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Vehicle-to-Grid Power: Battery, Hybrid, and Fuel Cell Vehicles as Resources for Distributed Electric Power in California

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Battery, Hybrid, and Fuel Cell Vehicles as Resources for Distributed Electric Power in California

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Executive Summary

Electric-drive vehicles can become an important resource for the California electric utility system, with consequent air pollution, system reliability, and economic benefits. We refer to electric power resources from vehicles as "Vehicle to Grid" power (V2G). The economic value of some forms of V2G appear high, more than enough to offset the initially higher costs of electric-drive vehicles, thus having the potential to accelerate their introduction. To realize this potential, some coordination of vehicle and infrastructure planning will be needed.

This study calculates three parameters of electric drive vehicles (EDVs) which are important for their use by the electric system: resource size, availability, and economic potential. Economic potential was calculated for three power markets: peak power, spinning reserves, and regulation services. Vehicles were not found to be competitive for baseload power. The analysis uses California electricity market prices for three years—1998, 1999, and 2000—as well as historical electric utility experience. This three-year comparison insures that recent disruptions, and historically atypical prices, in the 2000 California electricity market do not bias the results. In addition to electricity markets, "customer side of the meter" strategies are analyzed, in which vehicle power offsets time-of-use charges, demand charges, and interruptible rates. These multiple calculations of the value of EDV power make the conclusions about its economic viability more robust.

This report analyzes V2G power from three types of EDVs—battery, hybrid, and fuel cell. Battery EDVs can store electricity, charging during low demand times and discharging when power is scarce and prices are high. Fuel cell and hybrid EDVs are sources of new power generation. For economic reasons they would sell power only when prices are high. Battery and plug-in hybrid EDVs can also sell regulation services, which involves little or no net battery discharge. In the terminology of the California Air Resources Board (CARB), battery and fuel cell EDVs are considered Zero Emission Vehicles (ZEV), hybrids are considered Advanced Technology Partial ZEV (AT-PZEV), and battery EDVs are often referred to simply as EVs.

The report begins by describing the technical requirements needed to realize the most value from vehicle power. These include on-board power electronics, plug-to-vehicle connections, and communications facilities ("telematics"). The required technologies are all in production or in prototype vehicles, although they have not been put together in the ways we propose. We also discuss bridge strategies; for example, the conductive charging stations now being installed for recharging battery vehicles will later be valuable for carrying power from hybrid and fuel cell vehicles to the grid. Implications for current industry directions are also discussed; for example, existing on-board conductive chargers can be used for V2G whereas, current inductive chargers cannot.

Formulas are derived to calculate the power capacity of each vehicle type. Calculated capacity depends on the charger capacity, residential and commercial electrical service capacity, fuel or electricity needed for the next trip, whether a continuous piped gaseous fuel source is connected to the vehicle, and other factors. The battery vehicles have power capacity on the order of 10 kW and fuel cell vehicles have up

to approximately 40 kW. The hybrid vehicles are of interest when operating in the motor-generator mode, fueled by gasoline or a natural gas line, with power capacity up to 30 kW. For many scenarios, output is limited by line capacity to the existing 6 kW charging stations, or near term standards for 16 kW.

We calculate total expected resource size from CARB requirements for electric drive vehicles. In the year 2004, the required quantities of vehicles in California would represent 424 MW of generating capacity, and in year 2008 they would represent over 2,000 MW (or 2 gigawatts). The latter figure is the equivalent output of two large nuclear plants running at full power, or about 4% of current California electric generating capacity. As another point of comparison, a Stage 3 emergency occurs when electricity generation is within 1.5% of electricity consumption. In the California Independent System Operator (CAISO) territory, rolling blackouts have been used to recover roughly 0.5% of a 40 GW peak, or some 200 MW. By year 2004, the EDV fleet would represent twice this capacity.

One conceptual barrier to understanding vehicles as a power source is an initial belief that their power would be unpredictable or unavailable because they would be on the road. Although any one vehicle's plug availability is unpredictable, the availability of thousands or tens of thousands of vehicles is highly predictable and can be estimated from traffic and road-use data. For example, peak late-afternoon traffic occurs during the hours when electric use is highest (from 3-6 pm). A supposition one might have from driving, that the majority of the vehicles are on the road during rush hour traffic, is false. We calculate that over 92% of vehicles are parked and thus potentially available for V2G power production, even during peak traffic hours of 3-6 pm.

The cost of electricity generated by each EDV type is estimated. Battery vehicles can provide electricity to the grid at a cost of \$0.23/kWh for current lead-acid batteries, \$0.45/kWh for the Honda EV Plus with nickel metal hydride (NiMH) batteries, and \$0.32/kWh for the Th!nk City car with nickel cadmium (NiCd) battery. The fuel cell vehicle can generate electricity at a cost ranging between \$0.09 – \$0.38 kWh, the wide range depending on the assumed cost of H_2, with the lower figure based on the longer-term assumption of a mature hydrogen market. A fuel cell vehicle with hydrogen recharge through a garage reformer could generate electricity at \$0.19/kWh from natural gas (at \$0.84/therm). The hybrid vehicles in motor-generator mode can generate electricity at a cost of \$0.21/kWh if fueled with gasoline (at \$1.50 per gallon) and at \$0.19/kWh if fueled with natural gas. Based only on these simple costs per kWh, it appears that in the near term the most attractive EDV types are the lead-acid battery vehicle, a fuel cell vehicle recharged from a natural gas reformer, and the hybrid vehicle. However, the simple cost per kWh comparison does not provide an adequate evaluative framework.

The cost of electricity from the EDVs noted above is too high to be competitive with baseload power, which typically has a range from \$0.03–0.05/kWh. EDV power is competitive in three other markets: "peak power" (during peak demand periods), spinning reserves, and regulation services. The latter two electricity markets are called "ancillary services," and in each, the power producer is paid a contract price for being connected and available, in addition to per kWh energy payments. For each combination of vehicle and power market, we calculate the value of the power in the market and the cost to the vehicle owner for providing power, assuming V2G power is produced only when revenue will exceed cost. This method is more comprehensive than earlier methods that used avoided costs (Kempton and Letendre 1997) or retail time-of-use rates (Kempton and Kubo 2000). Other benefits, including reduced air pollution and increased reliability of the electric system, are not included in the economic calculations, nor are transaction costs. Calculation of vehicle owner costs is comprehensive, including capital costs of any additional equipment required, fuel, and shortening of battery pack and internal combustion engine lifetime due to additional use.

Abbreviated findings are summarized in Table ES.1 below. The top dollar figure in each cell is the net profit (revenue minus costs). This table assumes mid-values and does not reflect ranges, uncertainties or assumptions. Not all vehicles analyzed are summarized here and the current is limited to Level 3AC charging stations (16.6 kW and slightly higher for fuel cell vehicles). Also, the vehicle specifications draw from middle-ranges, the revenues assume 1998 market prices for spinning reserves and regulation services, and an industry rule-of-thumb for peak prices. Battery and hybrid vehicle costs include costs of degradation of the battery or engine, but fuel cell vehicles do not. The wide cost ranges for the fuel cell vehicle reflect the range in estimates for hydrogen costs.

Table ES.1 Vehicle owner's annual net profit from V2G; these are representative mid-range figures extracted from full analysis in the report. Key: $net (revenue – cost).

	Peak power	Spinning reserves	Regulation services
Battery, full function	$267 (510 – 243)	$720 (775 – 55)	$3,162 (4479 – 1317)
Battery, city car	$75 (230 – 155)	$311 (349 – 38)	$2,573 (4479 – 1906)
Fuel cell, on-board H_2	$-50 (loss) to $1,226 (2200 – 974 to 2250)	$2,430 to $2,685 (3342 – 657 to 912)	$-2,984 (loss) to $811 (2567 – 1756 to 5551)
Hybrid, gasoline	$322 (1500 – 1178)	$1,581 (2279 – 698)	$-759 (loss) (2567 – 3326)

From this summary table alone, one notices that some vehicles are better suited than others for individual power markets. This indicates that matching the vehicle type to power market is important, as it is possible to both gain and lose money.

Taking the three markets in turn, peak power is the least promising. In our model, battery-powered vehicles serve the peak power market by charging their batteries when demand is off-peak and price is low (*e.g.*, 4.5 ¢/kWh) and selling power to the grid when the price is high (*e.g.*, over 30 ¢/kWh). The fueled vehicles sell peak power when power prices are above the costs to produce power. Although the table shows potential profits by the historical rule of thumb, for two of the three years of actual prices we find that the price was never high enough to justify selling peak power.

Spinning reserves shows economic viability for most vehicles, and for all those shown in Table ES.1. Net revenues for the spinning reserve market is particularly large for the fueled vehicles and is relatively insensitive to fuel prices due to the contract payments.

Regulation services involve higher numbers, for both revenue and cost, because vehicles can sell regulation more of the time. The battery vehicles appear to be especially suitable for regulation because their shallow cycling causes less battery degradation, and because batteries experience very little discharge when providing both regulation up and regulation down. Plug-in hybrids with range similar to the city car would have economics similar to the city car when running V2G in battery mode. The estimated net value of regulation services from battery EDVs is several thousand dollars per year.

As the EDV fleet grows, it will begin to saturate these power markets. We estimate that the CAISO market for regulation services, the highest value market, could be met with 109,000 to 174,000 vehicles, and spinning reserves with an additional 76,000 to 273,000 vehicles. Peak power could be a still larger market, but only at lower V2G costs than currently projected. These numbers represent a small fraction of the total vehicle fleet in California, but they should be sufficient to stimulate more than a decade of projected sales, past the time that production volumes bring down EDV sticker prices.

Vehicles can provide ancillary services of a higher quality than currently available— fast response, available in small increments, and distributed. Our discussions with CAISO staff suggest that vehicle power could open new, high value markets for ancillary services. If new, high value electricity markets are realized, our calculations of value and market size may be too low. In addition, the demand for and value of V2G power will increase in the future as intermittent renewable energy becomes a larger fraction of electric generation.

In addition to considering electricity markets, we analyze the value of EDV power on the customer side of the meter. Any commercial electricity customer can implement this immediately without the need for regulatory or tariff changes. On the other hand, it requires a high level of interest and management on the part of the electricity customer. The potential for customer-side of the meter V2G exists because current electricity rates include three tariffs that place a premium on power at certain times: time–of–use rates, demand charges, and interruptible rates. We evaluate this opportunity based on published electricity rates for four California utility companies: Pacific Gas & Electric, Southern California Edison, Los Angeles Department of Water and Power, and the Sacramento Municipal Utility District.

Based on the existing utility rate structures, we find that financial gains of V2G from the customer side of the meter would be small or negative for most residential customers. Commercial and industrial (C&I) customers, unlike residential customers, have rates that typically include a demand charge in $/kW, added to their energy charge in $/kWh. These demand charges are often the largest component of a C&I customer's monthly electric bills. We find that such customers, if they have infrequent or short demand peaks, could realize economic benefits from V2G power. That is, bill savings can exceed the cost of power from on-site EDVs. Examining a database on hourly electrical load distinguished by business types, we find only one industrial type and several commercial types have sharp enough peaks to justify V2G to offset demand charges. A more refined inventory of the number of C&I customers with potential for customer-side of the meter V2G would require more disaggregated load data (per building and per day) than we found available from public sources.

