Several automakers have filed lawsuits to overturn the ZEV mandate, based largely on claims of high costs. This study was initiated to explore an innovative means to overcome cost hurdles. Electric vehicles that are not being driven represent a potential energy and power asset that could be deployed to the benefit of the operation of the power grid or to provide local benefits.

The range of functions that might be provided by vehicles can be segmented in two broad areas: (1) local services to benefit the electricity customer where the vehicle is connected, and (2) broad area services that benefit the operation of a power grid. The local services category includes functions such as providing backup power for homes or businesses, local voltage stabilization/power quality improvement, and peak shaving for demand charge reduction. The broad area services would be grid ancillary services. Ancillary services are power services (other than scheduled bulk generation) that are used by grid operators to maintain the reliable operation of the grid. Examples of ancillary services include spinning and non-spinning reserves – power generation capacity that can be called on short notice as needed. Previous studies [1,2] concluded

that a particular grid ancillary service called regulation had the best prospects for generating a real income stream from services that could be provided by battery electric vehicles. This project built on the previous studies by implementing grid regulation with an actual electric vehicle and evaluating the operating performance and value generation potential, and by exploring issues in implementing such a system.

2.2 Methods

An existing electric vehicle was retrofitted with a power system that allowed the vehicle to feed power from the vehicle's battery pack back to the grid as well as to pull power from the grid to recharge the battery pack. The vehicle was also fitted with a wireless internet connection, allowing the remote dispatch of its power capabilities. The operating scenario for a vehicle with this capability is that it would be plugged in to the grid during most of the time it was not in use. For this study, it was assumed that there were two main periods of grid connection: (1) at home after work through the night to the following morning, and (2) at the workplace during normal working hours. Tests of duration corresponding to home (14 hours) or workplace (9 hours) were carried out with different initial conditions and levels of grid services. In addition, a test over a 48-hour period of continuous grid regulation was performed to evaluate a situation in which a vehicle is connected and available for an extended period. In all, 227 hours of grid-connected test time were completed. An 'aggregator' function was developed to serve as the middleman between a grid operator and multiple vehicles. Power dispatch commands were sent wirelessly to the vehicle at 4-second intervals, and the vehicle response was monitored and recorded. Real time power dispatch for vehicle-based regulation was not available from the Cal ISO for this project. Instead, sample dispatch profiles were developed from historical ISO data by allocating vehicles a pro-rata share of the total regulation demand.

2.3 Results

Results showed that wireless data transmission times were within ISO system requirements, and that the daily energy throughput through the battery pack while performing regulation is of the same magnitude as that from typical daily driving. Battery heating during the test periods was negligible. The long term effects on battery life were beyond the scope of the study; however it was noted that battery energy capacity increased by about 10 percent during the course of the testing. The monetary value created by these services varies with the market price for grid ancillary services. A sample vehicle usage profile was developed, with on average 22.6 hours of grid connect time every day. The value of grid regulation was determined for this usage profile based on regulation pricing from sample weeks in December 2001, April 2002, and July 2002. The annualized gross value created with 80-Amp grid connections available at home and at work ranged from a low of \$3,038 for December 2001 to a high of \$5,038 for July 2002. The results support the ZEV program goals by demonstrating the feasibility of vehicle-based grid services or V2G.

2.4 Discussion

The adoption of V2G will be substantially aided by growth of the EV charging infrastructure. Access to workplace charging is especially important for V2G and future ZEV regulations should strive to encourage this. Having workplace charging available also means that driving range will be less of an issue, allowing consumers to be comfortable with the lower driving range offered by inexpensive batteries. The use of inexpensive batteries has large implications on the reported cost increments for ZEVs over conventional vehicles – the low cost of lead acid batteries virtually erases the claimed cost premium for ZEVs. Finally, the prospect for V2G is supported by CARB’s adoption of conductive charging as the standard in July 2001 – inductive charging would have precluded V2G as it is incapable of power flow from the vehicle to the grid.

2.5 Conclusions

Integrating electric drive vehicles with the electric power grid has been shown to be feasible and to have potential to create an income stream that offsets a portion of vehicle ownership costs. If V2G were adopted and deployed by one or more automakers, there is the potential to reduce costs to automakers and increase the desirability of ZEVs to consumers, with the ultimate potential of building a ZEV market based on demand rather than regulations. Further development of this concept should include: (1) finding a home and champion(s) for V2G within the state and federal governments; (2) addressing utility distribution grid issues; (3) a pilot demonstration with a fleet of existing electric vehicles performing a load-only form of grid regulation¹ and assembling and testing a small pilot fleet with full bi-directional V2G capability; (4) a detailed study by the Cal ISO (or other grid operator) on the amount of regulation (and hence battery degradation) that would be dispatched to V2G-capable vehicles; (5) battery pack cycling experiments to determine the effects of V2G operations on overall battery service life; (6) support changes in laws to extend net-metering to electric vehicles that provide grid services and to remove minimum capacity barriers to allow early market participation by small numbers of vehicles and develop model tariffs and rules tailored to allow automobiles to effectively participate in power and ancillary service markets; and (7) study of other beneficial applications of grid-connected vehicles, including transmission stabilization, local voltage support, and backup/uninterruptible power.

3. Introduction

As cars and light trucks begin a transition to electric propulsion, powered by batteries, hybrid engines, or fuel cells, there is potential for a synergistic connection between such vehicles and the electric power grid. The aggregate power rating of the US vehicle fleet is much larger than the total US electric generating capacity. If even a small fraction of vehicles were harnessed as storage and/or generating assets, benefits would accrue to the electric power grid operators,

¹ With a load-only form of regulation, the vehicle would draw power as a load from the grid according to commands from the grid operator, thereby creating value. The net energy drawn from the grid would still have to be paid-for, but this cost would be partially or fully offset by the regulation value created.

vehicle owners, and aggregators/service providers. The potential exists for the economic value generated to significantly offset the costs of electric, hybrid, and fuel cell vehicles and to bring a new source of economic returns to vehicle manufacturers.

Passenger vehicles are, on average, parked and idle for about 23 hours every day. During this time, they represent an idle asset and actually create negative value due to parking costs. The advent of electric drive vehicles introduces the prospect that parked vehicles can become assets that create value. By connecting such vehicles to the electric power grid, a large scale, dispatchable, electric power storage or generating resource can be created.

By itself, each vehicle will be small in its contribution to the power system. But, in aggregate, a large number of vehicles will represent significant storage or generating capacity. For example, five percent of California's passenger vehicle fleet could provide 10 percent of the state's peak power requirement. This geographically-dispersed capacity could be controlled remotely in order to provide power when and where it was needed. Power or energy from an electric drive vehicle could be sold from a vehicle connection point located at the vehicle driver's home or place of work. Such connected vehicles could provide a variety of services that have value to utilities and power grid operators.

Previous studies [1,2] have determined that a specific grid ancillary service, called regulation, is best suited for the capabilities of battery electric vehicles. Demonstration of grid regulation was the focus of this project.

3.1 Grid Regulation

Grid operators (often independent system operators or ISOs) must continuously fine-tune the balance between the generation of power and consumption (load). Each grid operator is responsible for balancing the flow of power in its own region, called a control area. The western United States and parts of Mexico and Canada are all on one interconnected grid known as the western interconnect. The western interconnect area, shown in Figure 1, is divided into 33 control areas. The California Independent System Operator, or Cal ISO, is responsible for most of the grid operations in California, as shown in the Cal ISO control area map in Figure 2.



Figure 1. Region covered by the Western Electricity Coordinating Council (WECC) and 33 control areas. (Source: Western Electricity Coordinating Council [3])



Figure 2. The California Independent System Operator's (Cal ISO) control area (source: Cal ISO [4])

For proper operation of the grid, generation must be continuously matched with load. A mismatch causes the grid frequency to deviate from the desired nominal operating point of 60 Hz. There are three principal methods used to match the generation and load. The first, called ‘load following’ is based on advance-scheduling of power generation in accordance with predicted and/or scheduled load. Advance-scheduled generation is dispatched or curtailed to provide a daily generation profile that closely matches the expected demand. The second method, called ‘reserves’ is the contracted availability of extra power to be dispatched on demand, with different types of reserves depending on how quickly it can come online. Reserves are used to fill in the variances between scheduled and actual load, or to fill in for a generation unit that unexpectedly goes off-line.

The third method is called regulation or automatic generation control (AGC). The California ISO defines regulation as follows [5].

Regulation: Generation that is on-line, and synchronized with the ISO controlled grid so that the energy generated can be increased or decreased instantly through automatic generation control (AGC), directly by the ISO EMS. Regulation is used to maintain continuous balancing of resources and load within the ISO-controlled grid, as well as maintains frequency during normal operating conditions.

Regulation is used for the last bit of fine tuning needed to balance generation, load and interchanges, and is continuously calculated and dispatched by a grid operator's computer system (usually called the Energy Management System, or EMS). A control area's instantaneous measure of the balance between generation, load, interchanges, and a frequency regulation contribution is called the Area Control Error, or ACE. Regulation is used to assure that the ACE of a grid-operator's control area complies with the performance standards required by the Western Electricity Coordinating Council (WECC) and the National Electric Reliability Council (NERC). As shown in Figure 3, ACE is typically less than 0.5 percent of the total statewide load under Cal ISO control.

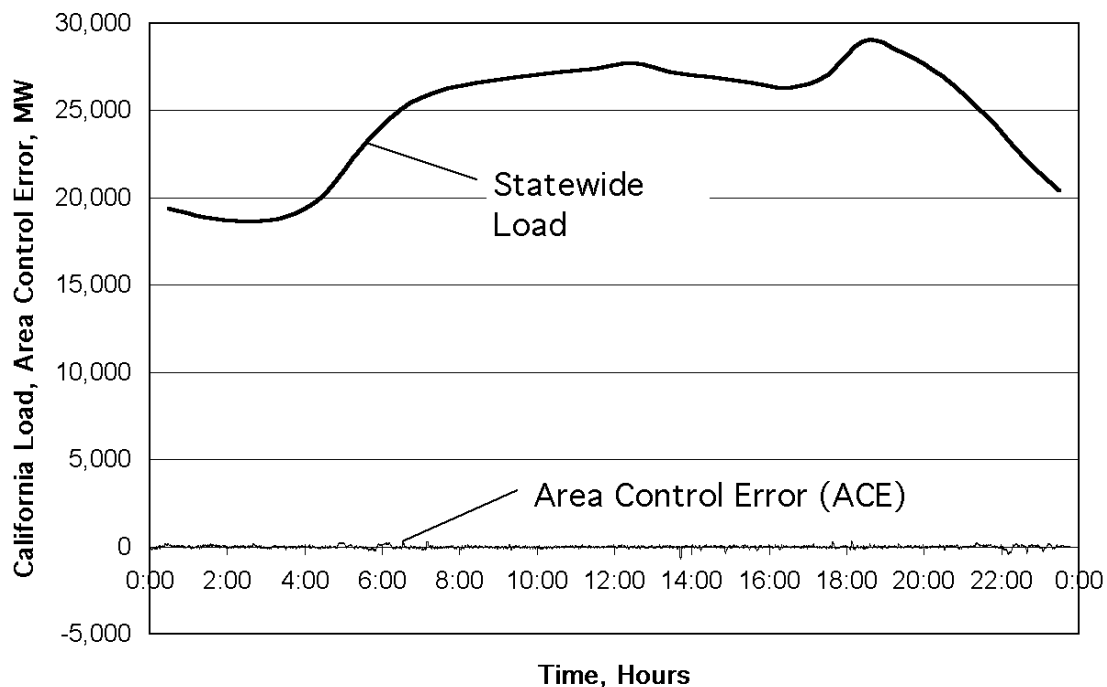


Figure 3. Example showing relative magnitude of system total load and Area Control Error (ACE) for March 14, 2001.

In some power markets (including California's) regulation is unbundled from power generation, and is procured as an ancillary service or is self-provided by users of the transmission grid. In California, regulation that is not self-provided is procured by competitive bidding on day-ahead and hour-ahead markets. Regulation is procured for each hour of the day as power capacity – not energy – that can ramp up or down from a nominal generation level. Grid regulation requires a power system that can ramp power up or down under real time control of the grid operator.

Today, powerplants and hydroelectric facilities perform the regulation function. Plants providing regulation are required to be under real-time direct control of an ISO's EMS computer system.

A provider of grid regulation will have bid into the system a nominal power generation level, and also maximum and minimum generation levels that can be commanded by the EMS computer. Generation capacity above the nominal generation level is called 'regulation up' and below is called 'regulation down'. Regulation up and regulation down are procured as separate ancillary services in California. Figure 4 shows an example power profile over a two-hour time period of a hydro powerplant in California providing regulation. The plant's operator contracted to supply a nominal generation power, and also contracted to be able to move generation up or down between limits according to AGC commands.

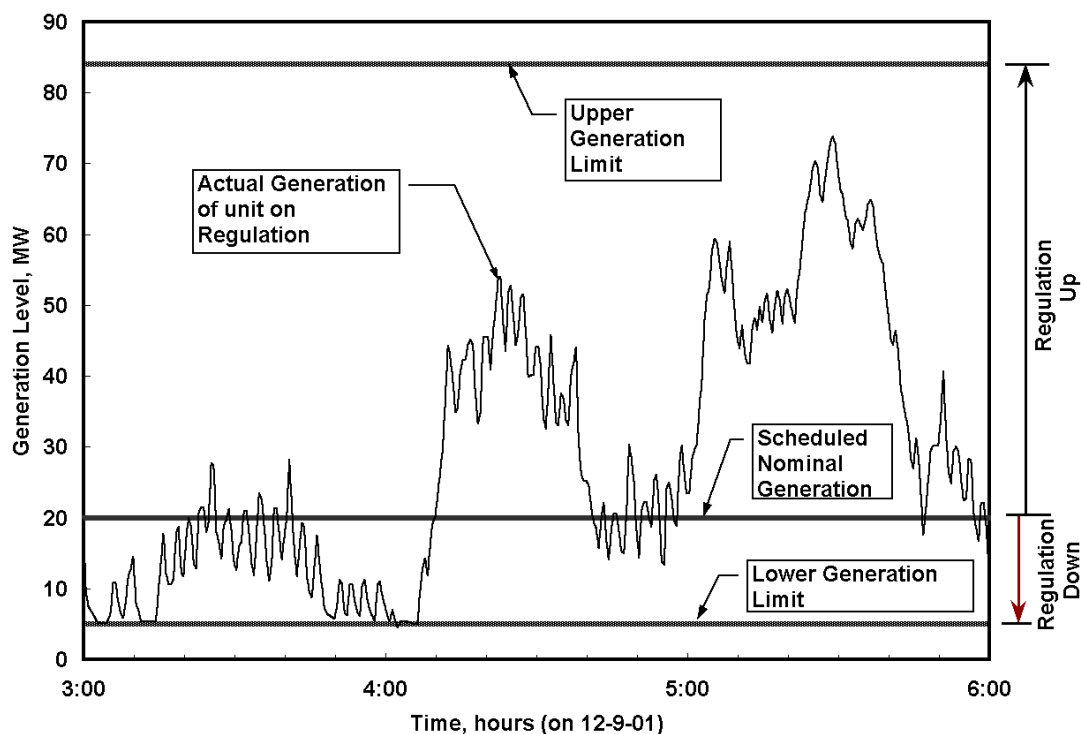


Figure 4. Example power generation profile of a hydro plant providing grid regulation (data source: Cal ISO).