Overall, we conclude that all three types of EDVs studied represent a significant source of electric power for the electric grid. The largest value is in ancillary services such as spinning reserves and regulation. For battery and fuel cell vehicles, and possibly plug-in hybrids, the net value of this power is over $2,000 annually per vehicle, enough to quickly and economically usher in the era of a low- and zero-pollution light vehicle fleet.

Several policy issues are raised by this analysis. Initially, demonstration projects would help answer questions which are not amenable to the paper calculation approach of the current report. Also, some policy review would be helpful now. From the grid side, it would be appropriate to review rate structures and interconnect and safety standards in order to lay out changes or additions appropriate for V2G power. Charging station infrastructure planning should similarly be reviewed for its application to V2G power. From the vehicle side, we observe that no current production EDV has V2G capability. The incremental costs, for battery vehicles in particular, are exceptionally small (low hundreds of dollars per vehicle)—assuming that V2G would be designed in, not added later, and that telematics are being put on-board for independent reasons. By contrast, as an add-on, the entire power electronics unit might need replacement at extremely high cost. This suggests that some incentives for vehicle V2G capabilities may be appropriate, even before a market for V2G develops. Finally, since the whole concept of V2G is predicated on interconnecting two distinct industries with distinct business models and separate regulatory bodies, near-term coordination across agencies (CARB, CEC, CAISO and/or CPUC) and across industries (electric utilities, automotive components, and automobile OEMs) would seem essential.

Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

A – Amperes
AC – Alternating current
ACE – Area control error
AT-PZEV – Advanced technology partial zero emission vehicle
CAISO – California Independent System Operator
C&I – Commercial & Industrial
CalPX – California Power Exchange
CARB – California Air Resources Board
CEC – California Energy Commission
CPUC – California Public Utility Commission
DC – Direct current
EDV – Electric-drive vehicles
EPRI – Electric Power Research Institute
ES – Energy storage capacity (of a vehicle battery or fuel tank)
ESCO – Energy service company
EV – Electric vehicle (used to refer to a battery EDV)
FC – Fuel cell
GJ – gigajoule
GPRS – General Packet Radio Service
GPS – Global positioning system
GW – gigawatt (10^9 watt, about output of one nuclear power plant)
Hz – Hertz (one cycle per second)
HHV – Higher heating value
IP – Internet Protocol
ISO – Independent System Operator (see CAISO)
kW – kilowatt (10^3 watt)
kWh – kilowatt hour
LADWP – Los Angeles Department of Water and Power
LHH – Lower heating value
MW – megawatt (10^6 watt)
NEC – National Electrical Code
NiMH – nickel metal hydride (battery)
NiCd –nickel cadmium (battery)
OEM – Original Equipment Manufacturer (in this report automobile manufacturer)
PC – Power capacity (the calculated kW a vehicle can produce)
PG&E – Pacific Gas & Electric
PZEV – Partial zero emission vehicle
RB – Range buffer
RDS – Radio Data System
ROM – read-only memory
SAE – Society for Automotive Engineers
SoCalEd – Southern California Edison
SMS – Short message service
SMUD – Sacramento Municipal Utility District

Abbreviations and Acronyms (cont'd)

SULEV – Super ultra low emission vehicle
TOU – Time-of-use (electric rates varying by season and time of day)
TW_e– terrawatt of electric power
TW_m– terrawatt of mechanical power
V2G – vehicle-to-grid
ZEV – Zero emission vehicle

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I. Concept: Vehicle-to-Grid Power

A. New ways to use vehicles to reduce air pollution

California and several Eastern states such as New York, Massachusetts, Vermont, and Maine, have embarked on policies to encourage the development and spread of electric-drive and low pollution vehicles. The goal of these policy initiatives is to reduce air pollution by decreasing pollution from mobile sources. This report concerns another opportunity for electric-drive vehicles (EDVs) to reduce air pollution, and at the same time increase the reliability and efficiency of the electric power system. This opportunity is based on using the electric storage and/or generation capacity of battery, hybrid and fuel cell vehicles to send power to the grid. We call this "vehicle-to-grid" power or V2G.

Our earlier analysis suggested that vehicles could not compete for baseload power, but could be competitive when called upon to provide peak power and ancillary services (Kempton and Letendre 1997, 1999; Kempton and Kubo 2000). Consequently, the current report analyzes the potential for vehicle-to-grid power in these non-baseload power markets. This report focuses primarily on the value of vehicle-to-grid power in California, although we do not make assumptions that rely on the current unstable electricity market situation.

Pursuit of the V2G concept would have three direct air-pollution benefits to California. First, by providing another source of value to the owner of an electric-drive vehicle (for example, payments from the electric utility company), an additional incentive is created for the adoption of low-polluting vehicles. We demonstrate that this incentive could be substantial—several thousand dollars per year. Second, peak and emergency power generation is typically obtained from fossil fuel plants, and often in population centers. Some EDV configurations would lower the emissions associated with these peak and emergency sources of power. The third air pollution benefit relates to renewable energy. Lack of storage is a major impediment to the introduction of renewable energy from intermittent sources, such as wind and photovoltaics. By having a large fleet of vehicles providing on-demand storage and generation, one major barrier to the introduction of renewables would be removed and the system cost of renewable energy would be lowered. These three benefits to cleaner air would alone justify the introduction of the interconnections we propose. Additionally, there is major reliability and cost benefits to the electric sector. Prior analysis (Kempton and Letendre 1997, 1999) has shown that these benefits are cost-effective even without considering the current, and presumably temporary, high prices in the California electricity markets. This conclusion has been confirmed by the more comprehensive and California-specific analysis contained in this report. This section proceeds by defining the three types of vehicles and four power markets we analyze. The section concludes with some commonly asked questions, which in turn, introduce the remainder of the report.

B. Electric-drive vehicles: Three types relevant to our analysis

Three types of EDVs are relevant to the vehicle-to-grid (V2G) concept: battery, hybrid, and fuel cell. We describe all three types together as "Electric Drive Vehicles"

(EDVs) because the term "Electric Vehicle" has come to mean vehicles using batteries as their only on-board energy storage. We use the term EDV for any vehicle utilizing an electric motor to provide mechanical shaft power, whether on-board energy comes from batteries, gasoline, natural gas, or hydrogen. The electric drive is critical because virtually any light vehicle with an electric propulsion motor will have power electronics already on-board that can provide grid power. The traditional internal-combustion light vehicle has, of course, been independent of the electric grid. EDVs, too, can be independent of the grid, as in a standard liquid-fueled hybrid. They may draw from the grid, but not provide power to the grid, as standard battery-powered EDVs currently on the road operate. But all EDVs have the potential to send power to the grid with the proper interconnections.

The table below outlines the interconnections of the different types of vehicles with the electric system, and their potential use by the system. This shows that, for example, the physical interconnection needed by a battery-powered EDV is already there—required for charging—although this physical connection requires added logic to allow two-way flow. The four major electricity markets are indicated in the right four columns. These are explained in more detail in the next section. The symbol "×" means that that vehicle is not expected to have value in that market, "√" indicates we expect it may, and "**?**" indicates that the question is quantitative and/or depends on complexities such as pollution and safety, so no prediction is possible in advance. This table is conceptual; it does not represent the output of our analysis. Depending on the assumptions, a "√" may change to "×" or vice-versa. Table I.1 does show that no vehicle is expected to be cost-effective as a source of baseload power, that battery and fuel cell vehicles could be valuable as a source of several types of non-baseload power, and that hybrid vehicles may or may not be practical in some electricity markets. These markets are explained in more detail in the next subsection.

Table I.1 Electric Drive Vehicle types, their interconnections to energy systems, and anticipated potential markets for their power. This is conceptual, not based on detailed analysis contained in the remainder of this report.

EDV Type	Interconnection	Potential electricity markets			
		Base-load	Peak	Spinning reserves	Regulation up/down
Battery	Two-way electrical (low cost logic modification to conductive charger)	×	√	√	√
Hybrid using storage	Two-way electrical	×	**?**	**?**	√
Hybrid using motor-generator	Electric from vehicle to grid; possible natural gas to vehicle	×	**?**	**?**	**?**
Fuel cell	Electric from vehicle; natural gas/H_2 to vehicle	×	√	√	√

A great deal is not covered in Table I.1: controlling power flow to the grid, restricting draw-down of fuel or battery to insure that functioning as a vehicle is never compromised, metering output and compensating the vehicle owner for costs, and matching of time of day availability of vehicles to time of day need for power. These are all covered, most by detailed analysis, in this report.

Since Table I.1 covers markets, it also ignores "customer side of the meter" use for vehicle electricity—for example, a large commercial electric user could strategically produce from its garaged employee or fleet vehicles to reduce their electric demand charges. Although customer side of the meter approaches cannot realize the full potential of vehicle-to-grid power, they are an intriguing transitional strategy, as they are simpler and more localized than full market participation. These strategies are discussed in Section VI.

C. Electric markets: base-load, peak power, spinning reserves, and regulation

There are three markets into which such V2G could be sold: baseload, peak, and ancillary services. Each of these is discussed below. Although baseload power and peak power are bought and sold on the same wholesale market, for discussion purposes it is instructive to talk about these two dimension's of the California wholesale market separately. Ancillary services comprise several types of power, two of which (spinning reserves and regulation) we see as promising markets for vehicle-to-grid power. Greater detail on ancillary services is presented in Section V.B. Here we briefly describe spinning reserves and regulation, the two ancillary services that seem most immediately promising. We presume that vehicles would be used in quantity, aggregated by an employer's parking management, an electric generating company, or by an independent aggregator.

C.1 Baseload power

Base-load power is provided on a round-the-clock basis. This typically comes from large nuclear or coal plants that have low costs per kWh but lack the technical and economic basis for turning on and off rapidly. Earlier studies (Kempton and Letendre 1997, 1999; Kempton and Kubo 2000) have shown that EDVs cannot provide baseload power at a competitive price. Historical wholesale prices for baseload power—ignoring recent fluctuations in California markets—are under 5¢/kWh. Per kWh prices of V2G power in this study are not competitive with this baseload power price. This would be true even considering that V2G baseload power would have a higher value at the point of end use. Furthermore, baseload generation does not take advantage of the unique value of EDVs for the power market, such as quick response time. Thus, the baseload power market is seldom considered in this report.

C.2 Peak power

Peak power is generated or purchased at times of day during which high levels of power consumption are expected—for example, on a summer afternoon predicted to be especially warm. This is typically generated by power plants that can be quickly switched on or off, such as gas turbines. Since peak power is typically needed only a few hundred of hours per year, it is economically sensible to draw on generators which are low in capital cost, even if they are more expensive per kWh generated. Or, to put it another way, these power plants are very expensive per kWh generated, because they have fewer kWhs to amortize the investment over. As a result, this is the most expensive power provided to serve California's energy needs. In the commodity provided, kWh of power, there is no difference between baseload power and peak power. In the deregulated power market in California, power purchases are made for the next day, and there are limited long-term contracts. Thus, in California, there is no real difference in the market for baseload and peak power. The factor that distinguishes peak power from base-load power is the size of the market demand and the time of day. In other jurisdictions, they are priced and contracted for differently, and in traditional utilities they are managed differently. Nevertheless, even in the California market, more expensive power sources are tapped during periods of peak demand, and a kWh sells for considerably more than during low-demand periods. Under traditional approximations used by utilities, there might be 200 peak hours in a year during which an incremental kWh of electricity would be worth 50¢/kWh (Savidge 2000). Although only an approximation intended as a rule of thumb, this may be a better guide to the long-term value of peak-time power than the current electricity market, which is today very much in flux.

C.3 Ancillary services

The primary function of ancillary services is to maintain the reliability and stability of the grid. Ancillary services are not straight kWhs of energy; they are contracted as reserve power ready to go on-line, as adjustments in voltage or frequency and other services. If the power generation and load consumption always matched perfectly, ancillary services would not be necessary. But, in practice, weather conditions, transmission outages, and other unforeseen conditions or normal fluctuations cause mismatches. Ancillary services are used – in electric industry parlance, "dispatched" – in order to balance the supply and demand of energy, and to insure regulation and quality of the power. Prior to restructuring, ancillary services were bundled with the energy supply and their cost and price was included in the energy rates. In the new market structure, suppliers compete in price for each service. In California, ancillary services are purchased through a market that is run by the Independent System Operator (ISO), which makes ancillary service procurements daily as well as through specific contracts. This makes it much easier to analyze their values since there are now market prices. Of the different ancillary services, regulation service, spinning reserves, non-spinning reserves, and replacement reserves are procured daily in the day-ahead and hour-ahead markets. Here we summarize only the two ancillary services that are most immediately relevant to vehicle-to-grid power: spinning reserves and regulation.

C.3.1 Spinning reserves

Spinning reserves are provided by additional generating capacity that is synchronized to the system. A generating station that is operating at part capacity could sell spinning reserves for its unused capacity. Spinning reserves must respond immediately and must be available within ten minutes of a request from the dispatcher. The principal difference between spinning and non-spinning reserves is that the spinning reserves generator is on-line, and contributes to grid stability helping to arrest the decay of system frequency when there is a sudden loss of another resource on the system. Spinning reserves are paid for by the amount of power, times the time they are available and ready. For example, a 1 kW generator to be made "spinning" and ready for one day might be sold as one kW-day, even though no power was actually produced. (Spinning reserves are sold in MW-hours in the CAISO's competitive ancillary services market.) If the spinning reserve is called, the generator is paid an additional amount for the energy that is actually delivered, based on the market clearing price of at that time. Note that this pricing arrangement is potentially favorable for EDVs, since they are paid as "spinning" for many hours, just for being plugged in, while they incur relatively short periods of generating power. This is true for battery EDVs (which will typically be plugged in, anyway), as well as hybrid or fuel cell vehicles, which can easily start generating within the 10-minute requirement.

C.3.2 Regulation services

Regulation represents contracts for power generation that are under direct real-time control of the ISO for increasing or decreasing output. The unit must be capable of receiving signals from the ISO's Energy Management System computer, and responding to those signals by increasing or decreasing the output of the unit. Regulation is used to fine-tune the frequency of the grid by matching generation with load demand. The objective is to maintain system frequency as close to 60 Hz as possible. If load exceeds generation, the running generators on the grid will slow down, indicating that more power is needed. Adding or subtracting power in response to a slight change, the frequency can be maintained at the ideal point. The frequency is regulated such that the number of power cycles in an hour is always the same, even if there are minor fluctuations during the hour.

Regulation services are split into two elements for the market: one for the ability to increase power generation from a baseline level, and the other to decrease power generation from a baseline. These are commonly referred to as "Regulation up" and "Regulation down" respectively which since 1999 have been auctioned separately, providing two different regulation prices. The CAISO typically procures 1600 MW of regulation (combination of up and down) every hour, and spends on the order of one to three million dollars each day for these services (CAISO 2001). This is billed on a per-kW (actually, per MW) rate, for each hour of regulation. Battery EDVs may be extremely well suited to perform in this market because: 1) they can respond very quickly to regulation signals, 2) they can perform both regulation up (V2G) and regulation down (charging), and 3) regulation up and down (combined) causes very little net discharge of batteries.

D. Frequently asked questions, or, "How can this possibly make sense?"

The idea we analyze is at first counterintuitive. It requires an intimate understanding of the fundamentals of both electric vehicles and of the electric power grid, yet analysts, industries, and state agencies are divided to cover one or the other, but not both. This concept *is* difficult to understand. To help in describing this concept, in this subsection we outline some typical questions with brief but specific answers. This organization, by frequently asked questions, is unconventional for a technical report, yet it may help readers to get a quick introduction to the concept. More detailed answers, with quantitative analysis are found in the other sections referred to in this introduction.

Q. Battery vehicles are range-limited, why should a driver allow any discharge?
A. Any vehicle used this way would have to include a controller with which the driver would limit discharge to insure sufficient charge to meet his or her driving needs (Section II.B). We calculate that there could be substantial incentives to the driver to provide power to the grid. Of course, the programs we analyze would be optional, and not all vehicle owners, nor all fleet operators, would choose to participate (see Q&A below on size of the resource). To illustrate with a simple example, assume that a battery-electric vehicle is used for commuting and is plugged in both at home and at work. The employer provides an incentive for employee vehicles by cash payment in addition to free charging at work. They warn employees that, depending on power needs, on some days there will be a net discharge at work, but insure that it will be limited according to the driver's commute needs. Figure 1.1 illustrates the charge level of an employee vehicle on one of the days during which power is drawn down from his vehicle battery. Days of substantial discharge, like Figure 1.1, would be rare; more commonly, parked vehicles might produce regulation while the vehicle is charging, at a net profit to the employer and with free electricity to the driver. Day scheduling and availability is analyzed in Section III, costs to the vehicle owner in Section IV, and value to the electric system in Section V.

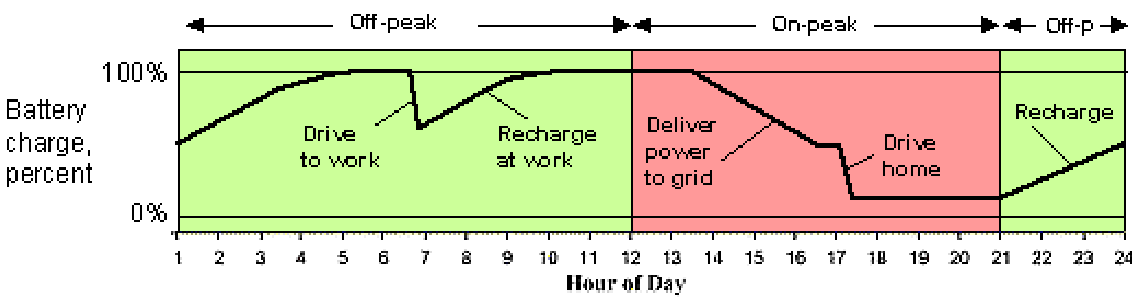

Figure 1.1. State of battery charge of a battery-electric commuter vehicle providing peak power at work, and charging both at work and at home.

Q. Ok, a fuel-cell vehicle generates electric power, but it's not hooked up. Plus, the driver would not want to drain the fuel tank in order to provide power.
A. We assume that the electrical infrastructure currently being developed to charge battery electric vehicles will also be used for hybrid and fuel cell vehicles but with

electricity flowing in the other direction. (Reverse flow is much easier with a conductive charger than an inductive one.) Fuel-cell vehicles can be used for short bursts of power (if fuel is from the on-board tank), or longer term use, if fuel is from a natural gas or hydrogen source in the garage (Section IV.C). Our economic analysis includes the capital cost of electrical and fuel connections (Section IV) and our technical overview describes controls needed to insure that sufficient fuel is available to meet driving needs (Section II.B).

Q. A battery vehicle doesn't generate any electricity—it must be charged from the grid. How can it power the grid?

A. Electricity is an unusual commodity – it must be produced at the same time it is being used. Battery vehicles are valuable to the electric grid as storage, and would provide power only when need is great, and thus, prices are high. A battery vehicle can charge when the price of power is low, say, 5¢/kWh, and sell to the grid only when it is very high, say, over 30¢/kWh. The basic idea is "Buy low–sell high." Additionally, as we explain below, there are other markets for electricity services, such as minute-by-minute regulation of voltage, and 10-minute calls to "spinning reserves" for which battery vehicles would be extremely valuable. These high values of electricity can be realized only if the power grid operator has control over the precise time that power flows from the vehicle to the grid.

Q. Vehicles are on the road at 5 pm, part of the peak demand period for the electric power system. They won't be plugged in when the power grid needs them.

A. The California electric system has peak demand for electricity typically in the afternoon, often extending through 5 pm. Although it may be difficult to imagine when stuck in traffic at 5 pm on a LA freeway, actually no more than 10% of the vehicles are on the road at 5pm; 90% are parked and potentially available to the grid. We calculate this number based on road traffic data. We additionally make a simpler calculation, based on conservative assumptions such as assuming that all EVs are used for commuting and even with these assumptions we get that 83% of vehicles are parked at 5 pm (Section III).

Q. If this idea makes sense, why use vehicles? Why don't the electric companies buy stationary batteries, fuel cell generators, etc, and eliminate the transaction costs?

A. Some electric distribution companies, and some power users, do purchase small generators. However, vehicles represent sunk capital required for driving. As noted above, even at rush hour 90% are unused. From the standpoint of the electric grid, the penetration of electric vehicles will represent a huge resource, idle 90% of the time, which someone else is buying for them. Why should electric companies buy more generators if there are idle ones? It is economical and more efficient to simply purchase idle capacity from the electric vehicle owners.

Q. Is this worth bothering with? How much power are we talking about?

A. Surprisingly, the vehicle fleet represents many times the power of electric utilities. Earlier analysis of the entire US showed that the light vehicle fleet has a mechanical power of 13 TW_m (Kempton & Letendre 1997). The capacity of all stationary power plants is 0.75 TW_e. In California, under current CARB mandates for ZEVs and AT-PZEVs, vehicles will have an electrical capacity over 400 MW in year 2004 and over 2,000 MW in 2008 (see Section III.A).

This section has described the concept of vehicle-to-grid power, answered some of the questions frequently asked about it, outlined the vehicle types and power markets of interest, and answered some common initial questions. The next section will describe the physical interconnections and vehicle capabilities needed for our proposal.

II. Interface and Infrastructure

This section will discuss connecting EDVs so that they can provide power to the electrical grid. Two connections are required: 1) power connection for electrical energy flow, and 2) control or logical connection, needed to signal to the vehicle when power is requested and to send from the vehicle the record of metered V2G power. These two connections are illustrated in Figure 2.1, which shows a physical power connection and a wireless control connection. The Figure also illustrates that control could be directly to a single vehicle, or to a parking lot or a third party aggregator which would tap groups of vehicles.

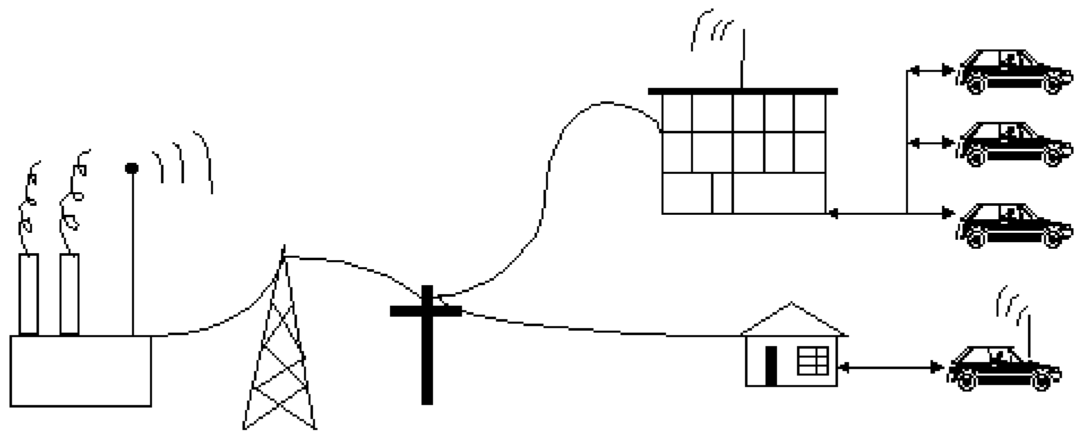

Figure 2.1. Illustrative schematic of possible power line and wireless control connections between vehicles and the electric power system.