Battery electric vehicles with bi-directional grid power capability are well-suited to providing regulation due to their ability to respond rapidly to power commands, and because the long term net energy requirement for regulation usually nets out to zero if the nominal generation level is set at zero². This means that the vehicle would be both sourcing and sinking power under real

² In practice, the nominal 'generation' level for an EV providing regulation would be set at a small negative power (i.e. load) in order to cover the expected small I/O losses of the battery/inverter system and to provide power to replenish the battery energy consumed in driving.

time commands from the ISO. Over an extended time period, the net total energy balances out to approximately zero. Because of this, a battery electric vehicle could perform regulation function indefinitely, without discharging the battery. The battery state of charge would be maintained at a level high-enough to afford the driver most of the available range, but not high enough to place a limit on the ability to sink power as required by the regulation AGC commands.

3.2 Drivetrain Technology with Bi-directional Grid Interface

AC Propulsion has developed a drive system for electrically-propelled vehicles that includes an integrated grid power interface. The system re-uses the power switches of the propulsion inverter (which drives the traction motor) as the power switches for a grid-tied inverter and uses the motor windings as the inductors needed for the grid-tied inverter (Figure 5). This provides a bi-directional high-power interface to the electric power grid with no extra power components over what are needed for propelling the vehicle.

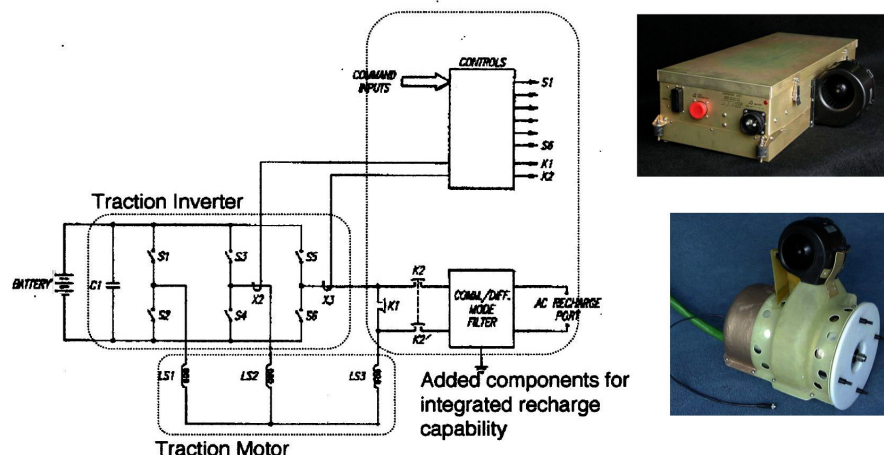


Figure 5. AC Propulsion AC-150 drivetrain with integrated bi-directional power grid interface.

In addition to operating as a battery charger to convert AC grid power to DC for charging the battery, the system can operate in reverse to convert DC power from the vehicle (from a battery, generator, or fuel cell) to AC power at the grid frequency. The AC power from the vehicle can be used to power stand-alone loads or it can be fed to the grid. Safety systems similar to those employed with small distributed generation systems prevent the vehicle from feeding power into the grid when the grid power itself is down.

3.3 Vehicle to Grid Operating Scenario

In a future scenario where tens of thousands of vehicles are connected to the grid performing ancillary services, it is almost certain that the grid operator will not want to deal with each individual vehicle. Instead, the grid operator will want to have control over the aggregate capacity of the vehicles. An intermediary entity, called an aggregator, would manage the

interactions between the grid operator and the connected vehicles. To the grid operator, the aggregator would appear to be a large source of rapidly-controllable generation or load – a good source of regulation capacity. The aggregator would contract with the grid operator through day-ahead and hour-ahead markets to provide regulation capacity. The grid operator and aggregator would communicate over a secure data link of the same type used to communicate with existing sources of regulation. The aggregator would receive regulation commands from the grid operator and allocates the required regulation out to the connected vehicles. A graphic of the system architecture is shown in Figure 6.

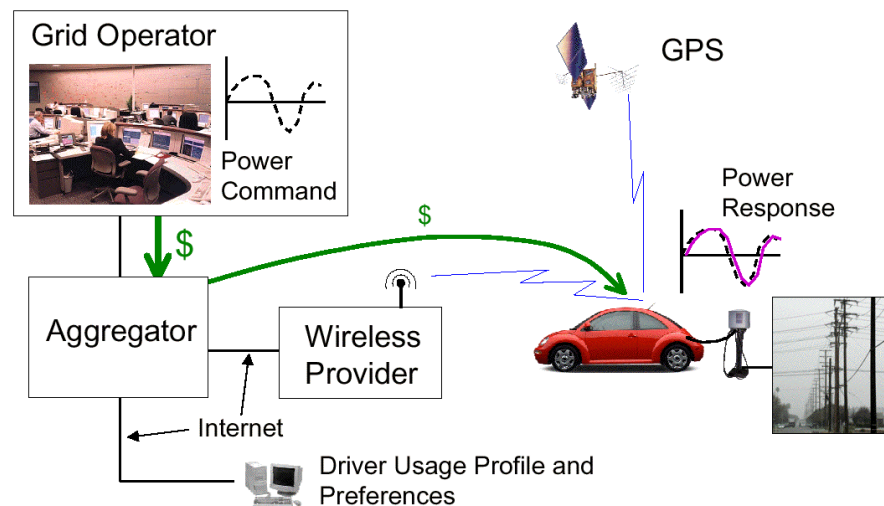


Figure 6. Architecture of vehicle-based grid regulation system.

The vehicle aggregator would keep track of vehicles that are connected and where they were located (with GPS). Location information is needed to determine which zone or control area a vehicle is currently connected in. The aggregator would also serve as the interface for each individual driver. A web server would allow drivers to log in to set up default profiles, check status of their vehicles, or monitor value created. A sample driver interface is described in section 4.3.1 below.

The aggregator would be providing a service to the grid operator, and would be paid for that service. The aggregator would then share the value created with connected vehicles. This could take many forms including direct payments, subsidized leases, or ownership and/or warranty of the vehicle battery pack by the aggregator.

3.4 Project Objectives

The purpose of this project was to develop and demonstrate technology and systems that would allow an electric vehicle to create value while stationary and plugged in to the power grid. By deploying the vehicle's power systems to perform ancillary services for the power grid operator, there is the potential for economic value to be created that will nullify the cost-per-emissions-benefit argument. With the value created through vehicle-based grid services, there is the possibility that electric vehicles could have a lower net cost than a conventional vehicle. This would invert the cost vs. emissions benefit tradeoff; there could be a cost benefit together with the emissions benefit.³

Specifically, this project aimed to demonstrate the feasibility and practicality of electric-vehicle-based grid regulation, and to assess the economic value based on real operating data and real market prices for the service being provided. Vehicle-based grid services may prove to be instrumental in overcoming market and cost barriers in the adoption of electric and other advanced technology vehicles.

Another project goal was to identify, research, understand, and propose approaches for the regulatory and implementation issues involved with providing ancillary services from vehicles. These include regulatory jurisdiction, interconnect standards, how to account for net energy transfer, the need for net metering, and consideration of performing regulation ancillary services at public and workplace charging sites.

4. Materials and Methods

This project implemented all of the essential elements needed to demonstrate the operation of a battery electric vehicle performing grid regulation while parked.

4.1 Vehicle Conversion to V2G Capability

The vehicle utilized for this study was a Volkswagen Beetle which had previously been converted to electric propulsion for Volkswagen by AC Propulsion. The vehicle was equipped with 30 12-V Panasonic lead acid model EV-1260 batteries (the same type used in the second generation lead acid EV1s). AC Propulsion's first generation AC150 drive system was part of the original vehicle conversion. For this project, the vehicle was upgraded with the second generation AC150 drive system, which is equipped with the bidirectional grid interface. With this system the vehicle is capable of feeding power to the grid as well as recharging by taking power from the grid. The vehicle was also fitted with a wireless modem to allow remote dispatch of V2G functions over the internet. Commands received over the wireless modem were routed to the grid AC line current control input for the system, allowing remote control of AC

³ The same thing happened with fuel injection: Fuel injection was required to meet emissions standard, and since engines operated so much more efficiently with fuel injection, the fuel savings over the life of the vehicle resulted in lower overall costs and lower emissions.

line power (within current limits of the connection; the drive system can handle up to 80A AC). The power system installation under the hood is shown in Figure 7.



Figure 7. AC150 Gen-2 drivetrain with bi-directional grid power capability installed in Beetle EV

4.2 Determine Suitable Vehicle AGC Dispatch Commands

The shape and form of the regulation power profile has a lot to do with how well a battery electric vehicle could perform regulation and how much battery degradation will be experienced. From a driver's point of view, it would not be desirable for a vehicle providing regulation to undergo large swings in battery state of charge. A driver would want some assurance that the vehicle won't ever have a nearly-dead battery caused by regulation operations. Large swings in state of charge could result if regulation power profiles had long periods of 'pegged' commands at the vehicle's grid power limit (i.e. the command remains at the full contracted value of regulation up or regulation down for an extended period). The amount of battery degradation caused by regulation will generally depend on how much the battery is 'used' for regulation. A reasonable measure of battery usage is the throughput energy (or similarly, throughput Amp-hours). Throughput energy (or Amp hours) is, in essence, the cumulative discharged energy (or Amp hours) over a specified period of battery use. A regulation power cycle that has a lot of back and forth power swings would result in high throughput energy and might also cause excessive battery heating.

Initially in this study, it was hoped that the Cal ISO would be able to provide a real-time regulation power profile calculated expressly for a vehicle. However, this was not possible for a number of reasons. First, the power capacity of a single vehicle is too small to be accepted in the Cal ISO energy management system⁴ (EMS). Second, the system is not set up to handle

⁴ An Energy Management System, or EMS, is the grid operator's computer system that keeps track of and manages

regulation sources where the nominal power level is zero with regulation down actually representing a load rather than reduced generation – unlike a powerplant, an EV would provide regulation down by pulling power from the grid as a load, rather than simply reducing generation output. (The end result to the grid operator’s area control error is the same, but the EMS was not originally configured for this kind of regulation source. This is not expected to represent a major impediment to the V2G concept. See sections 6.2.1 and 6.2.6 below for discussion). Finally, it would have been quite difficult to extract and transmit a real time signal from the EMS for the purposes of this project. The EMS is set up to communicate with large power plants through costly dedicated systems, and it was not practical to implement an alternate internet-based communication method just for this project.

Instead of real-time ISO dispatch data, the dispatch profile was calculated from historical data. This was accomplished through analysis of historical data provided by the Cal ISO for a six-day period from December 9-14, 2001. The data provided by the Cal ISO included 4-second time histories of dispatched regulation at a few hydro power plants along with the contracted nominal generation levels and regulation up and regulation down contract limits (which are constant over one-hour periods).

Also provided was the area control error (ACE) and processed area control error⁵ (PACE) for the Cal ISO control area. PACE represents an approximation of the ideal total regulation that would be dispatched at any given moment. The actual total dispatched regulation may differ from the PACE value due to ramp-rate limitations of the sources of regulation, or if the PACE value exceeds the total amount of regulation capacity available at that time. PACE has a long term average of zero, and it is positive about half the time and negative about half the time. Positive PACE means that there is more power in the control area than desired and that regulation down is called for.

It was initially hoped that the same algorithm that is used in the real EMS could be used to post-process the historical data to determine a vehicle dispatch profile. However, this was not possible as the algorithms embedded in the EMS are complex, and cannot readily be applied to a new source of regulation in isolation. The EMS calculates the ACE and processed ACE and then through a complex algorithm allocates the resulting total regulation requirement out among all the units that are on regulation. In determining how to allocate the regulation requirement, the EMS has to account for various limitations on each unit such as maximum ramp rate and jerk rate. As a result, some units may be commanded to regulate up while others are still regulating down.

Two approaches were ultimately developed for deriving the vehicle regulation power profile. The first was to scale historical dispatch data. The second was to allocate a pro-rata share of the

generation and other aspects of the operation of the grid.

⁵ Processed ACE (PACE) is the output of a control loop in the energy management system that is attempting to control ACE to zero. Processed ACE represents the total regulation power command; this total is divided up among the various providers of regulation by the EMS.

total regulation requirement to the vehicle. These approaches are described in the following sections.

4.2.1 Regulation Power Profile by Scaling Dispatch Data

The first approach to deriving a suitable vehicle power profile was to derive a vehicle regulation power cycle from the sample dispatch data from the hydro powerplant. A sample day of regulation by the plant is shown in Figure 8. Shown are the nominal contracted generation level, the upper generation limit, the lower generation limit, and the actual generated power. The power level generally stays within the upper and lower generation limits and averages to approximately the contracted power limit.

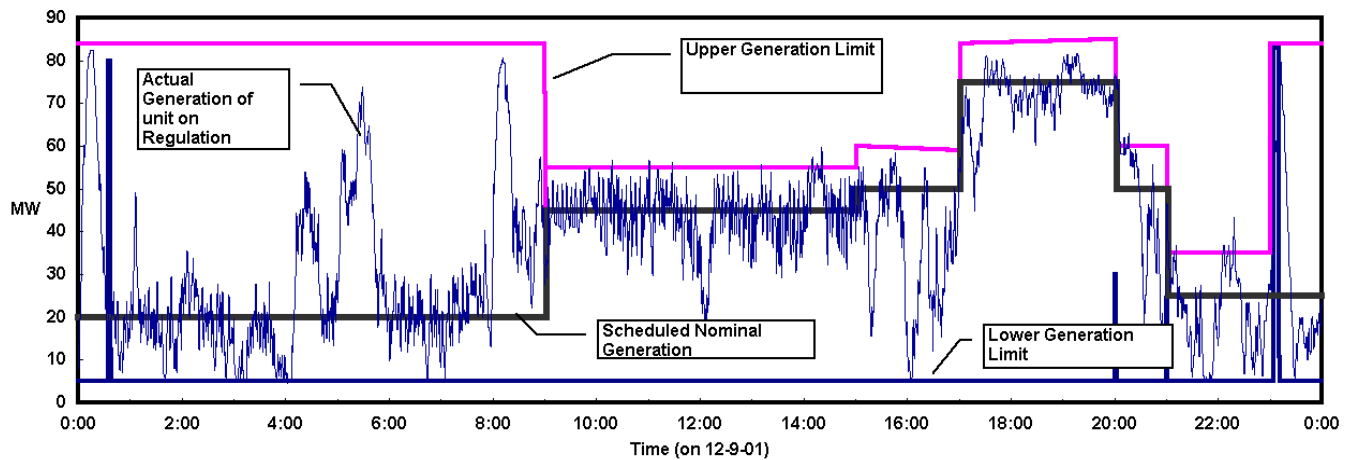


Figure 8. Full day power profile of a hydro power plant on regulation. Also shown are the scheduled nominal generation and upper and lower limits.

A vehicle performing regulation would typically have nominal contracted generation of close to zero, with symmetric limits of regulation up and regulation down on either side of zero (with regulation down being load (battery charging), regulation up feeding power to the grid (battery discharging)). An algorithm was developed that scaled the sample hydro powerplant regulation profile to zero nominal generation and scaled the regulation up and down limits along with the dispatched power down to symmetric and normalized values (limits of ± 1). The baseline powerplant regulation profile is shown in Figure 8. The resulting normalized profile scaled for a vehicle is shown in Figure 9.

The new profile was deemed flawed due to the uneven stretching of the profile between regulation up and regulation down during the times when the actual profile (Figure 8) had a nominal generation level that was skewed toward one of the upper or lower generation limits (i.e. the limits were not symmetric). For example, during the 9:00 to 15:00 time period, the scheduled nominal generation was close to the upper generation limit. For that period, an actual generation value on Figure 8 that is halfway between the nominal and maximum generation limit scales by this method to a normalized command of 0.5 or

50 percent in Figure 9. But an actual generation level that is below the nominal by an equal power amount scales to a much smaller magnitude, in this case about -10%. The result is that actual power fluctuations from the nominal level are scaled asymmetrically (from Figure 8 to Figure 9). Consequently the resulting long periods in Figure 9 with the average command above or below zero are not representative of the profile of the overall regulation requirement represented by PACE (see Figure 10 below).