For fueled vehicles (fuel cell and hybrid in motor-generator mode), a third connection for gaseous fuel (natural gas or hydrogen) may be added so that on-board fuel is not depleted.

The control signal is critical because vehicle power has value greater than the costs to produce it only if the party receiving V2G power can specify the precise time at which it is needed. As we will discuss, on-board metering is a desirable addition for many business models, and to expand the configurations and locations from which vehicles can provide power.

Other details on Figure 2.1 are simplified at some expense of accuracy. For example, the signal would be unlikely to actually originate at the power plant as the figure suggests; in California, it would more likely originate from the CAISO or a local distribution company. Also, the aggregator might be a third party, controlling dispersed vehicles, rather than a building operator with on-site vehicles as the figure suggests.

This section describes the design considerations for the electrical power connection necessary for all V2G and possible fuel connections desirable for some configurations of fueled vehicles (hybrids or fuel cell vehicles). It then discusses the driver controls to insure that driving range is not compromised as well as the signal or control connections to the vehicle. Finally, standards and tariffs are covered, and some possible business models are discussed.

A. Electrical connection—capacity, conductive versus inductive

For battery vehicles with on-board conductive charging, virtually all the physical connections already exist. Battery vehicles must already be connected to the grid in order to recharge their batteries. On-board conductive charging allows V2G flow with little or no modification to the charging station and no modification to the cables or connectors, assuming on-board power electronics designed for this purpose. AC Propulsion, Inc. tested the first vehicle power electronics built for this purpose in August 2000. When designed initially as part of the system, they found that there was "zero incremental cost" to a design allowing reverse power flow. The same control used to control rate of charge was simply extended to allow flow in the negative direction, with "a few lines of software added to the ROMs."[1] In short, the on-board power connections and power control we propose have already been demonstrated. They have little or no incremental cost if incorporated in the design from the start, but may be difficult or expensive to retrofit if added to a vehicle not initially designed for them.

The power capacity of charging stations and electrical service in buildings requires more consideration. We consider charging station capacity first, then the wiring capacity in buildings.

The capacity of the electrical connection to the vehicle, measured in Amperes (A), together with the voltage, determine the maximum power in kilowatts (kW). That is an upper limit of V2G power, as limited by the electrical connection. For some vehicles and power markets, the capacity of current Level 2 conductive chargers is adequate. These run 32 A, at 208 V in commercial buildings and at 240 V in residential ones. At a public charging station, with commercial power, this would be 208 V * 32 A or 6.6 kW capacity. In a residence with 240 V, this would be 7.7 kW capacity. For comparison, this is less than the draw of a household electric range, at 40 A or 9.6 kW. For the three battery vehicles and two hybrid vehicles we analyze, 7 kW is sufficient for peak power and spinning reserves.

For high power uses of battery and hybrid vehicles (such as regulation services) and for the fuel cell vehicles, higher capacities could be valuable. Such high-capacity uses could utilize conductive charging stations as they become available for battery vehicles conforming to the proposed Level 3AC charger standard (SAE 1996), with a 100-Ampere connection.[2] (Level 3AC was formerly called "Level 2+.") The current battery EDV infrastructure at public locations is 208 V, 32 A service, so the maximum

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[1] The zero incremental cost report is from the power electronics designer, Alan Cocconi, President and lead designer at AC Propulsion. Kempton and Letendre (1997) considerably overestimated the cost of this addition. Their estimate, deliberately erring on the high side for conservatism, was $250 incremental cost.
[2] The Society for Automotive Engineers (SAE) infrastructure committee is expected to approve Level 2+ as an appendix to the 1996 SAE standard J1772. There is no limitation of 100A inherent in the proposed revisions to J1772. They allow for up to 400 A at 240 V, or 96 kW. Given the capacity of vehicles, and typical residential service, a wall box with a 100-A rating is a reasonable maximum limit to expect for many single-family residences; some commercial locations might be higher. Continuous operation requires derating to 80% of nameplate. So the capacity would be 80 A times either 208 or 240 V (16.6 or 19.2 kW)

V2G power is 6.6 kW. A 100 A Level 3AC charging station is rated for 80 A continuous, so for a typical commercial location that is 80 A*208 V = 16.6 kW in a typical residence 80 A*240 V = 19.2 kW. In moderate volumes, these 100A charging stations might be expected to sell for $1000 to $2000.

We next consider building power capacity and line voltage. Table II.1 gives some typical building wiring capacities. One-hundred ampere capacity is easily accommodated in commercial buildings large enough to have their own parking lot. For residences, single-family residence electric service is typically at minimum of 150 A at 240 V or 36 kW. The largest typical household load would be for example an electric range at 40 A or 10 kW. Therefore, a Level 3AC charging station running at 16.6 kW is within the capacity for single-family residences but would require heavier wiring than typical appliances and in many cases could not draw power at that level due to limits on total rated capacity for the house. Thus, a charging limit (grid-to-vehicle) below the 100 A circuit capacity would typically be required. For example, if a home has 150 A service and existing circuits added to 100 A, charging would have to be limited to 50 A even if the charging station itself could carry more.

Table II.1 Comparison of charge/discharge units with building capacities.

	Volts	Amps	kW
Public Level 2 charger	208	32	6.6
Public Level 3AC charger (100 A line)	208	80	16.6
Residential Level 3AC charger (100 A line)	240	80	19.2
Large residential appliance (range)	240	40	9.6
Residential service (small single-family)	240	150	36.0
Air handling, small commercial building (3 story)	208	60	12.0

We are more concerned with the reverse direction, vehicle-to-grid (V2G), which would not have the same constraints. V2G would not be added to home loads; more logically, they would be "subtracted" from the V2G power. For example, consider a home with 150 A service, with circuits already wired to the maximum of 150 A. A fuel cell vehicle producing 100 A (19 kW) could still be added because the possible range of power through the main circuit breaker would then be –100 A (V2G only, minus indicating power from house backward through meter) up to +150 A (all loads and no V2G output). (We have not explored code and standards issues involved with additive circuit capacities.)

An electrical connection from an apartment or residence out to street parking is probably not practical, certainly not at 16.6 kW. Thus, we limit our home connection considerations to vehicle owners who either park in a home garage or who park in driveways adjacent to their house. Our assumption of at least 100 A electrical service also would not apply to small apartments.

If a separate building meter were required for the vehicle, additional power wiring would be required, increasing installation costs. A separate meter is typical for current

EV charging rates. We outline an alternative, an on-board meter possibly connected via telematics, for vehicle-specific metering. If the on-board meter were used for EDV rates, it would reduce the cost of wiring for battery EDVs, whether used for V2G or not. This is discussed below.

A final minor compatibility issue involves voltage match between the building power and the vehicle battery pack. For some vehicle-to-grid power electronics configurations, the DC battery pack voltage would have to be above the peak voltage of the AC side power. A 208 V AC line, would require a battery pack over 294 V DC, and a 240 VAC line would require at least a 340VDC battery pack[3]. Common battery packs for vehicles range from 288 V to 450 V, so choice of battery could affect V2G, especially for home circuits. However, this would only be a problem for some designs of power electronics, and could in any case be resolved by adding a step-up power transformer. Again, the general point is that vehicle power electronics, conductive charging and building power connections are compatible with the V2G concept, and they are especially easy to incorporate if considered at the design stage.

Electrical connections are also considered for hybrid and fuel cell vehicles. Traditionally, an electrical connection has not been contemplated for these types. Our analysis assumes that an electrical connection from grid to vehicle would be added. There are environmental motivations for an electrical connection to hybrid vehicles, the so-called "plug-in hybrid." The plug-in hybrid has enlarged batteries and can run in battery-only mode as a ZEV. That is, they recharge when parked so that for shorter trips they never run their internal combustion engine. The plug-in hybrid has benefits in reduced pollution, fuel costs, and driver convenience (no need to get gas). Nevertheless, for hybrid and fuel cell vehicles, our analysis treats the electrical connection as an added fixed cost, amortized and added to the per kWh cost of vehicle-to-grid power.

Our connection capacity assumptions vary somewhat for different vehicle analysis in this report. For example, when using the hybrid in motor-generator mode we assume a limit of 16.6 kW for hybrids, that is, we assume that their power value would justify use of Level 3AC charging station infrastructure. For fuel cell vehicles, somewhat further in the future and possibly having generation capacity that would justify larger electrical connections, in some parts of the analysis we assume a 22 kW (in some discussions up to a 40 kW) conductive connection could be available.

The above discussion covers conductive chargers with power conditioning on board the vehicle. Inductive charging is more problematic. Inductive chargers have a "paddle" on the grid side that is inserted into a "slot" on the vehicle side. Electricity is carried across from paddle to slot by induction; the inductive loop uses high-frequency AC in order to minimize the losses. Electrically, the paddle and slot are each one winding of a transformer. This design requires power electronics for sending the energy on the grid side (high-frequency oscillator, etc.), and different power electronics to rectify and filter the received power on the vehicle side.

Today's inductive charging stations are incapable of carrying vehicle-to-grid power, whereas most of today's conductive charging stations can do so already. An inductive charging station and vehicle could be designed to carry reverse power. Such a design would use the same paddle and slot, but would require duplicating the above-

[3] The 208V AC and 240 V AC are "root mean square" ratings whereas the battery pack voltage must match the peak AC.

mentioned power electronics on opposite sides of the connection. That is, components to send power would be added on the vehicle side and those to receive and condition it would be added on the grid side. This duplication would considerably increase the cost and complexity of inductive charging stations and vehicles designed for two-way power flow. A second problem is that inductive chargers require off-board electronics, requiring duplication of costs at each charging location, whereas conductive chargers can be economically configured with all power conditioning on-board the vehicle, minimizing infrastructure costs. An independent problem is that inductive chargers become considerably more expensive as power capacity is increased from today's designs to 20 kW. For all these reasons, the use of inductive charging for vehicle-to-grid power does not appear to be practical.

B. Gaseous fuel connection

For hybrid and fuel cell vehicles no additional fuel connection is required if we assume that fuel is used from the on-board tank. Drawing down a fuel tank for electric power requires careful control of the amount that can be used—this is similar to the case of draining a vehicle battery for power (discussed next) but not so easily recharged. A gaseous fuel connection (*i.e.*, natural gas) would allow power production of essentially unlimited duration, and may provide refueling advantages to the driver. Each of these configurations for fueled vehicles is analyzed in Section IV. We include these fuel connections in capital costs for configurations requiring them. One would also have to consider safety from gaseous leaks at couplings, and some means of minimizing the inconvenience to the driver of having to make both electrical and fuel-line connections to the vehicle when parked. These considerations argue for dual connections as more likely if they serve a refueling function or if the economic benefits are substantial.

Exhaust gases must be vented if either a hybrid (in motor-generator mode) or fuel cell vehicle is used. For such safety considerations a typical open parking structure at a commercial site would seem more appropriate than a private residence with a closed garage. For hybrid, but not fuel cell or battery vehicles, there would also be a question of emissions of criteria pollutants. We analyze the case of natural gas fuel for hybrid vehicles used in generation mode, since emissions would be lower than if liquid fuel was used. Nevertheless, safety and pollution considerations would need to be better analyzed for hybrid vehicles running in motor-generator mode, and safety considerations would have to be analyzed for fuel cell vehicles even if fueled by hydrogen.

C. Controls to give driver control of available range

For some of our scenarios, the vehicle providing grid power is draining a battery or emptying an on-board liquid fuel store. In such situations, it is essential that the driver limit the drawdown so travel is not affected. Following Kempton and Letendre (1997), we feel that the best way to do that is with a control that the driver sets according to driving needs. Working within the constraints of the driver's settings, the power buyer must limit the degree of battery discharge or fuel tank rundown.

An example control panel is shown in Figure 2.2. Whether the control is physical, on the dash, or on a web page, the idea is basically the same. The driver has two parameters to set—the length of the expected next trip (in the case shown in Figure 2.2, ten miles at 6:45 the next morning), and the minimum range ever allowed (in this case two miles, perhaps a round trip to the emergency room).

All of our calculations of power available from vehicles assume that the driver sets a limitation on discharge or fuel drawdown, which cannot be exceeded by the entity requesting power. This analysis is carried out in Section IV.

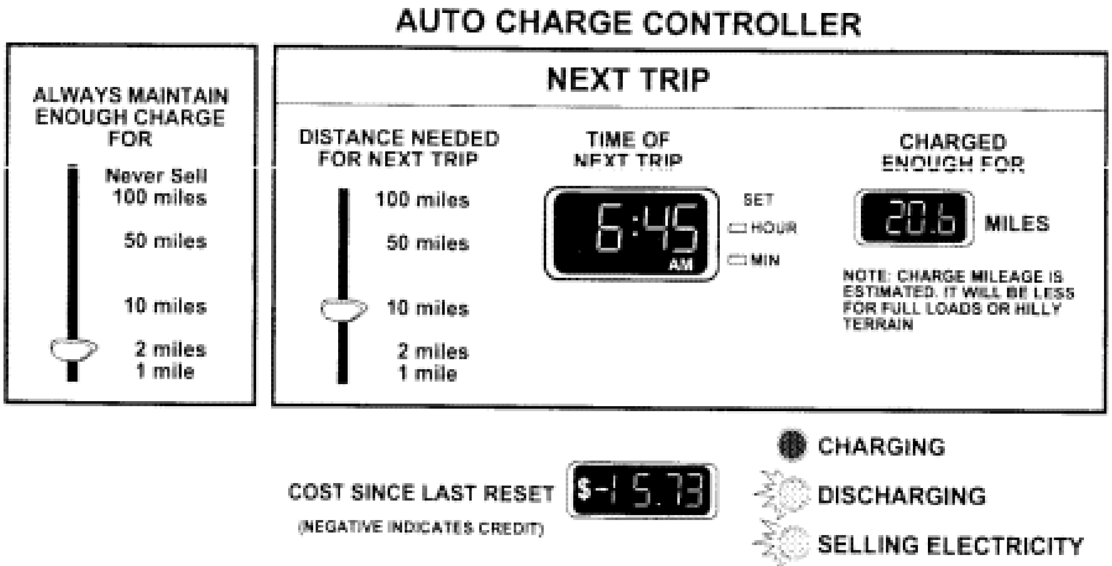

Figure 2.2. Suggested design of vehicle dashboard control, allowing driver to limit loss of range of vehicle and monitor power transactions (From Kempton and Letendre 1997). The control shown here is for a battery vehicle; similar controls would be used for fueled vehicles to limit the drawdown of the tank. These functions might alternatively be accessed via a web browser.

D. Control links: wireless access, positioning, and on-board metering

The automobile industry is moving towards making real-time communications a standard part of vehicles. This field, called "telematics" has already begun with luxury vehicles; over a period of time it will be available for most new car models. These capabilities are penetrating new vehicles independently of our proposed use of telematics. They offer services like mobile internet connectivity, real-time location, automated detection of mechanical problems matched to nearby facilities, location of nearest source of alternative fuels, and so on. Many of these services imply business models with a service provider capturing additional revenue streams after-vehicle-sale. As telematics develops, some of these service providers may be logical parties to function as aggregators of many vehicles' power, for sale to the grid operator as a local distribution company.

We briefly consider the capabilities of telematics, as the communication link is essential to our proposal. A telematics capability would presumably also add a unique identifier for the vehicle, such as an IP (internet protocol) number. A unique vehicle identifier is essential to bill or credit to the vehicle for V2G. Possible aggregators and business models are considered at the end of this section.

The physical medium for the telematics connection is radio, either broadcast or using the existing cell phone network. The best system in the mid-term may be GPRS (General Packet Radio Service), which allows for full-time always-on wireless internet connectivity. This is a few years from being deployed. Currently, short message service (SMS) is already available, which allows short data messages to be sent to and from digital cell phones.

Many telematics designs assume a form of positioning, and that would be useful for V2G as well. Positioning is accomplished either with a Global Positioning System (GPS) or using directionality of the cell phone network. Positioning will soon be required of the cell phone network anyway, to meet needs of 911 call response. Cell phone-type positioning would be cheap but not accurate enough for many V2G business models. The cell phone positioning requirements are to located within 100 m 2/3 of the time and within 300 m 95% of the time. Cell phones using GPS chips must be within 50 m 2/3 of the time and within 150 m 95% of the time. Either cell phone method gives sufficient accuracy, for example, to determine whether a vehicle was at home or office if the V2G aggregator knew the vehicle could be plugged into only those two meters, but neither could distinguish adjacent parking spaces and perhaps not even neighboring homes' garages. A more generally useful positioning would have to distinguish which meter the vehicle is plugged into, which we estimate would require positioning within approximately two meters (assuming the worst case of adjacent garages in townhouses). This level of accuracy is possible using GPS with a differential signal from the radio data system (RDS). Higher accuracy also would require that the vehicle stay in place for 5-10 minutes, a requirement compatible with V2G. These higher accuracies may be more than those required for telematics capabilities, expected to be put on vehicles anyway, for non-V2G reasons. To determine whether the high accuracy positioning would justify a cost of perhaps a couple of hundred dollars, cost and technical feasibility would have to be assessed in relation to the expected business model for V2G. For example, more accurate positioning could be an after-market plug-in only added to vehicles whose particular use of V2G justified it.

An alternative to positioning would be for the charger unit to transmit the meter number to the vehicle. This could use the existing "pilot signal" wire or could use a wireless channel. The existing channel, in Level 2 and Level 3AC charging stations, is a pilot signal wire connected along with the power wires when the vehicle is plugged in. This pilot signal now transmits the ampere capacity of the circuit via a 1 kHz square wave signal, information that the vehicle uses to limit the maximum power it draws. According to charging station industry sources[4], a serial number could be added to this pilot signal by transmitting it in serially encoded form, at a frequency different from 1 kHz. Such an addition would be compatible with existing equipment—old vehicles would work on the serial-number enhanced chargers and vice versa, but of course the charging station's serial number could be decoded only by vehicles set up to read it. The cost to add this capability is estimated at under $100 retail in current low production volumes, much less in an expanded market for chargers. An alternative medium to

[4] From telephone discussion with Jason France, CEO, Electric Vehicle Infrastrure, Inc.

transmit a serial number from charging station to vehicle would be to add a short-distance wireless technology, such as "Bluetooth."

A transmittable serial number may be a desirable capability to add to coming charger designs. It is not required for V2G, which can operate under business models not requiring it, and which should be compatible with electrical connections lacking any serial number. Thus, some form of positioning on-board is required, so V2G will work with existing chargers, and in the future will work at locations where a serial number is not available.

Finally, if the vehicle is to sell power from multiple locations, it would need precision certified energy metering on-board. The vehicle becomes a "metered account" whose power may be flowing through a tied-down traditional meter, which we will call a "fixed-meter", then through the on-board meter. As noted above, the problem becomes determining which fixed-meter the vehicle is plugged into, so that the mobile-meter amount can be added or subtracted to the amount registered on the fixed-meter to reconcile the fixed-meter's billing account. On-board metering and positioning together are required for business models that allow a vehicle to sell power while at a public power station or otherwise away from its home garage.

Of all the above telematics capabilities, only the on-board metering is not expected to be added to vehicles already, for other reasons. The incremental cost of on-board metering would be less than $50 (see Section IV), again assuming it were incorporated into the design rather than retrofitted. Based on all the foregoing, our analysis does not attribute telematics costs to the capital costs of enabling vehicle-to-grid power.

Given the above communications capabilities, a power aggregator would know the status and location of all participating vehicles. Such information could include parameters such as power capacity, stored energy, expected time of availability, and which meter it was plugged into. This information could be integrated and made available to both the vehicle owner and the power aggregator. For example, each vehicle could have a vehicle status page on the internet and a physical or virtual control panel like the one in Figure 2.2. Preferences or needs like those shown in Figure 2.2 could be set from the dashboard or over any internet connection.

E. Codes, tariffs, and interconnection standards

Some existing codes and standards facilitate the introduction of V2G power. Others are currently impediments that would have to be addressed for widespread adoption of theV2G concept. This section briefly addresses several such issues: site generation interconnection safety, net metering and other renewable energy tariffs, demand charges, interruptible tariffs, and the National Electrical Code (NEC).

Renewable energy systems that are grid-connected have approved interconnections and have a tariff for running the meter backwards. Similarly, co-generation systems are currently set up to feed the grid. Site renewable energy is a good comparison with V2G power in safety interconnections, but is the wrong model for tariffs.

In California, Rule 21 (Public Utilities Commission of California 2000) governs small power production interconnections for the large investor-owned utilities. This rule requires small generators to have facilities such as automatic lockout to prevent energizing utility lines that have been disconnected for service and automatic disconnection when voltage or frequency drift outside specified ranges. Vehicle-to-grid systems, as we describe them here, appear to meet these requirements, although some requirements not surprisingly assume that the system is site-built and stationary. For example, one area of particular safety concern for line workers is lockout of site renewable energy when power lines are turned off for service. Without this, workers could cut off power from the substation, but still be electrocuted from power coming back up the line from a customer's solar or co-generation unit. A similar safety interlock would have to be employed for vehicles. In fact, such an interlock has already been demonstrated as a low-cost design addition to on-board vehicle electronics.[5] When such controllers are built into vehicles, no additional external interlock would be needed in the house wiring.

Some concern exists regarding an article defined in the National Electrical Code and concerning the backfeeding of power from vehicle to grid. The current National Electrical Code, Article 625-25, includes the following language:

> Means shall be provided such that upon loss of voltage from the utility or other electric system(s), energy cannot be backfed through the electric vehicle supply equipment to the premises wiring system. The electric vehicle shall not be permitted to serve as a standby power supply. (Earley, Caloggero and Sheehan 1996)

This would prevent EDVs from being used for site power when the grid fails. This does not appear to prohibit vehicles from producing power or backfeeding as long as the grid is on. This section of the NEC should be clarified prior to implementation of the vehicle-to-grid concept, or the NEC would have to be amended.