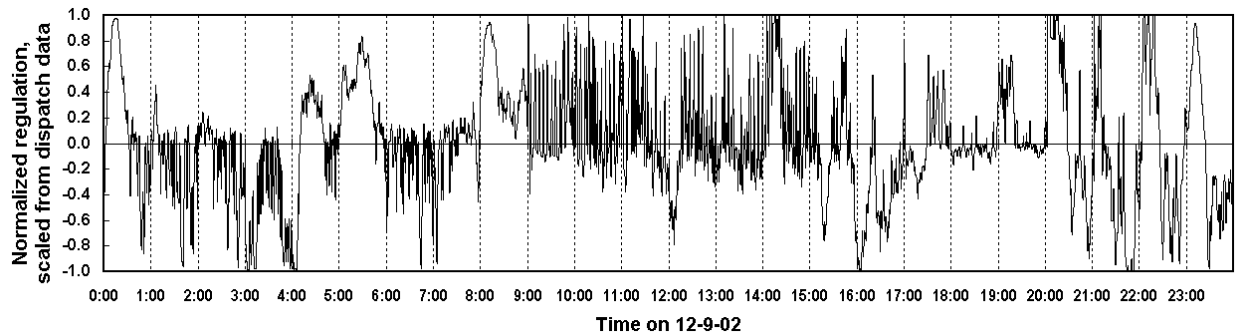


Figure 9. Sample normalized vehicle regulation power profile derived from regulation data. Long periods above or below zero are spurious and undesirable.

4.2.2 Regulation Power Profile by Pro-Rata Allocation

The other approach to deriving the vehicle regulation power profile was to allocate the regulation power to the vehicle as its pro rata share of the total regulation. The vehicle's 'fair share' of regulation was determined as the ratio of the vehicle's grid power capacity to the total regulation capacity available. For example, if the vehicle has 7 kW of regulation up capacity, and the total regulation up capacity is 700 MW (700,000 kW), then the vehicle represents $7/700,000$ or 0.001% of the total regulation, and would be allocated a 0.001% share of the total regulation dispatched at any time (0.001% of PACE).

In order to calculate the pro-rata vehicle regulation power profile, it was necessary to know what the total regulation up and regulation down capacity was for the six-days covered by the available regulation data. The regulation capacity needed by the Cal ISO to properly operate the state's control area is made available in one of three ways: the day-ahead market, the hour-ahead market, and self provision. In the day-ahead and hour-ahead markets, regulation capacity is procured by the Cal ISO on behalf of the users of the grid (and charged to these users in proportion to their usage of the transmission grid). Self-provided regulation is provided directly by the users of the grid; rather than paying Cal ISO to procure regulation, a user may choose to self provide some or all of their share of regulation capacity.

The regulation capacity data was obtained from the Cal ISO OASIS [6] web page. OASIS is a front end to a large database of public information available about the

operation of the California grid. Regulation is procured over three geographical zones within the control area denoted SP15, NP15, and ZP26. Data from these zones was obtained for each procurement method (day ahead, hour ahead, and self provided), and combined to determine the total regulation capacity (both up and down) available each hour over the six-day period. Figure 10 shows the regulation up and regulation down capacity over the first day of this period along with the total ideal dispatch of regulation as represented by the negative of PACE⁶.

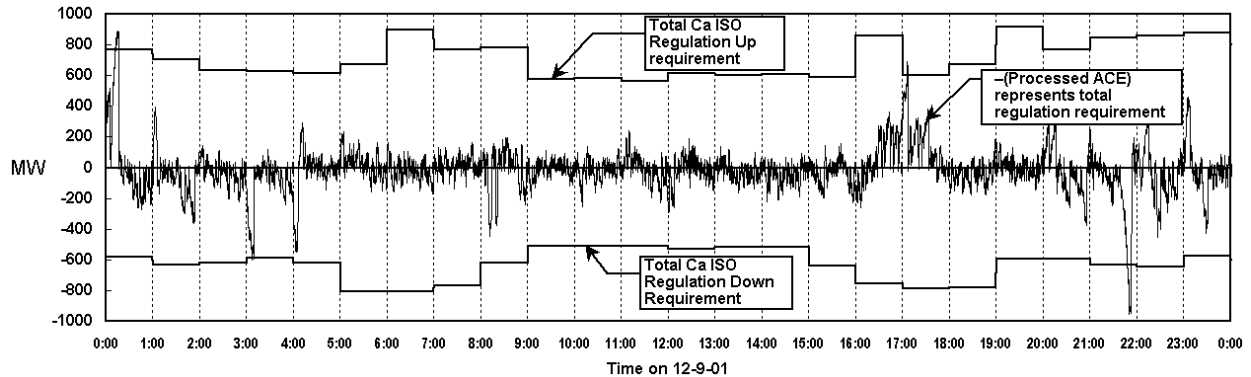


Figure 10. Total regulation capacity (procured+self) and regulation dispatch requirement (represented by -PACE).

The final form of the vehicle regulation power dispatch was calculated by normalizing the PACE data by the total regulation capacity available. The PACE data was normalized by regulation up capacity when PACE was negative and by regulation down capacity when PACE was positive. If PACE was larger than the regulation capacity available, the resulting normalized value was clipped to plus or minus one. A sign convention was chosen such that positive vehicle power command corresponds to feeding power to the grid. The resulting normalized vehicle power profile is shown in Figure 11. Actual vehicle power profiles were determined by scaling the normalized profile by the regulation power capacity available from the vehicle.

⁶ When PACE is positive, it means that there is at that moment more power than desired, indicating regulation down is called for. The ideal dispatched regulation power is then $-PACE$.

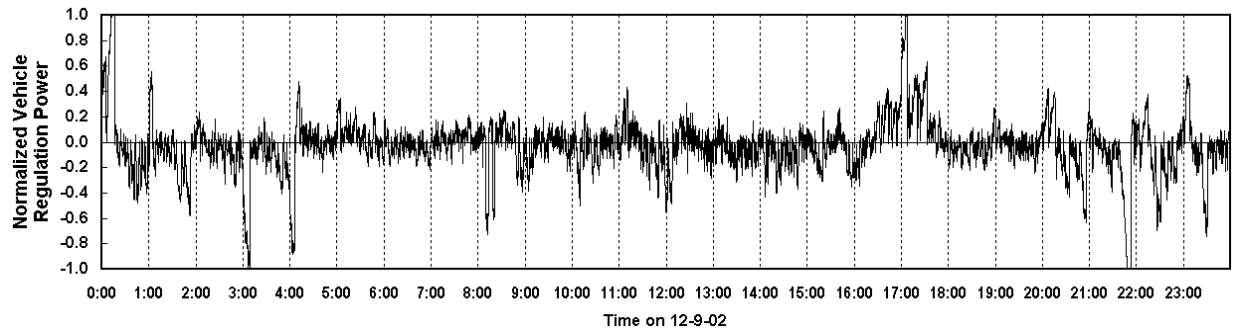


Figure 11. Normalized vehicle regulation power profile for 12-9-01

4.3 Software and Control Systems Development

Systems were developed to enable the vehicle to be commanded remotely according to the architecture shown in Figure 6 on page 5. Since it was not possible to get a real-time grid regulation command sent at 4-second intervals from the Cal ISO, a simulated ISO was created on a local server to send out regulation commands to the aggregator every 4 seconds. A basic aggregator system was developed to act as the middleman between the simulated ISO and the vehicle. Web pages were developed to demonstrate how a vehicle driver might set vehicle preferences and default usage profiles and track the status of their vehicle.

4.3.1 Simulated ISO

The role of the simulated ISO was simply to serve up to the aggregator a dispatch command every 4 seconds. The dispatch command values were the normalized vehicle regulation power profiles as described in section 4.2.2 above. Initial development and testing of the simulated ISO was carried out with a JAVA program running on a server physically located 20 miles away from the aggregator server. Communication between the two was via the internet. Data packets were not encrypted for this project; in a real deployed system, encryption and/or a dedicated link would be employed between the ISO and the aggregator. The time to transmit a command to the aggregator and have the aggregator acknowledge receipt was consistently on the order of only 50mS – essentially instantaneous for the time scales required for response to regulation (~4 seconds). As this time lag was not significant and to simplify testing, the simulated ISO was relocated to run on the same computer that ran the aggregator. Each was a separate task on the same computer. The simulated ISO task sent the regulation command to the aggregator task running on the same computer. The time lag from the aggregator to the vehicle(s) over the wireless connection was more of a concern, and was monitored and logged by the aggregator software.

4.3.2 Aggregator

In a deployed V2G system, the role of the aggregator is to be the middleman between the grid operator and thousands of vehicles connected to the grid. The aggregator needs to know the default usage profiles of all the vehicles in order to determine a projected aggregate vehicle availability profile. Default usage profiles are entered by each driver into the aggregator's database through a web interface (an example interface shown in section 4.3.3 below). The actual profile of available vehicles (and hence regulation capacity) will differ from the default profile since vehicle drivers will not operate their vehicles in exact accordance with their projected default usage. The difference between the aggregate capacity represented by default usage profiles and the actual aggregate capacity will diminish as the number of vehicles in the system increases. The combination of default profiles and historical actual vehicle usage will provide aggregators with sufficient data to determine in advance with some certainty the capacity that will be available at any given time. This will allow aggregators to bid into ancillary services markets with confidence that the capacity they are bidding will truly be there when it is needed. Individual vehicles will connect and disconnect from the grid at times determined by driver needs without significantly affecting the total capacity once the number of participating vehicles are in the hundreds. The aggregate power capacity will become more and more predictable as the number of participating vehicles increases.

The software to create a complete aggregator entity will be quite complex, and it was well beyond the scope of this project to create a full-featured aggregator. Instead, a limited aggregator function was developed that would receive regulation commands from the simulated ISO, and forward them on to the vehicle. Confirmation of receipt was relayed back from the vehicle and recorded by the aggregator.

Two forms of aggregator software were developed. The first was a JAVA-based application with links to an SQL database. This approach proved to be cumbersome during the testing as it was difficult to easily display on-screen the complete status of the vehicle. An alternative aggregator function was developed as a National Instruments LabView program. While not suitable as a basis for an aggregator function in a deployed system, the LabView approach proved to be far more useful in the test environment.

4.3.3 Driver Interface

A vehicle that is a participant in a V2G system would have a web-based home page to allow the vehicle driver to set up various default parameters and track the status of the vehicle. Sample web pages were developed to demonstrate the types of user interaction that might be accommodated. These are available for evaluation online at www.acpropulsion.com/Web%20interface/V2g_user_login.htm and are also shown below.

Figure 12 shows a 'home page' for the vehicle that would be reached after the driver logs in with a user name and password. This page shows the status of the vehicle: whether

V2G is active or not, its location, battery state of charge, and (possibly) a cumulative V2G value generated for the month.

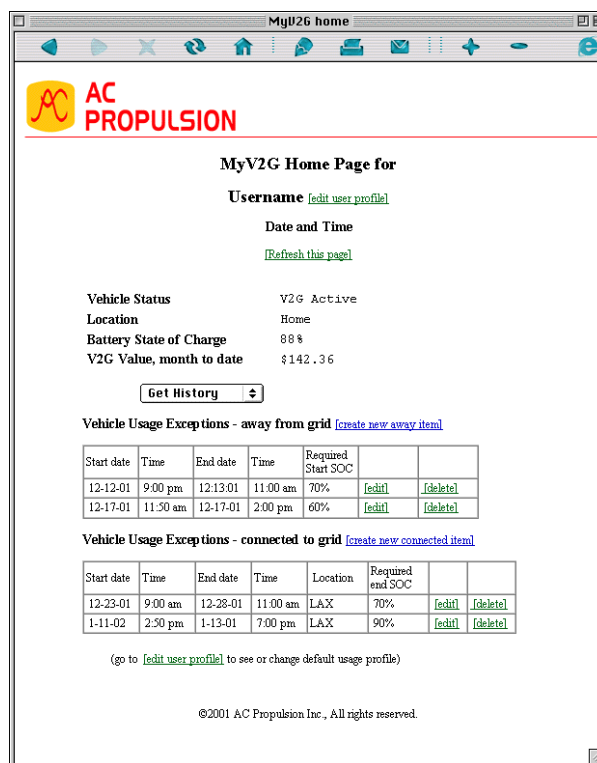


Figure 12. V2G user home page.

The page has a few linked functions. There is a link to a user profile page where default information about the driver and vehicle is setup. The other main functions are a listing of any exceptions to the default usage profile and links to pages to edit or delete these exceptions. By having a user enter significant exceptions to the default profile, it will help the aggregator develop a more accurate advance picture of the available capacity profile, which will allow for more accurate bidding into the advance markets. Examples of significant exceptions might include periods where the vehicle is away on a vacation trip and wouldn't be connected to the grid for an extended period, or when the vehicle was parked for an extended period connected to the grid (such as at an airport when the owner was away on a trip). Once the number of vehicles becomes very large, it may not be necessary to track exceptions, as the relative effect on the total caused by any individual exception is negligible. The pages for setting up exceptions are shown in Figure 13.

MyU2G Away Exception

Username

Create new exception: vehicle away from grid

Start of Away Time:

Jan 5

Feb 6

Mar 7

Apr 8

May 9

Jun 10

Jul 11

Aug 12

Sep 13

Oct 14

Nov 15

Dec 16

1

2

3

4

5

6

7

8

9

10

11

12

Minutes

00

10

20

30

40

50

am

pm

Min Batt SOC

30%

40%

50%

60%

70%

80%

90%

End of Away Time:

Jan 7

Feb 8

Mar 9

Apr 10

May 11

Jun 12

Jul 13

Aug 14

Sep 15

Oct 16

Nov 17

Dec 18

1

2

3

4

5

6

7

8

9

10

11

12

Minutes

00

10

20

30

40

50

am

pm

Submit

[return to V2G home](#)

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MyU2G Connected Exception

Username

Create new exception: vehicle connected to grid

Start of Connect Time:

Jan 20

Feb 21

Mar 22

Apr 23

May 24

Jun 25

Jul 26

Aug 27

Sep 28

Oct 29

Nov 30

Dec 31

1

2

3

4

5

6

7

8

9

10

11

12

Minutes

00

10

20

30

40

50

am

pm

pick location

Home

Work

Airport

Other

End of Connect Time:

Jan 20

Feb 21

Mar 22

Apr 23

May 24

Jun 25

Jul 26

Aug 27

Sep 28

Oct 29

Nov 30

Dec 31

1

2

3

4

5

6

7

8

9

10

11

12

Minutes

00

10

20

30

40

50

am

pm

Submit

[return to V2G home](#)

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Figure 13. Pages to input exceptions to default usage.

Figure 14 shows the user profile page. This setup page includes pull down menus to select vehicle type (Figure 15) and to select a minimum acceptable battery state of charge (Figure 16). The minimum state of charge value represents the lowest state of charge that driver will accept during the time the vehicle is providing regulation services. The battery will undergo swings in state of charge as the vehicle cycles energy to and from the grid. Extended periods of regulation up (battery discharging into the grid) could result in discharge of the battery pack down to this lower limit. In this case, the aggregator would have to stop further regulation up (discharge) for that vehicle and allocate the lost regulation up from that vehicle out among the other on-line vehicles. (Part of the testing goals of this project was to assess how often a lower state of charge limit would be reached in practice.)