Regarding tariffs, renewable and co-generation systems produce power when the sun is shining, when the wind is blowing, or when the site co-generation system needs to produce heat. This is resource- or site-determined timing, so the tariffs specify that the local distribution company pays in energy units, regardless of the time of day it is provided. Under one type of tariff, called "net metering," the power company buys power at the same retail rate as it sells it. This is generally considered an incentive rate, as the local distribution company is buying power at retail rates, that is, they are not compensated for bearing the grid system costs. But net metering is not adequate payment for V2G power. Vehicle power, as we propose it be configured, is much more valuable to the grid because it can be provided exactly when power or ancillary services are needed. Vehicles would deliver power, or other electric grid services, when the value is highest, not when the sun is shining or the wind is blowing. To capture this value, tariffs for vehicle-to-grid power would require that vehicles provide power precisely when needed, in exchange for premium rates well above the net metering rates for site renewable energy.

There are two existing tariffs, both for commercial customers, which might allow for economical use of vehicle power without rate changes. Because these rates already

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[5] This capability is already proven, as it has been built into the AC Propulsion AC-150 Gen2 drivetrain power electronics.

exist, and because the customer does all the controlling, no rate tariffs or control technologies need be added. Thus, these tariffs represent an opportunity for early introduction of V2G power.

The first existing commercial rate is demand charge. Most utilities bill residential customers only by energy, that is, the total kWh consumed. Commercial customers are billed by "demand" as well as energy. Demand is metered as the largest power flow, measured in kW, typically measured as a maximum over any 15-minute time during the month. This "demand charge" compensates the distribution company for expenses incurred by having to upgrade lines and transformers to handle the maximum, and for adjusting to fluctuations in load. It is common for the demand charge to be 50% of a commercial customer's bill. As will be seen from our detailed quantitative analysis, V2G can make money via demand charges only for commercial customers who have short and infrequent peaks, and sufficient vehicles to predictably offset those peaks.

The second existing tariff is interruptible rates. Under this tariff, large users get a year-round discount off their energy bills (*e.g.,* 15%) in exchange for agreeing to sharply curtail their consumption when asked by the grid operator. The role for V2G would be to allow on-site V2G to substitute for the curtailed grid power. Such commercial customers could achieve the 15% savings while not curtailing production or other business functions.

F. Business models

Combining the technical, regulatory, and tariff issues discussed above, we outline a vision for vehicles as a grid resource, then discuss possible business models. These business models assume on-board meters, and assume that power is provided to the grid—not used on-site as in the demand-charge or interruptible rate models mentioned above.

F.1 Mobile meters

We envision a fleet of vehicles available most of the day to provide power (see Section III for analysis of time-of-day availability.) Drivers would plug in the vehicles to power connections at home, at work, and possibly when in stores for extended time (say, over 1/2 hour). They would plug in battery vehicles to receive charge, and they would plug in all types of EDVs (battery, hybrid, and fuel cell) because they would be paid to do so.

Vehicles would not generate power for most of the time they were plugged in. Rather, they would fill in during times of system need, whether the need were due to equipment failure, unanticipated high demand, or—for a future grid with high renewable energy resources—at times of slow wind or low solar insolation. The driver would set restrictions on the amount of discharge or fuel drawdown permitted, based on driving needs (by controls like those shown in Figure 2.2). The vehicle would receive and automatically respond to signals via its on-board telematics. Such signals might include periodic queries as to its location, whether it is plugged in, and whether it has sufficient charge (or fuel) to provide power. When needed, the signal would request power output, or ancillary services. The on-board system would periodically report power consumed and produced, through which fixed-meters and at which times.

The complete range of business models works with just three elements. The three elements are an on-board, certified, tamper-resistant meter to record time and power flow, an IP number or other unique identifier on the vehicle to identify the account being billed or credited for vehicle power flow, and positioning or charging station ID to identify the fixed-meter account to be reconciled. We consider first the simplest V2G business model, one which is analogous to current rates for battery EDV owners.

F.2 Business model of each metered vehicle as a customer account

For mobile meters, a simple business model is that the metered vehicle becomes an account with the local distribution company. This has a close analogy in current "EV rates" for battery vehicles, in which a single vehicle is plugged in at home to a single home fixed-meter.

The current battery EV business model is that an additional meter is installed in the vehicle's home garage. Through this separate fixed-meter is offered night-time charging at a baseload power rate, such as 5 ¢/kWh, while a disincentive for daytime charging is provided through daytime rates such as 30 ¢/kWh. The flaw in the current EV rates model is that public charging cannot easily be billed; this has been temporarily handled by simply giving free charging at public outlets.

The business model of each vehicle as an account offers a better solution even within the limited scope of the "EV rates" business model. It simultaneously handles nighttime rates and the public charging problem, as well as V2G. The on-board meter reading would be added or subtracted to reconcile the account of whichever fixed-meter the vehicle is plugged into. For example, if the vehicle is charging at a nighttime rate of 5 ¢/kWh, on the vehicle owner's fixed-meter account normally costing 10 ¢/kWh, the difference would be credited to the fixed-metered account. When the same home-garaged vehicle is providing valuable peak power at 30 ¢/kWh, the fixed-meter running backwards at 10 ¢/kWh would not be sufficiently compensated. In this case the vehicle meter would be used to calculate the number of kWh to which it should apply the extra 20 ¢/kWh.

Consider a meter in a public place such as an airport or shopping center. In this case, the on-board meter is the primary device for measuring purchased or sold power. In some cases, the utility might use the fixed-meter only for validation, charging its kWh to an internal account. Customer billing would be based completely upon the on-board meter and would accumulate the amount billed for charging a battery vehicle, less credits for V2G power sales.

F.3 Business model of aggregator

Some business models posit that the vehicle owners would not directly have transactions with power markets. Rather they would work through an aggregator, serving as a middleman between the vehicle owner and the grid operator. The role of the aggregator is to consolidate power capacities (for peak, spinning reserves, or regulation), and sell them in the highest value markets. We can consider several possible aggregators, each of whom would have distinct market advantages. The aggregator might be:

• The local electric distribution company, who is already in the electricity business and would gain system reliability benefits,

• The automobile manufacturer's service organization, who, in the telematics era, will want to maintain a continuing relationship with the driver to sell vehicle-based information services,

• A cell phone operator, who is operating the communications network on which the V2G information system is based, and who is accustomed to making profit from many small automated transactions,

• A third party specializing in power markets.

Under current CAISO contracts, most of these services are contracted in larger quantities than individual vehicles, in MW rather than kW. Thus, assuming current contract minima, aggregators would be essential for individual vehicles to participate in CAISO markets. The aggregator would be certified as a Schedule Coordinator by the ISO (an entity that is certified to participate in the ISO markets), and would have the ability to communicate with all of the vehicles involved. Depending on the type, electric drive vehicles have different strengths and capabilities. Section V and VI quantitatively analyze how specific vehicle types would be best utilized, and in which electricity markets.

F.4 Example business model: Aggregator owns batteries

Of the various possible business models for aggregators, one is of particular interest. A business could be constructed for battery vehicles that would not involve payment for power. Instead, the aggregator would provide free replacement batteries and possibly free charging, in exchange for being able to tap vehicle power. Again, drawdown would be limited by driving needs, as in Figure 2.2. This model has the advantage that the power user need not keep account of battery wear, and the driver need not be concerned at how quickly additional cycling is degrading the battery, since the power user is responsible for battery replacement. Whether all or part of the battery cost is covered, and whether recharging electricity is also included, of course depend on the value of the power provided compared with the battery degradation and other costs to the driver. Much of the remainder of this report attempts to calculate these values and costs more precisely.

Comparing business models and comparing possible aggregators leads one to the question, "What type of business is this?" One view is that V2G is a business like an energy service company (ESCO). ESCOs manage energy in commercial buildings, in return for a proportion of the savings. The managers and the field personnel require a good deal of knowledge of energy systems. The ESCO business has not been as lucrative as was initially expected, so if this is a parallel to the V2G business, it would lead us to assume very large margins would be required for V2G to be worthwhile to an aggregator. But the ESCO business requires on-site installation and monitoring, each site has unique characteristics requiring analysis, building occupants greatly affect energy use. In short, labor can be a high cost input whereas returns of seemingly similar buildings are variable and difficult to predict.

A contrasting view is that the V2G aggregation business is more like a cell phone business. Each request for service is unique, billed devices are in motion, and transactions have small margins; however, virtually all of the operations and billing are automated, so virtually no labor is required per transaction. If the cell phone business were closer to the V2G business, only small margins per customer would be required for a profitable business.

III. Resource Size

From projections of the fleet of EDVs in California, this section calculates three critical quantities. The first part projects the total size of the V2G electrical resource based simply on projected sales. The second part of this section uses several methods to calculate approximately what percentage of the EDV fleet would not be on the road at any one time, and would thus be available for V2G power. The third part calculates the number of vehicles needed to satisfy the total state markets for regulation, spinning reserves, and peak power.

A. Projected EDV fleet and its total power capacity

Currently, California Air Resources Board (CARB) mandates increasing percentages of each manufacturer's new vehicles sold in the state to be zero-emission vehicles (ZEV) or partial ZEV (CARB 2000a, 2000b). An alternative to meeting the requirement with ZEVs (currently conceived as full–function, battery vehicles), the current requirements allow substitution with larger number of "city EVs" (smaller, limited range battery EDVs) or AT-PZEV (advanced technology PZEV like extended range hybrids for example).

Table III.1 shows the projected numbers of different EDVs that are expected on the market from 2003 to 2008 based on options of either 4% full function ZEVs or 2% ZEV and 2% AT-PZEV. These are minimum requirements. Actual sales could be higher if consumer demand exceeds the mandates, or could be lower if the mandates are subsequently lowered.

Table III.1 Projected ZEVs and hybrid vehicles (AT-PZEV) delivered for sale annually in California from 2003 to 2008[a] (CARB 2000b).

	Number of Vehicles Sold Annually					
	2003	2004	2005	2006	2007	2008
If 4% ZEV(no AT-PZEVs)						
ZEVs						
If 100%full function EV	9,300	9,300	9,300	9,300	9,300	9,300
If 100% City EV	23,500	23,500	23,500	29,400	29,400	29,400
AT-PZEV[b] (e.g. ,Hybrid)	0	0	0	0	0	0
If 2% ZEV and 2% AT-PZEV						
ZEVs						
If 100% full function EV	4,650	4,650	4,650	5,800	5,800	5,800
If 100% City EV	11,750	11,750	11,750	14,700	14,700	14,700
AT-PZEV[b] (e.g.,Hybrid)	10,700	21,500	32,200	43,000	43,000	43,000

[a] Figures do not include the potential effect of efficiency credit or power train warranty credit.
[b] AT-PZEVs are assumed to be vehicles with a 0.45 allowance (before multiplier), such as the hybrid vehicles, Toyota Prius and Honda Insight.

Using the numbers from Table III.1 and the available power from each type of EDV, we can estimate the size of the resource, that is, the total potential MW of power from EDVs. Detailed description of available power from each type of vehicle is presented in Section IV. The values in Table III.2 were determined assuming 11 kW from full function EV, 4 kW from City EV, and 10 kW from a hybrid EDV running in motor-generator mode.

Table III.2 Cumulative power available (in MW) from various EDVs according to the projected number of vehicles to be sold in California from 2003–2008.

	Cumulative Power (MW)					
	2003	2004	2005	2006	2007	2008
If 2% ZEV and 2% AT-PZEV						
ZEVs						
If 100% full function EV (11 kw)	51	102	153	217	280	345
If 100% City EV (4 kW)	47	94	141	200	259	317
AT-PZEV[b] (e.g.,Hybrid) (10 kW)	107	322	644	1,074	1,504	1,934
TOTAL[a]	158	424	797	1,291	1,784	2,279

[a] The total is the sum of AT-PZEV and either full function EV or City EV.

Table III.2 shows that under the current CARB requirements of 2% ZEVs and 2% AT-PZEV in 2003 there will be 158 MW of power in this vehicle fleet, in 2004 it will be 424 MW, and the number will increase to 2,279 MW by 2008. For comparison, 424 MW would be a quantity similar to the load reduction of statewide rolling blackouts[6] and 2,000 MW is equivalent to two large nuclear power plants, or 4% of the statewide generating capacity of 54,000 MW. The majority of the power would come from hybrid vehicles (or AT-PZEV) since their phase-in is expected to be more rapid. Regardless of the proportion of full function and City EVs, the MW potential from battery vehicles is expected to be close to 50 MW in 2003 and around 330 MW in 2008.

B. Time-of-day availability of fleet

If EDVs are to be a significant source of power, they must be available when needed. So far, we have only calculated total resource size, not availability. To be available, vehicles must not be driving and must be parked near a plug. In conducting this research, we found no data on the times of day or locations at which vehicles park. The data, more oriented to road planning, give miles and duration of driving, and the

[6] Rolling blackouts occur when state 3 power emergency is reached, defined as generation available being less than 1.5% above load. For the CAISO control area, maximum load is about 46,000 MW. If we assume rotating blackouts would drop 1% of that load, that would be 460 MW, close to the V2G potential power in 2004.

volume and time of day of road usage. From the existing data, in this section we derive estimates of the availability of vehicles for V2G power.

The average personal vehicle is in use only 4% of the day leaving 96% of the day when it is not in use. This number is derived from the average time spent driving per driver (59.5 min) and the ratio of licensed drivers to vehicles, which is 1.0 (Hu and Young 1999). Further, each driver on average uses a vehicle to travel 32 miles per day. The time that a vehicle is in use and the daily average miles traveled suggest that most personal vehicles are stationary most of the time. Additionally, the Nationwide Transportation Survey shows that the average vehicle makes 3.7 trips per day (Hu and Young 1999); this may be somewhat lower for the average commute vehicle, but we can assume at least two trips per day as a lower bound. We need additional data to know time of availability.

For regulation services, the time when the vehicle would be needed is distributed evenly throughout the day. For spinning reserves and especially for peak power, however, the need is more likely at the times of peak traffic load. Thus, for these markets it is especially important to determine that a sufficient proportion of vehicles would be parked during those hours, and thus available to provide V2G power.

Figure 3.1 represents a daily electricity load for the California electric grid for a summer weekday (August 8, 2000) (CAISO 2000). The peak demand for electricity on this day occurs around 4 pm (16 h). Since the total available generating capacity of the CAISO control area system is 46,000 MW, the peak demand at 4 pm this day represented the system running at 97% of its capacity. In general it can be said that the daily electricity peak occurs between 3-6 pm, is more prominent in the summer season and that the size of the peak corresponds to the temperature and time of day (due to the predominance of air conditioning in peak load). The concern raised by Figure 3.1 is that, for peak power and to a lesser degree for spinning reserves, the greatest need for V2G power overlaps with the afternoon rush hour.

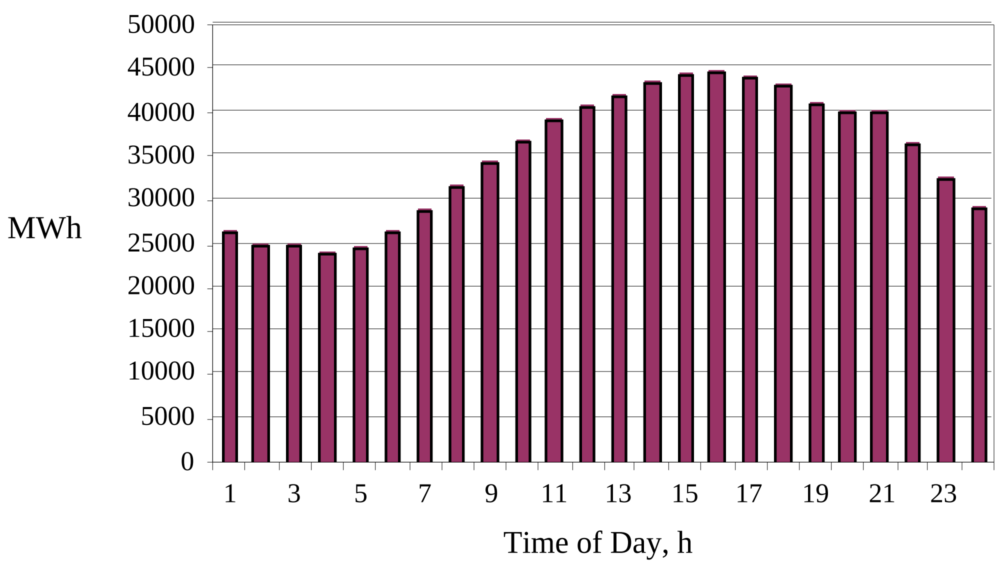

Figure 3.1. Daily electricity load profile in CA on a summer weekday (Aug 8, 2000) (CAISO 2000).

Figure 3.2 represents the daily traffic flow shown as percent daily traffic versus time of day. The daily traffic measurements were aggregated over one-hour periods and the percentage was derived from vehicle-hours during each hour over total vehicle-hours for the day. These data are for the city of San Diego on a typical summer weekday (July 21, 1999) (Green et al. 2000) but are similar to typical US hourly traffic pattern described in Handbook of Road Technology (Lay 1998) and to recent traffic patterns in other urban areas (Green et al. 2000). The traffic data are also consistent with personal travel data by time of day from Hu and Young (1999). Two peaks are observed, 7-9 am and 3-6 pm. We presume these are due to commuting traffic to and from work, in agreement with the Nationwide Transportation Survey (Hu and Young 1999) which gives traditional work travel times as 6-9 am and 4-7 pm.

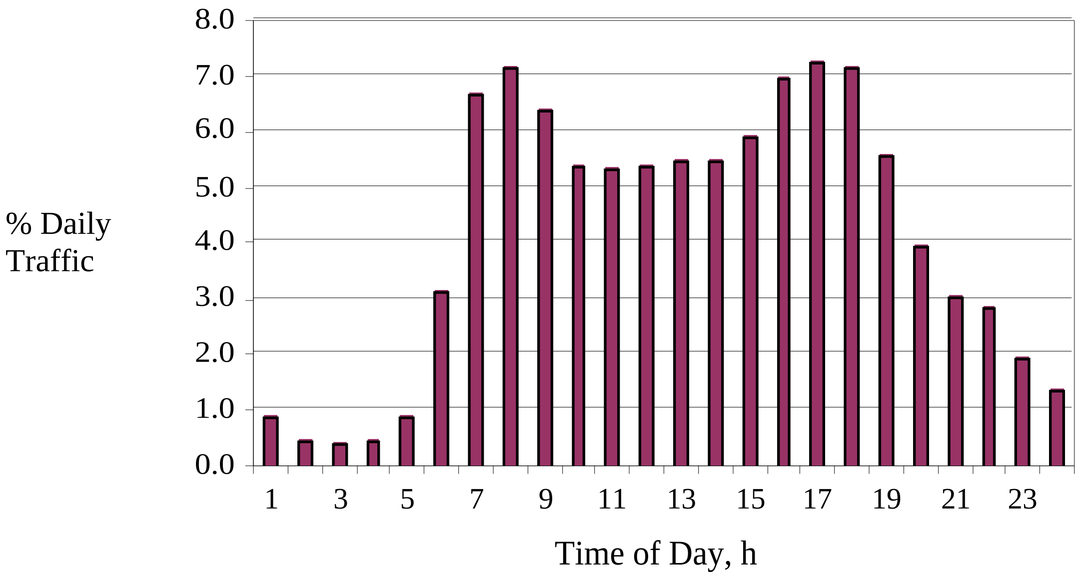

Figure 3.2. Hourly distribution of daily traffic in San Diego, CA during a summer weekday (July 21, 1999) (Green et al. 2000).

As an initial simplifying assumption, we assume that all registered vehicles are on the road each day. This is fairly accurate for today's EDV owners. If we accounted for vehicles that are garaged a significant number of days, availability of vehicles for V2G would be higher than we calculate below.

We calculate time-of-day availability of vehicles by three independent methods. Each method of calculation requires assumptions or extensions of existing data, so comparing the three results provides cross checks on our conclusions about availability.

Our first method is a simple calculation, not based on traffic data. This can be thought of as a "back-of-the-envelope" calculation. It is the simplest to understand and, even if not perfectly accurate, makes our two other more detailed calculations more understandable. Let’s assume that we have 100 EDVs that can be connected to the grid and that they are all commuting vehicles that will be on the road sometime from 3 to 6 pm. During these three hours there is a total of 300 vehicle-hours divided between time driving and time parked and potentially connected to the grid. Since an average vehicle is on the road approximately one hour during the day (Hu and Young 1999), we assume that during the 3 – 6 pm rush hour each vehicle will be on the road for 0.5 hour. The actual number of vehicle-hours used for driving is 0.5 hour * 100 vehicles, or 50 vehicle-hours. This leaves another 250 vehicle-hours available for grid connection during peak traffic period from 3 to 6 pm which is equal to 83% of the initial 300 vehicle-hours. By this simple calculation we estimate that on average 83% of vehicles are available at any one moment during the peak traffic period.

Availability is probably greater than this simple calculation indicates because not all EDVs are used solely for commuting. A survey of EV owners showed that there is an equal split of use of the EVs for commuting purposes and shopping or other errands during the week (California Air Resources Board 2000: 108). This would mean that during the commuting time from 3 to 6 pm the actual time on the road for an average vehicle is 0.25 hour (15 min). Using this data to modify the above simple calculation means that the number of vehicle-hours on the road is closer to 25 vehicle-hours of the 300. This would increase vehicle availability to 92%.

Our second method of computing availability uses the daily traffic data from Figure 3.2. The percent daily traffic at the peak interval is only 7.3% of the total daily traffic, while the total sum of percentage of daily traffic for the three-hour peak period is 21.5%. Since we know that the average time a personal vehicle is on the road during a weekday is roughly one hour, and we assume that the majority of vehicles on the road at this time (3 – 6 pm) are commuting from work, then we can estimate that these vehicles will be on the road half of the average daily driving time, or roughly 30 minutes.[7] Thus, of the 21.5% daily traffic between 3 – 6 pm, most vehicles will be on the road only 30 minutes, or 1/6 of the 3 hours. We can calculate the proportion of vehicles off the road, and presumably parked, at any one point as 78.5% + (5/6* 21.5%), or 96.4%. That is, if we assume that electric vehicles are plugged in before and after their commute time, no more than 3.6% of the vehicles are unavailable at any one moment, even at the peak traffic hour of the day.