V2G User Profile Setup

Last Name	Brooks	
First Name	Alec	
Street Address	441 Bornego Ct	
City	San Dimas	
State	CA	
Zip Code	91773	
Phone	909-592-5399	
Email	abrooks@serpropulsion.com	
Vehicle	Beetle	Select Vehicle Type
Min allowable SOC during V2G (ending SOC set below)	40%	Min U2G Batt SOC

Baseline Usage Connect Hours:

	Begin	End	Location edit location	Minimum SOC needed at end of period
Weekdays			pick location	Min Batt SOC
	12:00 am	7:50 am	Home	80
			pick location	Min Batt SOC
	8:20 am	5:40 pm	Work	90
			pick location	Min Batt SOC
	6:20 pm	12:00 pm	Home	30
Weekends			pick location	Min Batt SOC
	12:00 am	10:00 am	Home	70
			pick location	Min Batt SOC
	1:00 pm	6:30 pm	Home	90
			pick location	Min Batt SOC
	11:30 pm	12:00 pm	Home	30

Submit

[return to V2G home](#)

Figure 14. User profile setup page.

Select Vehicle Type

- Beetle
- AC Propulsion tzero
- Dell Dimension E1
- Sun Microsystems sparqjet
- Compaq Epaq
- Intel Energium U

Figure 15. Vehicle type menu.

Min allowable SOC during V2G (ending SOC set below)	40%
---	-----

Baseline Usage Connect Hours:

	Begin	End	Location edit locati	OC d of

Min U2G Batt SOC

- 30%
- 40%
- 50%
- 60%
- 70%
- 80%
- 90%

Figure 16. Menu to select minimum state of charge (SOC) allowable at any time during V2G operation.

The user profile page also has the setup for baseline usage connect hours for the vehicle. This information allows the aggregator to build up the nominal expected regulation capacity profile. The form of the baseline usage profile includes beginning and end times for times the vehicle will be connected to the grid. The typical usage profile would have the vehicle connected at home during most non-work hours and on the weekends, and at work during working hours.⁷ The profiles are entered separately for two time classes: weekdays and weekends. Individual day profiles would be possible but probably not necessary. For each time period of the baseline usage profile, the driver enters a location (Figure 17), and minimum battery state of charge desired at the end of that period (Figure 18). This minimum state of charge is different from the minimum at any time during regulation. A driver may find it acceptable to allow the state of charge to dip to a low value at some times, but wants to guarantee the state of charge is at a certain level at a specific time (such as at the end of a workday for the drive home). Alternately, if preferred by the driver, the minimum state of charge menu selections could be configured as minimum range requirement selections.

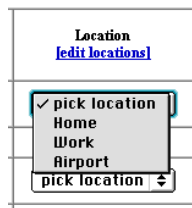


Figure 17. Vehicle location menu for setting up nominal usage profile.

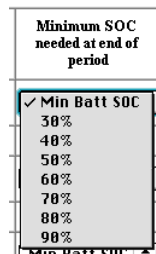


Figure 18. Minimum state of charge (SOC) menu for setting minimum state of charge at the end of a nominal grid-connect period.

The user home page also has a pop up menu to call up an operational history of the vehicle over a selected time period.

⁷ Workplace grid connection (charging) is very desirable for a V2G system. If workplace charging is not available, the value generated for that vehicle will be diminished (quantitative assessment of workplace charging is given in section 5.1.4.

Any of these web pages could also be formatted for Wireless Application Protocol (WAP), the web standard for displaying content on handheld devices such as personal digital assistants and web-enabled wireless phones.

4.3.4 Vehicle Software and V2G Controls

The overall architecture of the test vehicle's power system is shown in Figure 19. The standard components common to an electric vehicle without V2G include the string of battery modules, the power electronics unit (PEU), the drive motor, recharge port, and the Vehicle Management System (VMS). The components added to provide wireless control of V2G capability consist of a control computer and wireless modem. The control computer serves as the interface between the modem and the VMS. It tells the VMS when to switch the PEU into V2G mode, and converts V2G power commands into AC line current commands based on the nominal grid connect voltage sensed by the system. It also reports back several operational parameters (such as voltage, current, amp hours, battery temperature) to the aggregator over the wireless link.

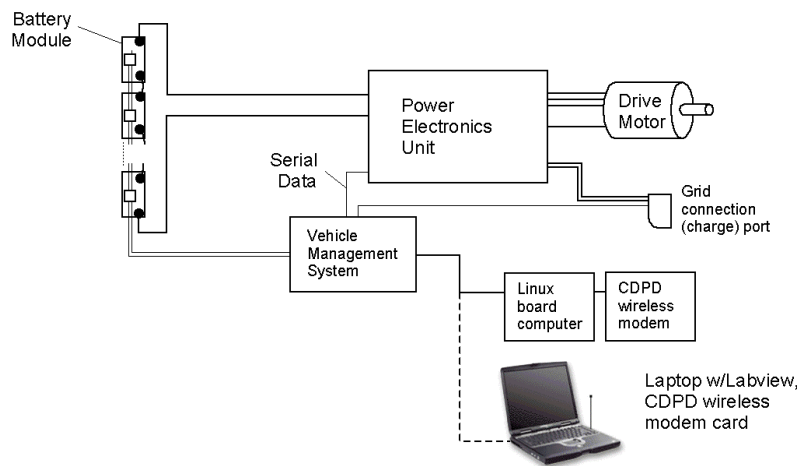


Figure 19. Architecture of vehicle power system with V2G capability.

4.4 Grid Regulation

For this study, the operational scenario assumed two main periods of grid connection: (1) at home after work through the night to the following morning, and (2) at the workplace during normal working hours. Tests of duration corresponding to home (14h) or workplace (9h) were carried out with different initial conditions and levels of grid services. In addition, a test with a 48-hour period of continuous grid regulation was performed to evaluate a situation in which a vehicle is connected and available for an extended period. All testing was performed using regulation power profiles from December 9 and 10, 2001.

A vehicle providing grid regulation will normally need to also recharge batteries to recover the energy used in normal driving. For this purpose, a small offset power was added to the

regulation dispatch power. The offset power was calculated based on approximately achieving a targeted state of charge at the end of the test period. The offset power also included a small amount of bias power to cover the losses in the system (on the order of 250W). The actual achieved end point state of charge will vary from the target since the regulation power profile may contain significant net energy changes over the period of the test, even though in the long term, these average out to near zero. Part of the goal of these tests was to assess whether the state of charge fluctuation due to regulation services will be more than would be acceptable to a driver.

Individual test runs were made at a variety of initial conditions, durations, grid connect voltages and current capacities. A few tests were also made with the vehicle power profile scaled up by a factor of two, but with the same overall upper and lower power limits. For example, in a normal run if a command at any moment asked for 1 kW, in this scaled up version the vehicle would deliver 2kW. The purpose of this test was to assess the impact of higher levels of regulation power cycling. As discussed in section 4.2 above, there is some uncertainty in the form of the actual power dispatch that a vehicle would experience. The test with two-times scaled commands was intended to assess the impact of operating at higher power levels (and higher levels of energy throughput). The principal impacts would be expected in the areas of battery heating and battery life.

Tests were programmed to run automatically from the LabView program that simulated the aggregator function. A test methodology was developed to provide an accurate assessment of the initial and final battery state of charge, as indicated by integration of battery current, or Amp hours. Before the regulation cycling began for a particular test, the battery was pre-conditioned by first recharging the pack fully, then performing a full discharge test to a defined end point, and then recharging back to a desired initial condition by adding a controlled number of Amp hours back in. At this point, the regulation power profile was initiated. The time in the vehicle command profile (Figure 11 above) at which vehicle dispatch data started was 8:00 am on Dec 9 or 10 for the workplace case, or 5:30 pm for the home case. The workplace test duration was 9 hours, ending at 5:00 pm and the home case duration was 14 hours, ending at 7:30 am on Dec. 10. At the end of each regulation cycling test period, a discharge test was again made to accurately assess the remaining capacity at the end of the test.⁸ Figure 20 shows a sample trace of the vehicle's reported battery Amp-hour depletion over the course of a test.

⁸ The vehicle control system also keeps track of the battery state of charge by integrating battery current. However, after extended back and forth cycling of grid regulation, small offsets or errors can lead to inaccurate results. A discharge test at the end of the test is a direct method of determining the remaining capacity.

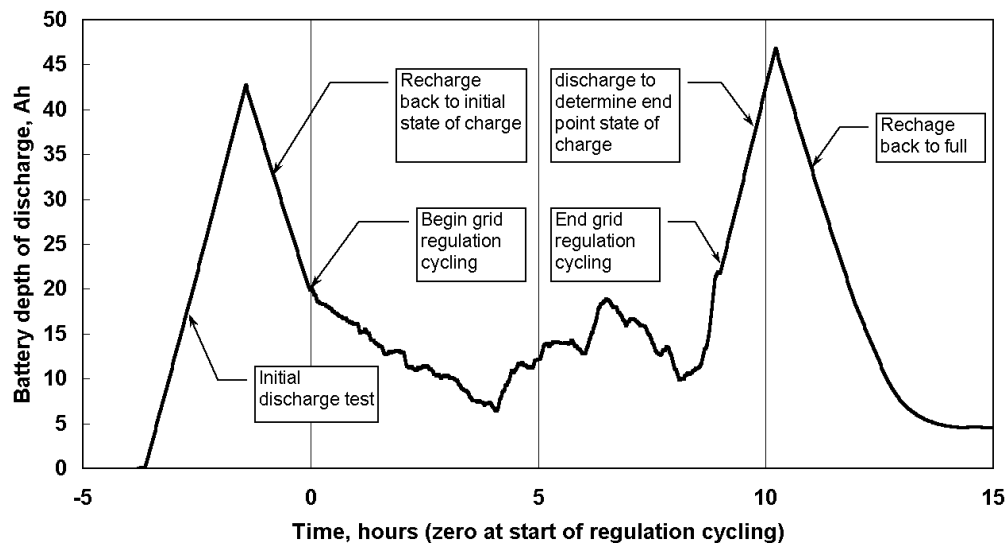


Figure 20. Example of battery Amp-hour discharge over a complete test cycle (test #15 in Table 1 below).

Power dispatch commands were sent wirelessly to the vehicle at 4-second intervals⁹, and the vehicle response was monitored and recorded. The power command took the form of an AC line current command, which was derived by dividing the power command in Watts by the nominal line Voltage of either 208V or 240V. (The power factor is normally unity). The following data values were recorded:

Time	Real time of day
Index - command file	the data point number in the command file. The first point corresponds to 0:00 hours on Dec. 9, 2001. Subsequent point are spaced at 4 second intervals
Latency	Time (in milliseconds) from when command was sent to vehicle until acknowledgement is received back from vehicle. Acknowledgment also includes vehicle response data from the prior command.
Commanded line current	AC Line current command: desired power / nominal line voltage
Actual line current	AC line current as measured by the vehicle's power system

⁹ Most grid operators' energy management systems operate at a 4-second update rate.

Line Voltage	AC line voltage as measured by the vehicle's power system
Battery Voltage	Voltage of the battery pack as measured by the vehicle's power system
Battery current	Battery pack current (Amps) as measured by the vehicle's power system
Amp Hours	Battery Amp-hours, as integrated and reported by the vehicle management system
Battery Temperature	The highest temperature of the 30 batteries in the pack. Measured by the BatOpt battery management modules (one on each 12V battery).

4.5 Battery Efficiency

In a related project, the battery test lab at the National Renewable Energy Laboratory assessed the energy input-output efficiency of a smaller version of the Panasonic lead acid battery in the test vehicle. Energy losses in the battery were accurately measured by running the test with the battery inside a very sensitive calorimeter. The tests involved imposing a hybrid driving cycle on a battery module at various initial states of charge. While the tests did not directly use the grid regulation power data from this study, the results (given in section 5.2 below) show qualitatively how battery losses from small cycles vary with state of charge.

4.6 Value Assessment

The value generated by vehicles providing grid regulation was evaluated based on several operating scenarios and grid connection power capacities. Data on market pricing of regulation up and regulation down was obtained from the Cal ISO OASIS web site [6]. Data was obtained for three different 7-day periods; the first corresponding to the time period regulation of the dispatch data (Dec 9-14, 2001) plus one day to fill out the week. Since regulation pricing continues to be volatile in California, two other periods were also evaluated: the weeks of April 14, 2002 and July 7, 2002. The hourly gross value of vehicle-based regulation was determined as the product of the vehicle's regulation power capacity (in kW) and the sum¹⁰ of the regulation up and regulation down hourly prices (scaled from quoted per MW values to per kW values):

¹⁰ The vehicle is compensated for both regulation up and regulation down capacity simultaneously because it has the ability to ramp power up (to grid) or down (from grid) from a zero-power nominal level. At any given moment, the vehicle is providing regulation up or regulation down, but it is being compensated for providing the capacity to provide either one on demand.

$$(1) \quad \text{Hourly value} = (\text{vehicle reg capacity up or down}) * (\text{reg up price} + \text{reg down price})^{11}$$

A sample of the regulation pricing data for Dec 9 and 10 is shown in Figure 21 along with a depiction of the timing of the test periods. Electric vehicle grid regulation value results are given in section 5.1.4 below.

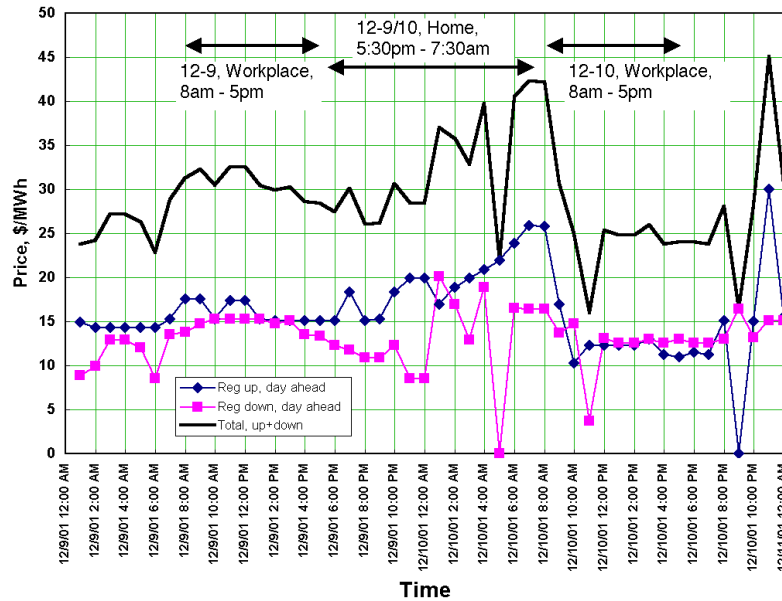


Figure 21. Regulation pricing for 12/9/01 and 12/10/01.

The expected net value is determined by subtracting costs from the gross value. For this study, the only cost considered is the battery wear-out caused by the additional use. Other costs, such as operation of the aggregator, are not known. These will have to be covered by the net remaining value after accounting for battery wear-out costs.

4.7 Deployment Issues

There are many issues to be addressed and overcome prior to commercial deployment of a vehicle to grid systems. These relate to areas such as grid interconnection standards, ability of the distribution grid to accommodate two-way power flow, the regulatory and market landscape, how services from vehicles would be measured and compensated, who the customer for V2G is, and the relevance of physical location of the vehicle. A number of approaches were taken to research and understand these issues and to formulate a proposed framework for addressing the issues as part of a deployment strategy. The research approach was to become very familiar with the current state of affairs distributed generation (also known as distributed energy resources, or DER) and then to communicate with players in and related to the DER industry to

¹¹ Regulation prices are quoted in \$/MW of capacity over a one-hour period. The quoted prices are divided by 1000 to obtain \$/kW for use in this formula.

get reaction and feedback to the V2G concept. This involved internet research, personal communications, both written and verbal, and attendance at conferences and a workshop¹².

5. Results

5.1 Grid Regulation Test Results

In all, 227 hours of grid-connected test time were completed over 16 individual tests. The tests covered three basic scenarios: (1) connected all day at work, (2) at home after work through the night to leaving for work the next morning, and (3) an extended period of continuous connection, such as the vehicle being left for a few days at an airport parking lot with charge stations. Table 1 below lists the basic parameters for the 16 tests.

Table 1. Summary of tests completed

Test number	Test date (all 2002)	Start time for regulation profile	Duration, hours	Description	Grid connect Voltage, VAC	Grid Connect Current Rating, Amps	Grid Power capacity, Watts (Note 1)	V2G command mult.	Target Start SOC	Target End SOC
1	5/8	12/9/01 8:00	9	Work	208	32	±6,656	1	60	80
2	5/9	12/9/01 8:00	9	Work	208	32	±6,656	1	60	80
3	5/14	12/10/01 8:00	9	Work	208	32	±6,656	1	60	80
4	5/15	12/10/01 8:00	9	Work	208	32	±6,656	2	60	80
5	5/20	12/10/01 8:00	14	Work	240	32	±7,680	1	60	80
6	5/30	12/9/01 17:30	14	Home	240	32	±7,680	1	40	70
7	5/31	12/9/01 17:30	13	Home	240	32	±7,680	1	40	70
8	6/3	12/9/01 17:30	14	Home	240	32	±7,680	1	50	70
9	6/4	12/9/01 17:30	14	Home	240	32	±7,680	2	50	70
10	6/5	12/9/01 17:30	14	Home	240	32	±7,680	1	50	70
11	6/12	12/9/01 17:30	14	Home	240	32	±7,680	2	50	70
12	6/13	12/9/01 17:30	14	Home	240	32	±7,680	1	20	70
13	6/14	12/9/01 17:30	14	Home	240	32	±7,680	1	20	70
14	6/17	12/10/01 8:00	9	Work	208	80	±16,640	1	50	70
15	6/18	12/10/01 8:00	9	Work	208	80	±16,640	2	50	70
16	6/24	12/9/01 0:00	48	Long term Parking	208	32	±6,656	1	50	50

Note 1: Grid power capacity is the amount of regulation up or down the vehicle can provide

5.1.1 Battery Energy Throughput

The battery pack of a vehicle that is providing regulation services will undergo additional energy cycling compared to a vehicle that is just used for transportation. This additional cycling will likely ‘consume’ some part of the battery pack’s useful life. How much degradation or wear-out is not yet known, and is subject to some debate. The amount can be reasonably bounded between a strictly pro-rata allocation of cost based on what

¹² Conferences attended: “Electric Transportation Industry Conference,” Electric Vehicle Association of the Americas, Dec. 2001; “Distributed Generation Opportunities & Obstacles,” California Alliance for Distributed Energy Resources, Nov. 2001; “Power System 2002 – Impact of Distributed Generation,” Clemson University Electric Power Research Association, March 2002. Workshop attended: “Microgrids As A Distributed Energy Resource (DER) Alternative,” California Energy Commission Public Interest Energy Research (PIER) program, May 2002.

fraction of a the battery's total throughput energy capacity¹³ is consumed by grid regulation and zero additional degradation. This approach gives no 'credit' for small cycles and low power typical of regulation being easier on the battery than deeper cycles typical of driving. At the other extreme, the cost of adding regulation on top of driving could actually be zero. This surprising result might occur if the life of the battery was limited by calendar time rather than actual usage¹⁴.

A measure of the additional battery cycling due to regulation is the throughput energy of the cycle. The nature of a regulation power profile is that energy is cycled back and forth. This back and forth of energy represents throughput energy in the system. The amount of throughput energy of a cycle is determined by adding up all the energy represented by positive power and negative power separately. In general, over a given cycle, one of these will be greater than the other, indicating a net energy from beginning to end. The throughput energy of the cycle is the energy that cycles back and forth during the cycle that does not contribute to the net energy at the end of the cycle. The value of the throughput energy is the smaller of the absolute values of the integrated positive and integrated negative energy values at the end of the cycle. For example, consider a simple test cycle: power flows from the grid for 1 hour at 1 kW, then back to the grid for 1.5 hours at 1 kW. The integrated negative energy is -1 kWh and the integrated positive energy is 1.5 kWh. The throughput energy of this cycle is 1 kWh, and the net energy is 0.5 kWh. An example for a more complex cycle (the regulation power profile of 12-9-01) is shown in Figure 22.

¹³ Total throughput energy capacity is defined as the product of a battery's rated energy capacity and its rated number of discharge cycles.

¹⁴ For example, the Panasonic battery pack in the EV1 is rated for 1000 cycles at 80% depth of discharge. This would represent 83,000 miles of driving at 180 Wh/mi, or about 7 years of normal use. It is generally accepted that lead acid batteries will last only 3 to 4 years calendar life, so an EV1 driver would have to drive 27,000 miles per year to use up the cycle life within a 3-year calendar life. Based on in-use experience, calendar life limiting may be more of an issue with lead acid and lithium battery types than with nickel metal hydride batteries.

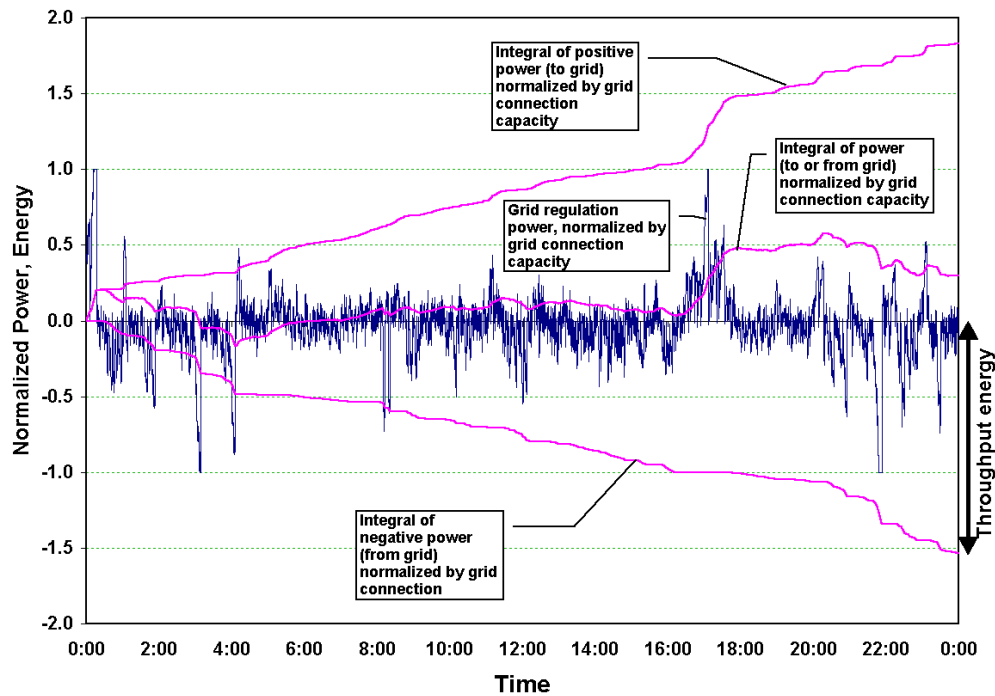


Figure 22. Example showing how throughput energy of a cycle is defined.

The calculated throughput energy for the cycles employed in the vehicle testing are given in Table 2. The overall energy throughput is seen to be about 5 percent of the hourly rated regulation capacity. For example, a vehicle providing 20 kW of regulation up and 20 kW of regulation down over a one-hour period would experience 1 kWh of energy throughput. The two-times scaled cycle, representative of a possible case in which the vehicle is worked ‘harder’ by the ISO than the nominal pro-rata allocation of regulation power, shows about twice as much throughput energy.

Table 2. Throughput energy of tested regulation power cycles.

Test power profile	Test numbers	Duration, h	Total cycle throughput energy per kW rated regulation, kWh/kW	Throughput energy per hour per kW rated regulation, kWh/h-kW (dimensionless)	Net Change in energy, per kW rated regulation, kWh (pos: to the grid)
work 12-9	1,2	9	0.465	0.052	0.112
work 12-10	3,5,14	9	0.350	0.039	0.339
work 12-10, 2x	4,15	9	0.700	0.078	0.678
home 12-9	6,7,8,10,12,13	14	0.827	0.059	0.617
home 12-9, 2x	9,11	14	1.653	0.118	1.233
long term 12-9,10	16	48	3.290	0.069	1.071

Average, cycles w/nominal reg. profile	0.055
Average, cycles with 2X req. profile	0.098

As described above, there are a range of possible battery ‘wear out’ costs associated with throughput battery energy. Calculating a range of possible costs and comparing with typical market prices for regulation provides an overall reality check of the viability of vehicle-based grid regulation. Table 3 below lists battery costs for Panasonic EV1260 lead acid batteries, both for current and future volume production cases. The EV1260 battery is rated at 1000 cycles to 80 percent depth of discharge, yielding a total lifetime throughput energy of 720 kWh per 12V module. The first two lines in the table calculate battery throughput energy costs assuming that the type of shallow cycling from grid regulation is equally degrading to the battery as are larger and higher-power cycles typical of driving. The third line assumes that the smaller cycles use up lifetime throughput capacity at half the rate. The last three columns show that the value of regulation services comfortably exceeds the battery cost for the two production pricing cases. The value and costs are about equal, however, when considering the current pricing, which is based on very low volume production. Until real extended testing of batteries under these cycling conditions is performed, these results should be considered only as an estimate. As noted above, it could turn out that performing grid regulation does not shorten battery life (as measured by miles of driving usage) at all.

Table 3. Cost of throughput energy and battery wear-out relative to typical value of regulation service provided .

Case	Battery production scenario	Battery Degredation Assumption	Module cost, \$ (Panasonic data)	Nameplate energy capacity, kWh	Cycle life	Total throughput energy capacity, kWh	Cost per throughput energy, \$/kWh	Cost per kW regulation capacity, per hour, nominal profile, \$/kW/h	Cost per kW regulation capacity, per hour, 2X profile, \$/kW/h	Typical regulation value (sum of reg up and reg down), \$/kW/h
1	Current low-volume production	shallow regulation cycling has degrades same as deeper cycling from driving	330	0.72	1000 cycles to 80% DOD	720	0.458	0.0252	0.0449	0.02 to 0.05
2	Volume production (30K modules / month, 12,000 veh/year)		90	0.72	1000 cycles to 80% DOD	720	0.125	0.0069	0.0123	0.02 to 0.05
3		shallow regulation cycling has degrades half as much as deeper cycling from driving	90	0.72	2000 equiv cycles to 80% DOD	1440	0.063	0.0034	0.0061	0.02 to 0.05

5.1.2 Battery Pack Capacity

The Panasonic EV1260 batteries installed in the test vehicle are nominally rated at 60Ah. In actual electric vehicle duty, achievable capacity ranges from 50 to 55 Ah when new. The pack in the test vehicle was about two years old with 12,000 EV miles when the tests started. Figure 23 shows the progression of measured capacity of the pack over the course of the testing. The pack finished the testing with 13% more capacity than at the start. No conclusions can be drawn from this other than there was no apparent immediate harm done to the pack as a result of the testing.

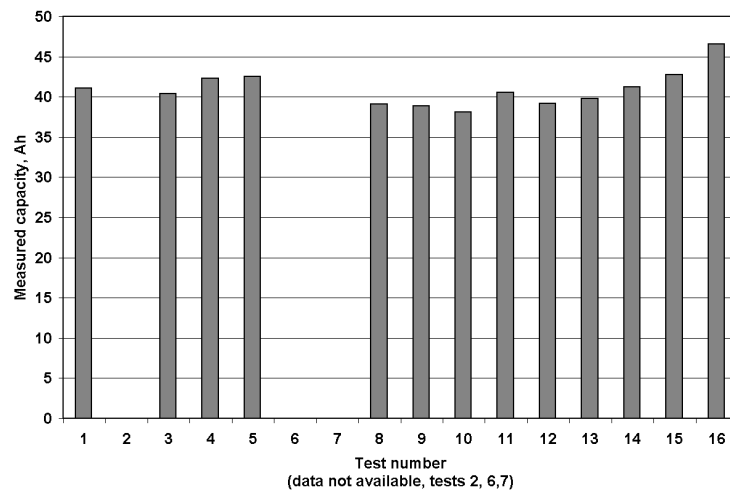


Figure 23. History of measured battery pack capacity over the course of the tests.

5.1.3 Wireless Performance

The wireless link between the aggregator server and the vehicle was not as robust as would be required for a deployed system. The link was expected to have been a transparent always-on TCP/IP connection at 5-10k bps. The wireless data service was based on the CDPD (cellular digital packet data) system and was provided by AT&T Wireless. At times a connection would be difficult to make. Moving the receiving antenna a few feet often brought back the connection. At locations with poor cellular coverage or at some indoor sites, a connection was never achieved. Once a connection was made, the response time was entirely adequate. The aggregator server logged the time latency between sending out each command and receiving an acknowledgement back from the vehicle. Figure 24 shows a histogram of response times for test number 16 (the longest test, at 48 hours). Fully 99.55% of all responses were received in less than one second and 99.94% in less than two seconds. This response performance is well within the Cal ISO AGC timing requirements, which require a maximum of two seconds of communications latency each way between the EMS computer and the powerplant's AGC control interface [7].

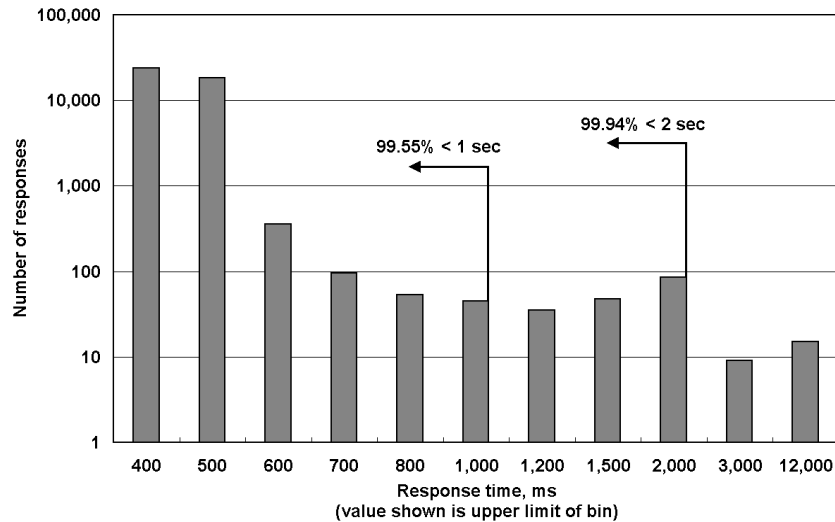


Figure 24. Wireless response time histogram.

The communication difficulties noted in this project are not considered to be an impediment to implementation of V2G, as wireless data communication is evolving very rapidly and several new options will be available soon.

5.1.4 Value Created

The potential revenue generation by an electric vehicle performing grid regulation was assessed for six scenarios involving various combination of home and workplace connection (charging) availability and power capacity. In all cases, it was assumed that a home connection was available, either at the current standard of 32A, 240V (7.68 kW) or at an up-rated high current connection of 80A, 240V (19.2 kW). The availability of a connection at the workplace is highly desirable for maximizing the benefit of V2G as well as the ability to increase the daily driving range capability. However, it is not assured that an EV driver would have access to workplace charging, so values were calculated with and without. The type of connection that might be available at a workplace is a standard 32A 208V¹⁵ (6.7kW) service. A workplace option with 80A, 208V (16.6kW) was also analyzed. The vehicle availability to the grid when parked at home was assumed to be, on average, 90 percent of the time on weekends, and all of the time during the non-working periods on weekdays (midnight to 7:30 am and 5:30 pm to midnight). At work, the availability was assumed to be from 8:00 am to 5:00 pm on weekdays. Overall, the vehicle is assumed to be available 94.2% of the time (67.4% of the time at home, 26.8 % at work).

Values for sample weeks were calculated for a vehicle providing grid regulation with the methods and regulation pricing data described in section 4.5 above. Regulation up and

¹⁵ The charging voltage available at most non-residential sites is at 208V.

down prices were obtained for every hour of the sample week. The value for any given hour of connect time was calculated according to equation 1 in section 4.5. The total values shown in the table include a summation of all weekend hours, scaled by 0.9 as described above, and all vehicle connect hours on weekdays. Half-hours were counted as 50% of the hourly value. The value results for the six scenarios are presented in Table 4. The values shown are annualized based on regulation pricing data for the week shown. The following equation summarizes the calculation of each annualized gross value shown in the table.

$$\text{Annualized value} = 52 \cdot \left\{ \begin{array}{l} 0.9 \cdot \sum(\text{weekend hourly values}) \\ + \sum(\text{weekday hourly and half hourly values at home}) \\ + \sum(\text{weekday hourly values at work}) \end{array} \right\}$$

The values are the gross amounts of income; battery depreciation costs (which are unknown at this time) would need to be subtracted to determine the net value.

Table 4. Annualized gross value of EV grid regulation (does not include battery depreciation costs).

Case	Connection Current Rating, Amps (Note 1)		Annualized Gross Value (\$) based on market prices from week of:		
	Home (240V)	Work (208V)	12/9/01	4/14/02	7/7/02
1	32	none	\$ 967	\$ 1,130	\$ 1,402
2	80	none	\$ 2,417	\$ 2,826	\$ 3,504
3	32	32	\$ 1,215	\$ 1,440	\$ 2,015
4	32	80	\$ 1,587	\$ 1,905	\$ 2,935
5	80	32	\$ 2,665	\$ 3,136	\$ 4,118
6	80	80	\$ 3,038	\$ 3,601	\$ 5,038

Note 1: The regulation up or down capacity is the product of the connection current rating and the voltage

To put these numbers in perspective, it is useful to consider the total value of the California ISO's ancillary services market over a several-year period. Figure 25 shows the annual value of all ancillary services in California (including self-provided services valued at market rates). Regulation typically accounts for about 75% of the total ancillary services costs¹⁶. It is seen that the volatility of the ancillary services spending makes it very difficult to determine with any certainty what the future value of V2G will be. But if it is assumed that in the long term prices will stabilize at their 1998/1999 levels, an estimate of the average annual regulation spending is $0.75 \cdot (404 + 638) / 2$, or

¹⁶ Determined through analysis of data in ISO "State of Market Report" to FERC, June 2002 [8].

\$391M/year. A vehicle could provide on the order of 0.001% of the total regulation (or put another way, 100,000 connected vehicles could provide all of California's regulation). So with these assumptions, there is roughly \$3,900 of gross value per year that could be provided by each vehicle – a result in line with the results in Table 4 above.

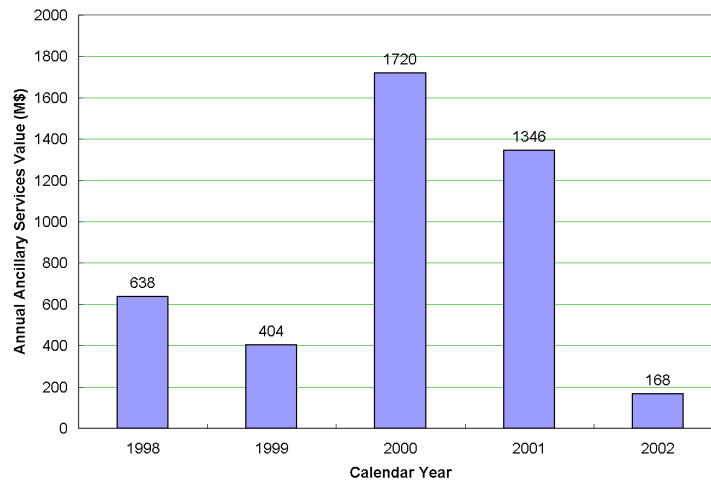


Figure 25. Historical annual value of ancillary services in California, Data from Cal ISO [8]. 2002 value extrapolated from first five months of year.

5.2 Battery Efficiency Test Results

Figure 26 shows the results of the single battery module hybrid cycling tests carried out at NREL. The test profile was not one of the grid regulation profiles, so the values for the heat rate in the battery and the overall efficiency are not directly applicable. However the overall trend is relevant, and shows that the highest energy throughput efficiency is achieved at between 50 and 70 percent state of charge. A vehicle driver would generally want the battery pack maintained at somewhat higher state of charge in order to have more range available for driving. This results in more losses, but not enough to cause any problems. Battery heating was not an issue in any of the grid regulation tests run for this project. Battery temperature stayed constant or decreased slightly over the course of the tests. (The pack does have a forced-air cooling system controlled by the battery management system). The vehicle's forced-air battery cooling system was set to come on when any battery module was at or above 40C. It cycled on and off during some of the tests. Test 15 which had an 80-Amp grid connection and the 2-times multiplier on the regulation profile had the highest battery throughput usage per unit time, and hence the highest battery heat generation. The battery cooling system maintained the highest module temperature at a constant 41C during this test.

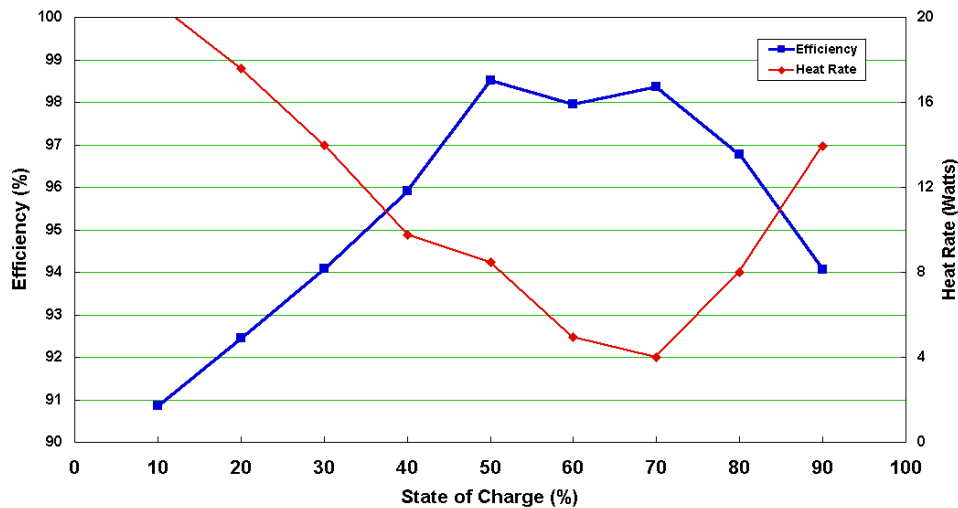


Figure 26. Battery cycle efficiency data as a function of SOC (source: NREL)

6. Discussion

6.1 Value Generated

As seen in Table 4 above, the annual gross value potential of an electric vehicle performing grid regulation varies from about \$1000 to \$5000, depending on assumptions. Following are some interpretations of the data and discussion of the future prospects for V2G.

- At \$1000 gross income per year, there may not be a compelling value proposition to the end user. The gross value must be reduced by the aggregator costs and the battery depreciation caused by doing V2G services. The amount that is left is the net value to the driver. There are a number of ways this value could be delivered to the drivers including cash payments or a lifetime warranty on the battery pack. In one scenario, the aggregator would own the battery pack, and pay for its replacement when needed. The vehicle driver would only be required to keep the vehicle plugged in to the grid for an agreed amount of time each month. They would be guaranteed of having a good battery pack for as long as they owned the vehicle. For example, a lead acid EV pack of 28 modules (at \$150 each) would cost on the order of \$5000 to replace (28@ \$150 + 8h labor @\$50/hr). If the battery pack lasted only 2.5 years, the replacement cost allocation would amount to \$2000 per year. If the aggregator's share of the gross income was 33%, then the gross value created would have to be at least \$3000 per year to cover battery replacements every 2.5 years. This amount could be achieved with home charging only if the connection were up-rated to 80Amps (19.2kW).
- The relative utilization (as indicated by throughput energy) of the battery pack between driving and V2G services is of interest. In typical cases the V2G usage will range from about equal the driving usage to more than twice the driving component. For example, consider a vehicle that is driven 12,000 miles a year. An efficient EV will have throughput energy of 250 Wh/mile, or 3,000 kWh/year. This vehicle providing V2G services at home only would

have an additional 2500 kWh/year throughput with a 32-Amp connection, and 6200 kWh/year with an 80-Amp connection. While it may seem on the surface to be undesirable to use the battery this much more, it is in fact a revenue generating function, and the more it can be used the better (except if it should turn out that battery throughput energy costs exceed the revenue generated). The driver will reap more net value as the ratio between V2G usage and driving usage increases.

- The value generated from the workplace connection is much smaller than from the home connection; the vehicle spends 2.5 times as much time parked at home as it does at work. An 80-Amp connection at home with no workplace connection yields more value than 32-Amp connections at both home and work. While workplace charging is very desirable for other reasons, it is not a deal-breaker for the viability of V2G.
- If batteries have a calendar life that is relatively short compared to the cycle life, then V2G services can be very beneficial to the overall economics by ‘using up’ more of the battery before the calendar life is reached. For example, consider a lead acid powered EV with 80 miles range and a battery pack rated at 1000 80% cycles but with a calendar life of three years. Translated to miles, the rated cycle life provides $80 * 0.8 * 1000$ or 64,000 miles of life. If the EV driver drove 12,000 miles a year, then after three years – 36,000 miles – the battery pack would reach its calendar life limit after having used only 56 percent of its lifetime throughput energy capacity or cycle life. V2G services could fill in this hole with little to no marginal battery cost. The real situation with batteries is far more complicated than this example, but it does illustrate the concept.
- If battery life is decreased as a result of providing grid regulation, there will be a corresponding increase in battery recycling needed relative to the miles traveled. An assessment of vehicle battery recycling technology and possible health impacts is documented in a prior CARB-sponsored study [9].

6.2 Deployment Issues

While the vehicle and communications technologies to support V2G are developed and are available for commercialization, there are many issues and barriers to overcome in order to deploy and operate a V2G system. V2G represents a new paradigm for the role of automobiles and a new paradigm for how power grids use and procure ancillary services. The following sections discuss the deployment topics and steps that could pave the way for V2G.

6.2.1 Grid Operators’ Acceptance of New Forms of Regulation

There are several characteristics of vehicle-based regulation that are different from the current practice. These are:

- **Nominal scheduled generation at zero or negative power (load)**

Currently the regulation ancillary service is performed by powerplants. A grid operator has a direct real time link to plants that are ‘on regulation’, sending Automatic Generation

Control (AGC) signals to the plants (typically every 4 seconds) directly from the energy management system (EMS) computer. Each plant on regulation has a nominal level of power generation that is scheduled. The plant also has upper and lower limits of generation. The EMS system sends AGC commands to the plant to move output up and down to any level between the upper and lower limits. Each plant also has ‘ramp rate’ limits, which specifies the rate at which it can change its power generation level. The EMS aims to operate the plant such that the average generation is equal to the scheduled nominal generation (see Figure 8 above for example).

With a battery electric vehicle providing regulation, the nominal level of generation for the vehicle will either be zero or will be ‘negative generation’ or a load (for recharging). From the EMS point of view it shouldn’t matter what the nominal generation level is, or even that it is negative. The EMS needs to have direct real time control over changing the balance between generation and load – the Area Control Error (ACE) – and it doesn’t matter whether this is accomplished by modulating generation, modulating load, or a mixture of both. However, EMS systems are not currently configured to operate with regulation sources that are capable of being both sources and loads¹⁷.

- **The small size of each regulation source, and small total capacity in early stages of deployment**

Existing sources of regulation have capacities from tens to hundreds of MW. Vehicles will have capacities from 5 to 20 kW. It would take on the order of 10,000 cars to match the capacity of a typical small powerplant. Understandably, grid operators will not want to contract with individual vehicles or with an aggregator that can offer the capacity of only a few vehicles. Yet, if V2G is to become a reality, it won’t happen overnight. It will start out very small with only a few vehicles and grow gradually from there. Over a longer period of maybe 20 years, the number of connected vehicles could grow to 100,000 or more, enough to meet all of California’s regulation requirements. Powerplants could go back to generating power at constant output levels. But for this to happen, grid operators will need to accept V2G into the market and nurture it when it is still young and insignificant in capacity.

- **Energy Constraints**

There is a functional difference between vehicle-based and powerplant-based regulation. The vehicle is providing the service by charging or discharging its battery pack while the powerplant is changing its level of generation. Since the vehicle is using energy storage, there is an inherent limitation on the amount of energy that can be delivered or absorbed. This limitation can be quantified by a net energy deviation from the starting point of the

¹⁷ There are load curtailment programs, but these are not the same as regulation. Load curtailment is used to maintain margins when overall generation capacity is getting low relative to load. Loads as sources of regulation are not currently employed (and for most loads, rapid modulation up and down is not practical).

cycle. Typically, the nature of regulation is that the fluctuations of power changes between positive and negative are fairly frequent so that a large cumulative energy deviation from zero is avoided. However, there are cases when the demands from the AGC computer may require extended periods at the upper or lower limit of the contracted regulation power. In this case, the vehicle battery may be incapable of sourcing or sinking the required power over the duration due to running up against battery discharge limits (as set by the driver) or the battery becoming fully charged. Excessively-large deviations in battery state of charge were not apparent in most of the test cases run. The largest deviation during a test was in test 15, a simulation of workplace V2G which had a high power grid connection and the two-times multiplier on the nominal regulation power profile. In this case, the battery discharged on average between the 4th and 7th hours of the test, depleting the capacity by about 30 percent. This cycle is shown in Figure 20. If the driver had requested a high value of the minimum allowable state of charge at anytime during V2G service, then there would have been a conflict at some time during the simulated workday when the battery state of charge would have dipped below the driver's specified minimum state of charge.

There are several ways in which this situation could be dealt with. First, and least useful, is that the vehicle simply ceases providing grid regulation service when battery state of charge limits are reached. The lost capacity would be small in relation to the total capacity available from the other vehicles online, and could be made up by small adjustments to the commands sent to the other vehicles. But if a single vehicle is running low on energy, then it is likely that many more vehicles are or soon will be in a similar situation. It would not be acceptable to lose the regulation capacity of a significant fraction of vehicles over a short time period. A better solution would involve a new form of regulation that is controlled to keep the energy excursions of the cycle within a defined limit. This limit would be operated such that the integral of the power command never strays more than, say, the energy represented by 12 minutes (0.2 h) of operation at the full contracted regulation up or regulation down power level. This would be achieved by filtering out the longer period components of the AGC signal. For example, if a vehicle contracted to provide regulation at 10kW up, 10 kW down, then that vehicle would not experience more than 2.5 kWh up or down deviation in the integral of the power dispatched to the vehicle. If the vehicle had a 20-kWh battery pack, then it would see no more than 12.5% deviation up or down in the battery state of charge¹⁸.

6.2.2 Grid Interconnection

Any form of generation or storage system that is tied to the grid and is capable of feeding local loads or exporting power to the grid will need to meet technical grid interconnection

¹⁸ In general, a vehicle that is connected to the grid would also need to be recharged. When spread over the full workday or evening time period that the vehicle is connected to the grid, the energy needed to recharge will result in only a small average level of recharge power. In practice, vehicles would set the nominal regulation power level to be a small constant load (for recharging), and then do regulation up and down from that baseline.

standards. These standards help ensure the integrity of the power grid by enforcing certain standards on all connected power systems. These standards provide that systems will disconnect from the grid upon certain faults or out of range conditions. Most importantly, they include an anti-islanding provision, which requires that systems stop energizing the grid whenever the grid itself goes down. This is to protect utility workers from being exposed to unexpected and dangerous powered lines during maintenance operations. In California, the Energy Commission led the development of a distributed generation interconnection standard which has now been promulgated as “Rule 21” by the PUC. The Energy Commission continues to monitor the implementation of Rule 21 through a working group [10]. Rule 21 does not, however, apply to vehicles that connect to the grid to perform ancillary services, as it does not cover any cases in which power is exported¹⁹. It is not clear what interconnect standards would actually apply – the closest may be those for small solar systems (IEEE Std 929-2000), which under net metering provisions, are allowed to export power. On a national level, a unified distributed generation interconnection standard is being developed by the IEEE Standards Coordinating Committee 21 (IEEE SCC21) [11].

All of these standards are similar in their overall requirements, and it is reasonable to assume that grid connected vehicles will at least have to meet the prevailing interconnect standards for stationary distributed generation systems.

6.2.3 Distribution Grid issues

There has been concern among those in the electric power distribution industry about possible ill effects of distributed generation systems that export power back to the grid. Power grids were not initially developed with consideration of generation dispersed throughout the distribution system. Power was always assumed to flow ‘downstream’.²⁰ Distribution grids are usually structured in either a radial configuration or networked configuration. In a radial configuration, a number of feeders emanate from a substation and deliver power to loads along the feeders. Any individual load can only be served by only one feeder. In a networked grid, there are a number of nodes and cross connections. Power can flow through alternate paths to loads allowing flexibility and redundancy.

The concerns about systems that export power into the distribution grid center around two primary issues: (1) possible tripping of network protectors and (2) disruption of distribution system voltage control systems.

¹⁹ Rule 21 applies to distributed generation systems that are used to offset local loads on the customer side of the meter. Export of power – running the meter backwards – is not covered by Rule 21. Vehicles providing regulation will likely be net exporters of power some of the time, especially when operating at a residential setting at night.

²⁰ There is nothing inherent in power lines or transformers that requires power to flow in only one direction. Technically power can flow in either direction just as readily as water can flow either direction in a pipe. Transmission lines are routinely used to send power in either direction (e.g. California’s N-S Path 15). The potential issues arise from certain protection and control devices added to distribution grids.

Network protectors are circuit breaking devices that open a connection in a networked grid if reverse power flow is detected. These circuits are assumed to always have unidirectional power flow. The network protector allows portions of a networked grid to be shut down for maintenance or repair by preventing power from ‘downstream’ location from flowing across the network in an upstream direction to a section of the grid that has been otherwise powered down for maintenance. If enough exporting distributed generation were connected to a networked grid, there is the chance that in normal operation power flows in some lines could reverse direction and cause an unwanted trip of a network protector. However, vehicles providing regulation services would be unlikely to cause this situation. Regulation power levels peak out at about 2 percent of the statewide load. If vehicles performing regulation were geographically dispersed in rough proportion to where the loads were, then it is almost certain that the power flow through the network protectors would (1) stay unidirectional all the time, and (2) that the fluctuation in power caused by the vehicles would be on the order only of a few percent.

There is the potential for V2G vehicles (or any exporting distributed generation system) to have an effect on the systems that control voltage in the distribution system. Voltage is stepped down to the end user levels through a series of transformers. Some of these transformers have the means to vary the voltage transformation ratio through automatic selection of a range of transformer taps. As load increases in a distribution circuit, voltage will drop due to resistance losses in the distribution wires. Tap changers attempt to keep the voltage level delivered to customers constant as the load changes through the day. By nature, tap changers are not continuously variable. Changes come in discrete steps. Figure 27 shows a time history of line voltage²¹ during one of the test cycles. The very short period voltage swings are caused by the regulation power cycle. The overall voltage variation over the course of the day was not caused by the vehicle and is likely due to operation of tap changers and load conditions in the distribution system. Overall, the natural variability of the grid voltage appears to be much larger than voltage variations caused by V2G vehicles. However, there is one possible exception in a residential situation. Consider the case of several V2G vehicles in one neighborhood and all connected through the same distribution transformer. It is likely that there could be reverse power flow through the distribution transformer much of the time – especially at night when residential loads are low. These transformers generally do not have network protector devices and so they will not trip off with reverse power flow, but voltage may rise higher than desirable and/or there is a potential for changes in vehicle power to lead to changes in voltage at that transformer – and hence possible ‘flicker’ in the lights of houses connected to that transformer.

Qualitative testing for visible flicker at a residence with one vehicle connected with a varying power profile showed no noticeable flicker. More vehicles and/or higher power

²¹ The voltage of the line as measured at the vehicle. Resistance losses in the cable connecting the vehicle to the grid result in apparent voltage fluctuations. The voltage seen by the rest of the building does not vary as much.

connections might still be an issue. If voltage does become an issue, it is possible to mitigate unwanted voltage changes with reactive power. Usually, the vehicle would interface with the grid with unity power factor (current in phase with voltage). From the power company's point of view, unity power factor is usually preferred. However, reactive power (current out of phase with voltage, called VARs) when controlled properly, can be used to adjust the voltage up or down without any real power flowing. Initial results with pure reactive power from the test vehicle demonstrated the ability to move the voltage in the test facility up or down by about 3V (on a 208V base). In a residential setting, V2G vehicles could be controlled to counteract any voltage deviations caused by real power flow with reactive power²².

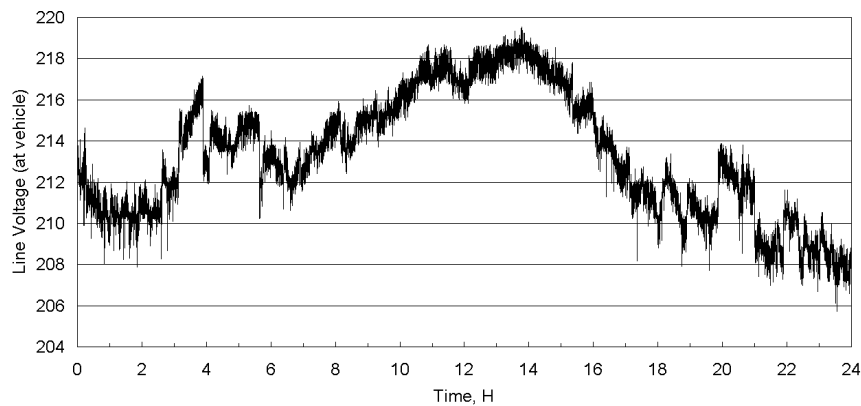


Figure 27. Line voltage history during test 16 (measured at Vehicle).

California's Rule 21 avoids the reverse power issue by disallowing systems that export power back to the grid (local generation can only offset local load on the customer side of the meter). However, California does allow net metering of interconnected solar power systems and requires the distribution utilities to accommodate (and pay for distribution upgrades as required) up to 1000 kW of solar at any given site.

The overall conclusion is that while there may be some technical issues with distributed generation systems that export power, these will not be permanent roadblocks. Many of these same issues are being overcome as they relate to solar systems and other forms of distributed generation.

6.2.4 Regulatory - Markets

The regulatory environment for electricity did not evolve with consideration of vehicles as part of the grid power system. A number of new issues will need to be resolved as

²² A V2G vehicle might also improve local power quality if it is programmed to counteract out voltage fluctuations caused by other household loads or even minor voltage fluctuations from the grid itself.

vehicles are added to the grid. Generally, these issues revolve around the differences between wholesale and retail markets, and their associated tariffs and regulatory jurisdictions. Retail energy transactions are those between end users of energy and a distribution company. Wholesale energy transactions take place between energy generators, grid operators, and bulk energy purchasers. Retail is generally associated with the distribution grid, and wholesale with the transmission grid. Retail is regulated from within a state; wholesale is interstate by nature and is regulated at the federal level. In California, retail power rates for investor-owned utilities are set by the California Public Utilities Commission (PUC) and the overarching laws under which the PUC operates are set by the California State Legislature. The wholesale market is regulated by the Federal Energy Regulatory Commission, or FERC.

Grid ancillary services such as regulation are wholesale products. A vehicle that is performing regulation is providing a wholesale ancillary service but it is connected through a retail connection point²³. This is an unusual circumstance. There is existing precedent in the form of a Wholesale Distribution Access Tariff, or WDAT, which provides a means to access wholesale energy markets from a connection point in the distribution grid (e.g. SCE WDAT [12]). WDATs are typically used to provide wholesale access to renewable and cogeneration energy producers, called qualifying facilities, or QFs. There is no known precedent for a small source deep within the distribution system being operated under a WDAT[13]. A V2G electric vehicle would have two reasons to be connected to the grid: first, to draw energy to recharge its battery pack to replace the energy used for transportation, and second, to provide a V2G ancillary service (regulation in the case of the present study). The former is logically a retail transaction; the customer buys electricity to recharge the vehicle. The latter is by definition a wholesale transaction. A vehicle connected to the grid will be involved in both retail and wholesale transactions simultaneously.

The logical way to separate these is to charge for net energy as a retail transaction (no change from present practice for EVs), and to contract for the regulation ancillary service as a wholesale transaction (through the aggregator). In this way, the distribution utility gets paid for all net energy delivered to the vehicle just as it is now. The retail transaction is for net energy; the wholesale transaction is for the ability to control the timing of the

²³ The vehicle will be connected at a low voltage – probably 208V or 240V. The transmission grid operates at very high voltage. There have been suggestions that distribution-system based ancillary services will incur unacceptable losses in transforming back up to the high transmission voltages. This is not the case; regulation power profiles from a vehicle applied at the distribution level will be reflected back at the transmission level at very overall high efficiency. All the transformers in the systems are already excited and are incurring magnetization losses regardless of current. Additional losses in these transformers due to vehicles superimposing regulation power will be exceedingly small. Part of the time vehicles will add power, reducing conduction losses, and part of the time they will pull more power, increasing conduction losses. If ϵ represents the rms value of the fluctuating regulation power normalized by the total system load, then the additional transformer resistance losses caused by the fluctuating regulation power profile will be ϵ^2 and the efficiency will be $1-\epsilon$. For example, consider the case if all grid regulation in California were performed from the distribution grid. The rms value of grid regulation power is on the order of 0.5% of the state load, so the overall efficiency would be $1 - 0.005$, or 99.5 percent.

power capability. This form of separation is well suited to the existing retail metering system. A vehicle that is plugged in for recharging and for providing regulation would be billed for retail energy in just the same way a vehicle that is just recharging would be billed. The regulation value would be handled as a separate transaction through the aggregator. No hardware changes would be required at the retail access point. There would be the likelihood of reverse power flow part of the time through the retail service meter, even though the net usage over a long time period will always be a load. To provide for this it will be necessary for the retail meter to provide credit for the reverse power flows (i.e. spin backward). This is much the same capability that is offered with retail customers that have rooftop mounted solar systems. Under California net metering laws, excess power during the day is credited by spinning the meter backward (either directly or indirectly with dual meters). So for vehicles to provide grid regulation, they will have to be allowed by legislation to have a net-metering treatment, and the distribution utility will need to accommodate for this in its metering hardware (if it is not already accommodated).

6.2.5 Competition

If vehicles enter into the regulation market, the overall supply of regulation will increase, tending to drive down market prices. This is of course a desirable outcome for electricity ratepayers, but not for the providers of regulation services. There are, however, mitigating factors. The overall demand for regulation will grow due to growth in statewide load and growth in wind energy generation capacity. Wind energy is an intermittent resource and cannot be accurately forecast or scheduled. Additional regulation capacity will be needed to fill in for the variances between the forecast and actual wind generation [14]. Vehicle regulation capacity will grow slowly over time; initially the small regulation capacity represented by vehicles would be expected to have a minor influence on market prices of regulation.

6.2.6 California Electricity Market Redesign

In the wake of the California electricity problems in 1999 and 2000, the California ISO undertook to overhaul the way the ISO and its energy markets operate. The ISO submitted a plan titled “Comprehensive Market Redesign Proposal” to FERC on May 1, 2002 [15,16]. On July 26, 2002, FERC issued an order in response [17]. The order accepted some of the ISOs plan and ordered several specific steps for the ISO. (see [18] for ISO analysis of the FERC order). Of particular relevance to V2G is the inclusion of “Locational Marginal Pricing”, or LMP, for future energy and ancillary services markets. Instead of statewide markets, or the 3-zone system currently in place, there will be far more – potentially thousands – of locations at which prices for energy and ancillary services will be set by market forces. This has relevance to V2G in that the value of services may vary substantially depending on where a vehicle is located. An aggregator dealing with LMP pricing will need to make use of the vehicle’s location information, which the vehicle will determine from its GPS receiver and send to the aggregator.

In the FERC order, section 113 is especially relevant to V2G. In it, FERC orders the ISO to find ways to include demand response into ancillary services markets:

113. In addition, we require the CAISO to change the rules of its spinning reserve market to enable the full participation of demand response as a resource. The CAISO shall work with the demand response community and other stakeholders to determine how demand response programs can participate in other ancillary service markets, and file a compliance report by October 21, 2002 outlining the measures taken to improve demand response participation in all CAISO markets. The CAISO and California transmission owners should work with NERC to change those NERC rules that prevent demand resources from being full and equal participants in the spinning reserve and other ancillary services markets.

This is relevant because a vehicle that is providing regulation is acting as a controllable load (or demand resource) approximately half of the time. The FERC order makes it very clear that demand resources that can be modulated according to an AGC signal from the ISO have just as much right to participate in the regulation market as do generators.

6.2.7 Metering and Settlements

Metering and settlements represent the process of measuring the performance of an ancillary service (such as regulation) and then paying for it. In today's power system there is a stringent requirement that every source of regulation to be in continuous and secure communication with the ISO. Every power command from the ISO's AGC computer must be acted upon and acknowledged in real time. Payments to these providers is made afterwards according to a defined schedule. Payment is contingent on the supplier of the service meeting certain minimum standards of response. These are in essence responding to a command immediately and achieving the as-bid ramp rate (rate of change of power generation).

With thousands of vehicles connected to provide grid ancillary services, it may not be practical or necessary to have each vehicle acknowledge AGC commands every 4 seconds. The aggregator will need to know how much capacity is online and available, and will have predicted this information beforehand based on historical data and default usage profiles for each vehicle. The aggregator would use the predicted data to bid regulation capacity into the day-ahead and hour-ahead markets. The bid capacity will probably need to be lower than the predicted capacity to provide certainty that the bid capacity will truly be available. As the number of vehicles increases, the difference between the bid capacity and predicted capacity can probably decrease.

Vehicles would 'sign on' or 'sign off' through the wireless data system with a short message to the aggregator when connecting and disconnecting from the grid. The message would include power capacity, current and desired future state of charge, energy limits up and down, and where the vehicle is located (from GPS). Once signed in, the vehicle would begin receiving regulation commands and act upon them by feeding power to the grid or pulling power from the grid on demand. At the end of a grid connect session, the

vehicle would report back to the aggregator a summary of the services provided for that session in the sign-off message. If an individual vehicle's response to commands was in any way compromised or modified during the session (for example running up against a driver-specified minimum state of charge), the vehicle would report the event to the aggregator at the time it happened. This information combined with vehicle sign-on and sign-off information will allow the aggregator to have an accurate real-time picture of the current online regulation up and regulation down capacity.

The aggregated sign-off reports from all connected vehicles would serve as final confirmation to the ISO that the capacity that the aggregator contracted for was actually up and running. This *post-facto* confirmation is different from current practice, in which the ISO has continuous real time confirmation. With current regulation sources, each source is so large that it is necessary to continuously monitor its performance. Also, with existing sources, ramp rate limitations complicate matters because some units may still be regulating up when the need is for regulation down. Other units may need to compensate with even more regulation down. With vehicles, there are no ramp rate limits; they will be doing what is commanded. Consequently, the EMS computer system can take into account that vehicles will respond without any ramp rate limitation, and that the vehicles' regulation power capacity is in fact out there, even though there is no real-time confirmation from each vehicle. This confidence in the vehicles performing as commanded will be built slowly over time as the population of vehicles grows. It will not be necessary to take on faith (i.e. without real time confirmation) that, all of a sudden here is a new multi-megawatt source of regulation that is doing what is asked of it.

6.2.8 Distribution Companies as an Alternate Customer for Regulation

Local electricity distribution companies, or DISCOs (e.g. SCE, PG&E) are users of the transmission grid, and are responsible for their fair share of ancillary services – including regulation. They can meet their responsibility for regulation either by providing it, or by having the ISO procure it on their behalf and bill them for it. (Approximately half of the regulation in California is self-provided.) So far, it has been assumed in this study that vehicles that provide regulation would contract through an aggregator directly with the ISO. An alternate approach could be to contract with the local DISCO that services the area where the vehicle is usually plugged in. The regulation service provided by the vehicle would then be counted as self-provided by the DISCO – and would reduce the amount of regulation that would be billed to the DISCO by the ISO. An advantage of this approach is that it may be more practical from a transaction point of view from the ISO perspective, especially early on when the aggregated regulation capacity of vehicles is small. For example, consider a fleet of 30 electric vehicles that could provide 200 kW or 0.2MW of regulation. This is a very small amount, worth on the order of only \$5-10/hour. It would be inefficient to treat this as a separate transaction with the ISO. On the other hand, if it could be 'piggy-backed' onto a much larger amount of regulation that is already self provided by the DISCO, it would result in marginally larger amount of self-provided regulation and a marginally smaller bill from the ISO for non-self-provided

regulation. This captures the monetary value of the regulation provided without a new transaction by a small change in the size of an existing transaction. A possible benefit of this approach is that DISCOs are generally supporters of electric vehicles and might be willing to nurture the concept along in the beginning.

6.2.9 Vehicle Location

When vehicles sign in with the aggregator that they are parked and connected to the grid, they will need to report where they are located. The location information is needed in order to determine in which market or zone the vehicle's services can be used. The California ISO control area has a distinct boundary, and within its boundary are three zones (NP15, SP15, and ZP29). There are also significant LADWP and SMUD 'island' regions within the overall ISO control area that are not under Cal ISO control. Vehicles that were parked in these regions would not be able to provide services to the Cal ISO.

For vehicles performing only regulation service, it may not be necessary for the vehicle and aggregator to 'know' which meter or service the vehicle is connected to the grid to. This is because, as described in section 6.2.4 above, the energy component should be handled as a retail transaction, separate from the regulation transaction. Any charging site that freely allows electric vehicles to recharge should have no problem allowing an electric vehicle to also provide grid regulation. Over the course of a day, a vehicle providing regulation will draw less energy than a vehicle that is charging, since the vehicle providing regulation intentionally does not charge its pack up to full in order to provide headroom for state of charge fluctuations due to regulation.

If it becomes necessary to know which meter the vehicle is connected to, it may be possible to accomplish this by GPS through a database containing of the geographic location of electric vehicle charging stations and their associated electricity metering points. With this approach, determination of which service the vehicle is connected to is accomplished entirely by GPS and wireless communication, eliminating the need for direct communications between the vehicle and the infrastructure. This keeps the infrastructure the same as that used for non-V2G-capable electric vehicles – a big advantage.

6.2.10 Automaker Support

In order for V2G to become a reality, automaker participation and support will be required. Automakers might consider becoming the aggregator(s) themselves in order to develop an ongoing after-sale income stream. While battery-electric vehicles may be the most straightforward vehicle type to implement grid regulation, there is a stated lack of automaker interest in these vehicles. Hybrid vehicles could be configured to connect to the grid with bi-directional interfaces, and could provide regulation with battery stored energy and spinning reserves with the generating capacity of the engine (probably limited to 10-15kW since the vehicle would be stationary). This would require a substantially larger battery pack than that of current hybrid vehicles. This would have the side benefit

of offering substantial engine-off ZEV range, allowing grid electricity to power a significant fraction of miles traveled, and eliminate a higher fraction of cold starts.

Several automakers have explored vehicle-based generation and/or grid connection. General Motors has proposed a power generation role for its future fuel cell vehicles [19]:

“...we see the role of the automobile within the global power grid changing. Vehicles could at some point become a new power-generation source, supplying electricity to homes and works sites. Most vehicles sit idle about 90 percent of the time, so imagine the exponential growth in power availability if the electrical grid could be supplemented by the generating capacity of cars and trucks in every driveway or parking garage.”

In 2000, DaimlerChrysler announced a production program for a hybrid pickup truck capable of stationary generation at up to 20kW to provide power at worksites and backup power for homes [20]. Also in 2000, Nissan Motor Company received a US patent for a system that uses a bi-directional power connection between an electric vehicle and a house in order to provide power services to the house [21].

7. Summary and Conclusions

Battery, hybrid, and fuel cell vehicles are at the leading edge of a transformation of personal transportation. These new vehicles, which have in common electric drivetrain technology, offer the promise of personal transportation with the smallest-possible environmental footprint. However, as with most new technologies, these vehicles also bring higher costs in the near term. These, like other personal vehicles, are driven on average for only an hour a day, and are otherwise idle the rest of the time. If electric drive vehicles were integrated with the power grid in a mutually beneficial way, the economic value created could help offset the ownership costs of such vehicles.

Previous studies of the potential for vehicle-to-grid services [1,2] concluded that the grid regulation ancillary service was best suited to electric vehicles. Regulation is a means for the operator of the power grid to continuously make small adjustments to the power generated in the system to achieve the needed balance between generation and load. This study built on the previous study by actually implementing and demonstrating grid regulation with a battery electric vehicle and conducting a detailed evaluation of operational, economic, and market integration issues. The study included the following major elements:

- Retrofitted an existing electric vehicle with a bi-directional charger/grid interface
- Selected and implemented a wireless communication system
- Developed embedded software for the vehicle controls and wireless interface

- Developed sample grid regulation power profiles and obtained regulation price history data
- Implemented transmission of real-time commands to test vehicle
- Developed test and prototype software for vehicle aggregator function
- Developed sample web interface for driver access to vehicle status and usage profile
- Performed 227 hours of grid-connected testing with regulation power profiles
- Evaluated issues relating to implementation of a vehicle-to-grid system, including interconnection, market integration, regulatory, metering and settlements, and role in future electricity market structures.
- Demonstrated the vehicle and presented the concept at an industry conference.

The study showed that integrating electric drive vehicles with the electric power grid is technically practical and the concept has the potential to create an income stream that offsets a portion of vehicle ownership costs. Specific conclusions and perspectives are given below:

- **Vehicle Feasibility.** The technical implementation of a vehicle with a grid interface capable of safely feeding energy to the grid has been demonstrated. The drive system employed incorporated the same basic interconnection safeguards that are typically specified for small distributed generation systems.
- The wireless communication link that was implemented had some issues with coverage areas and a different system would likely be needed for a commercial V2G implementation. Wireless communication systems are evolving and improving very rapidly, so this is not seen as a significant future impediment. When the test system was working, the transmission and response times were very satisfactory, with an acknowledgment reply received within 2 seconds of sending a command 99.94% of the time.
- The vehicle battery pack had no problems in following the commanded power profiles and the battery cooling system easily controlled battery temperatures during the tests. The power levels associated with regulation are typically an order of magnitude lower than those associated with driving the car. The effect of the regulation power profile on battery life is unknown. It is expected to vary between (1) degradation based on the fraction of rated cycle life that is consumed and (2) no additional degradation if calendar life is the dominant battery life limiting factor.
- The actual magnitude of the regulation power (relative to the contracted regulation limits) that would be dispatched to vehicles is not certain. For this project, the dispatch profiles were developed as scaled versions of historical total ideal regulation power profiles. The vehicle power profile was scaled pro-rata based on the vehicle's total regulation capacity

vs. the total statewide regulation capacity. To test the sensitivity to this assumed scaling, some tests were run with a two-times multiplier on the resultant profile (clipped at the vehicle's grid connection power limit). No technical issues were encountered with the two-times scaled profiles, but the battery throughput energy was proportionately higher. With the nominal profile, the throughput energy per hour represented by the cycle was about 5.5% of the regulation power limits (i.e. a vehicle with 10 kW regulation up limit and -10kW regulation down limit would see, on average, a power dispatch cycle with 0.55 kWh of throughput energy over a one-hour period).

- The gross value potential of vehicle based regulation varies between \$1000 and \$5000 per year based on market prices sampled in December 2001, April and July 2002. The market price for regulation has varied by approximately a factor of ten over the last few years (peaked in late 2000, early 2001) making future projections very uncertain.
- The cost of the battery wear out using the pessimistic assumptions on battery life and the two-times scaled regulation power profile results in battery costs that are between 20 and 60 percent of the gross value created, assuming lead acid batteries in production to support manufacture of 12,000 vehicles/year (case 2 in Table 3). The most optimistic assumption that the battery life is limited by calendar life instead of cycle life gives, of course, zero marginal battery cost due to the regulation function.

8. Recommendations

8.1 Find a Home/Champion/Lead Agency for V2G

The concept of vehicle-to-grid spans transportation, the environment, and energy, and would have relevance to a large number of government regulatory or research agencies. Yet because it is interdisciplinary, V2G has not yet found a home or champion(s). Its closest fit is with distributed generation activities of the CEC and DOE. The CEC Public Interest Energy Research (PIER) program specifically excludes transportation-related research by policy. In the DOE, advanced transportation is separate from distributed generation. There is no readily apparent path to finding a home for V2G or for funding that can go toward development of the integration of the transportation and grid connected aspects. Research funding for development and demonstration projects is needed before V2G will be adopted by the business community. State and federal agencies (such as CEC and DOE) should recognize the potential for V2G and develop plans for a funded research and development program with industry. This program should have a defined connection with the federal government's new FreedomCar program for fuel cell vehicles.

8.2 Address Utility Distribution Grid Issues

There should be an effort to work with local utility companies to understand, address, and resolve technical issues and concerns relating to feeding power to the grid. These issues include real and perceived safety of systems capable of feeding power to the grid, local voltage effects and whether they need to be mitigated, and the impact of reverse power flow on grid protection

devices. Many of these same issues are already being considered as they relate to integration of stationary distributed generation. There are, however, specific issues related to vehicles that will need to be addressed. In California, there are several large investor owned utilities and many more municipal utilities of varying sizes. A fully developed vehicle-to-grid system would ideally be ‘plug-n-play’ when the vehicle connects to the grid through any of these utility companies.

8.3 Pilot Deployment in Fleet

A fleet demonstration program should be initiated using existing electric vehicles. Since these vehicles do not have bi-directional grid interfaces, the test would be limited to regulation down (turning the battery charger on whenever regulation down is called for). Without any limitations that would be imposed on a distributed generation system, a fleet of battery EVs could perform a grid ancillary service with load only. Prospective fleets include the electric postal vehicles in California or the SCE or LADWP electric vehicle fleets, or even all of them. The combined regulation down capacity represented by this combined fleet is on the order of 3-5 MW. A small test group of vehicles should be fitted with full bidirectional grid interfaces and operated in a pilot study of full grid regulation.

8.4 Operations – Better Determination of Grid Regulation Dispatch levels for vehicles

A better understanding is needed as to how much a vehicle would be dispatched relative to its contracted regulation limits. This may involve adding a simulated aggregated group of EVs to the ISO’s EMS computer. This has relevance to the amount of throughput energy experienced by the vehicle battery pack, and therefore has some relevance to the economic performance of the V2G concept.

8.5 Battery Testing

Battery testing should be funded in order to perform long term cycling testing of representative EV battery types on test cycles with and without the V2G component. By nature, these tests are long term and cannot be accelerated.

8.6 Regulatory Development

A number of steps are needed or desirable from the regulatory side. First, net metering provisions need to be extended to electric vehicles (or any other form of storage) that are engaged in providing ancillary services to the grid operator. Next, minimum capacity limits for ancillary services should be lifted to allow equal access to these markets by all potential suppliers, large or small. This will be needed in order to get through the early years of V2G when there aren’t many vehicles. Waiver of capacity limits could be on a case-by-case basis aimed at supporting sources that have the future potential to grow large. New forms of regulation and other ancillary services and associated tariffs should be developed that are tailored to the fast response and energy constraints of vehicles.

8.7 Future Applications

This study focussed on one specific ancillary service. Future research should investigate the full range of existing and new services that could be offered by vehicles. Some of these include potential for transmission stabilization, local voltage support, microgrid support, and using connected vehicles as a dispersed data acquisition system that could report local grid conditions, including voltage, phase angle, and power quality.

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10. Glossary of terms, abbreviations, and symbols

ACE	Area Control Error, a measure of how well generation and load are in balance within a grid control area. Also includes control areas share of power to regulate grid frequency.
AGC	Automatic Generation Control, the process run by the grid operator's energy management system (EMS) to generate commands to power units that are providing regulation.
CAISO	California Independent System Operator, the organization that manages the flow of electricity on most of the transmission grid in California.
DISCO	Distribution Company, the 'wires' company the distributes electricity to end users (e.g. Southern California Edison, PG&E)
EMS	Energy Management System, the computer system at the grid operator that keeps track of and manages generation and other aspects of the operation of the grid.
FERC	Federal Energy Regulatory Commission, the federal agency that regulates wholesale electricity markets
NERC	North American Electricity Reliability Council, The industry organization that sets standards for the quality of operation of power grids.
PACE	Processed Area Control Error, Processed ACE, this is the output of a digital filter and proportional/integral control loop. The control loop is regulating the value of ACE with a target value of zero. The value of PACE represents the grid operator's ideal amount of regulation power at any given time.
PUC	Public Utilities Commission, a state agency that sets electricity rates for consumers.
PURPA	Public Utilities Regulatory Policy Act (1978). A 1978 law that requires electric utilities to buy power from Qualifying Facilities at the utilities' avoided cost.
QF	Qualifying Facility, a renewable or cogeneration power generation source that meets the standards in PURPA which allow it to sell power to the utility at avoided cost
Regulation Up	This is the ancillary service that increases the output of a generating source above its nominal level according to AGC commands. Regulation

up is under real-time automatic control of the grid operator EMS computer.

Regulation Down	This is the ancillary service that decreases the output of a generating source below its nominal level according to AGC commands. Regulation down is under real-time automatic control of the grid operator EMS computer
V2G	Vehicle to Grid, an abbreviation that encompasses the general topic of vehicles interconnected with the grid. (Coined by AC Propulsion in 2001.)
WDAT	Wholesale Distribution Access Tariff, the tariff which allows access to wholesale markets from the distribution grid (usually used by QFs).
WECC	Western Electricity Coordinating Council, The group that manages the operation of the grid in the Western part of the United States, called the “Western Interconnect”.

The California ISO maintains a complete glossary of related terms on its web site at:
<http://alhiweb1.caiso.com/aboutus/glossary/>