Because 96.4% of vehicles parked during rush hours seems counter-intuitive to those who have personally experienced rush-hour traffic, we crosscheck by calculating a different way. Starting again from Figure 3.2, the maximum traffic during the peak electrical need hours is 7.3% of daily traffic total. One-hour data is the fundamental unit available, since raw traffic data are instantaneous counts aggregated over one-hour intervals. However, for V2G power, we want to know how many vehicles are available at any moment, not where a vehicle was in use previously during an aggregated hour. Since our analysis already discounts availability by state-of-charge (or fuel remaining), our basic availability calculation is not concerned if we are drawing from one vehicle 5 – 5:30 pm, and a different one 5:30 – 6:00 pm. Thus, since we assume the average commuter vehicle is on the road only one-half hour per commute trip, the average traffic-counted vehicle is only on the road for one-half of that hour. Again, assuming the vehicle is plugged in when not driving, this means that in reality there is maximum 3.7% (half of 7.3%) of vehicles driving and unavailable to provide power to the grid at any moment, even during the peak traffic hour. Shoulder traffic hours, with 7.0% or 7.2% of the daily traffic, would have lower percentages of unavailable vehicles. The important conceptual

[7] In fact, some would be non-commuter vehicles, which travel on average 3.7 trips/day, so the average time would be less than 30 minutes. If we added this complication, our calculated availability would be higher.

point is that, although 21.5% of the vehicles may be on the road between 3 – 6 pm, at no one instant will more than 3.7% of them be on the road. Thus we calculate by this method 96.3% availability through the peak traffic period, confirming the prior calculation from traffic data.

Our third method adds a further refinement to the above calculation and provides a simple sensitivity analysis. This calculation includes stops at intermediate locations between work and home, which may occur as a combination of the commute trip with other trips. We know that close to one-half of all person trips are for family or personal business such as shopping, running errands, and dropping off and picking up others (Hu and Young 1999). When these trips are combined with the simple commute trip, then there are intermediate destinations when the vehicle is briefly parked but presumably not connected to the grid (such as a bank or childcare center). Therefore, we need to add the total duration of the intermediate stops to the driving time to obtain the total time when the vehicle is unavailable for on-grid connection. Since we focused on the potentially worrisome commute from work to home (3 – 6 pm) which was estimated as an half-hour trip, and we estimate that on average the total time of the intermediate stops is 15 minutes, then the total afternoon time that the vehicle is unavailable for on-grid connection is 45 minutes. Analogous to the calculation shown earlier we calculate the percentage of vehicles unavailable for on-grid connection at the "peak hours" as 5.5% or conversely that 94.5% of vehicles are available to power the grid during the peak traffic period.

Our third calculation, that adds in a stop with no connection to grid to the return commute trip, also offers a simple sensitivity analysis. That is, even when we make "worst case" assumptions—that all vehicles stop an additional 15 minutes on the way home without plugging in, increasing unavailability of the fleet by 50%—the net effect is to change fleet availability from 96.3% to 94.5%. Practically speaking, further refinements of this analysis are unlikely to make a significant effect on calculated time-of-day availability.

The above analysis of added time for stops also provides a quantitative guide for the sensitivity of our conclusions to our assumptions. For example, we use a national average figure of one-hour driving time per day, while California could be somewhat longer. But the above sensitivity analysis of a stop on the way home shows that large percentage changes in driving time (30 to 45 minutes) have very little effect on percent availability figures. Similarly we need not perform a separate analysis for different times of electricity peak loads for different regions, since we have already calculated availability for the worst driving hour. Thus, we shall assume that the electric power is needed during the afternoon vehicle peak, the worst hour for vehicle availability, knowing that any shift in the exact time of the peak electrical need will increase availability by only a few percent and can be disregarded.

In summary, the three methods above produce similar results; 92%, 96.3%, and 94.5%. We estimate that between 92% and 95% of vehicles are available for V2G power, even during the afternoon rush hour.

The overlap of electric load peaks and afternoon vehicle use peak raised concern about unavailability of vehicles when V2G power was most needed. The above analysis shows that although electricity load and road traffic have similar hourly profiles, almost all generators are on at peak electric hours of the year, whereas only a small proportion of all vehicles are on the road at peak traffic hours. This finding reaffirms our starting perspective—utility generation equipment is utilized to capacity, whereas the vehicle fleet is a large investment in equipment that is currently underutilized. Given the assumptions outlined above, the proportion of vehicles unavailable for on-grid connection because they are on the road or parked at intermediate stops should never exceed 5.5%. Given our example analysis of sensitivity—a 50% increase in time–on–road changed V2G availability from 96.3% to 94.5%—we judge that further refinements to those figures would have little practical significance.

C. Saturation of market for V2G power

We next estimate the point at which the projected EDV vehicle fleet will saturate the markets for V2G power. This section makes simple calculations of market size by assuming that electric markets continue to buy current amounts at current prices. In fact, V2G will lower the price and increase the quality of some forms of ancillary services. Economic principles would predict that in comparison to today's market, the amount paid per unit power will drop gradually and the amount purchased by grid operators will increase. Nevertheless, our simple analysis based on current market prices and volumes provides a minimum estimate of market size.

As mentioned in Section I, we analyze three markets for V2G power: peak power, spinning reserves, and regulation services. As subsequent analysis will show, the economic value of V2G power is highest for regulation up/down, with spinning reserves and peak power offering less annual revenue. We consider first the size of the highest-value market, regulation services.

CAISO currently contracts for regulation on a daily and hourly basis. Based on CAISO hourly data, the contracted amount fluctuates between roughly 800 MW and 1,600 MW of regulation up plus regulation down. CAISO guidelines suggest buying regulation at 5 – 10% of day-ahead scheduled load, which would imply higher numbers—as high as 4,000 MW (CAISO 2001). For estimation of market size, we use the figure of 1,000 MW of fairly steady contracts for regulation, with fluctuations up to 1,600 MW.

For simplicity we assume each vehicle is available 22 of 24 hours; one hour on the road plus one hour parked away from a plug. This assumption is also consistent with the 92 – 95% availability calculated in part B. Thus, a vehicle with 10kW power must be discounted by 22/24, to 9.17 kW. For a 1,000 MW regulation market, this is 1,000 MW/9.17 kW = 109,000 vehicles, and for the high level of 1,600 MW, it would be a maximum of 174,000 vehicles selling regulation at times of highest demand. If we assume that no more than half of battery EDV owners will have the plug availability and the desire to sell regulation from their vehicles, then roughly 300,000 battery EDVs would be sold in California before saturating the CAISO regulation up/down market. As subsequent analysis will show, battery EDVs or large-battery plug-in hybrids are best suited for regulation. Under current projections the total number of battery vehicles (city cars) by year 2008 is 159,000 (See Table III.1).

The spinning reserves market is similar in size but fluctuates more. CAISO hourly data show spinning reserves frequently contracted at levels between 600 and 800 MW, but occasionally above 2,500 MW. We estimate market size by using 700 MW as a fairly steady base and 2,500 MW as a high. Again we assume 10 kW per vehicle discounted by 22/24. These numbers suggest a spinning reserves market met by 76,000 vehicles steadily, with 273,000 vehicles meeting high levels of demand for spinning reserves. Subsequent analysis will show that the greatest net revenue from spinning reserves is realized by the fueled vehicles, but all vehicle types are profitable, under most assumptions about spinning reserves.

Peak power market size is much harder to estimate because it depends on the price. The lower the price of V2G power, the more of the market it can capture from traditional generation. As a maximum figure, which would apply to the fueled vehicles and only at fuel prices much lower than those we assume, we might imagine V2G meeting up to 1/5 of the California peak load of 54 GW. Assuming fuel cell vehicles in this market at 14.7 kW (16 kW each discounted by 22/24), this would be a maximum market for peak power of 734,000 vehicles.

Thus, depending on which power market is considered, the V2G power market could range from 109,000 vehicles (for only the steady, high-value regulation market) to a maximum estimate of over a million vehicles (174,000 regulation + 273,000 spinning reserves + 734,000 for 1/5 of peak power). This range spans from under 0.5% to 5% of the California light vehicle fleet. As we show in Section III, there may be additional markets for V2G in customer-side of the meter strategies. Nevertheless, there would not be a market for V2G power for every vehicle in a 100% EDV fleet. Our perspective on these market sizes considers both the vehicle side and the electric system perspective. On the vehicle side, V2G power is important for the light vehicle market because it provides substantial incentives to introduction of EDVs, essentially buying down EDV prices for a decade or two, until larger volumes bring down vehicle prices. It is important to the electric system in the longer term because it will provide lasting benefits in reliability, grid stability, and lower cost of ancillary services. Even when markets for existing and new V2G ancillary services are saturated, continuing expansion of a V2G-capable fleet will expand opportunities for wider use of intermittent power sources such as renewable energy.

IV. Analysis of Vehicles

This section develops equations to calculate the electrical power output capacity of EDVs and the cost of providing that power. We develop general formulas for power capacity and cost from any EDV, then refine those general formulas to apply to each of the three types of EDVs—battery, fuel cell, and hybrid. We also calculate the annualized capital costs of additional equipment needed to allow V2G power. The first part of this section develops the conceptual model, general equations and methods of calculation.

A. Conceptual basis of calculations

A.1 Electrical power capacity from EDVs

First we define the electrical power capacity of EDVs, that is, the kilowatts of EDV power available for V2G, to the grid or to an outside electricity user. This quantity is a function of the energy stored onboard, the amount of time the power will be needed, and the driver's requirement for range. Vehicle power capacity is calculated using equation (4.1)

$$PC = \frac{\left(ES - (DD + RB) \times Eff_{veh}\right) \times Eff_{inv}}{DH} \tag{4.1}$$

where PC is power capacity in kW, ES is energy stored on-board in kWh, DD is the distance driven in miles since the energy storage was full, RB is range buffer required by the driver in miles, Eff_{veh} is energy efficiency of EDV in kWh/mi, Eff_{inv} is efficiency of the inverter and other power electronics (dimensionless), and DH is discharge hours in h.

The efficiency and energy components in equation (4.1) are defined by the specifications of each EDV. For example, the *ES* for a battery EDV is the energy storage of the battery, whereas for a fuel cell EDV it would be the electricity which could be produced from a full fuel tank (*e.g.*, mass of compressed H_2 converted to kWh at the efficiency of the fuel cell). The value of *DD* begins with the average daily vehicle miles traveled per driver of 32 miles (Hu and Young 1999)[8]. We assume for these calculations that, on average, half the average daily vehicle miles will have been depleted when the vehicle is parked and power is requested. This value will be highly variable depending on the driving characteristics, the vehicle type (*e.g.*, battery EDVs may be recharged at work), and the driver's strategies for being prepared to sell power. Even so we believe that 1/2 daily average is a reasonable approximation as a V2G fleet average. The *RB* is determined by the vehicle owner's driving requirements and refers to the minimal range required by the driver, for the return commute, or for an unanticipated trip to a convenience store or hospital. Based on interviews with California drivers, Kurani et al (1994) found that 20 miles was sufficient for most drivers; we use this value for RB, and sometimes vary it among 10, 20, 30 and 40 for sensitivity analysis.

[8] This value is the average for the entire week, weekday and weekend combined.

The number of discharge hours (*DH*) will depend on the needs of the party receiving the electricity, *e.g.*, if the power is going to the grid, what duration does the buyer require from providers of peak power or from spinning reserves? For peak power, reasonable values for *DH* are 1, 2, or 4 hours. For spinning reserves, power is rarely requested for more than 1/2 hour, but current contracts in California require the ability to provide spinning reserves for 2 hours. For regulation, 15 minutes would be sufficient.

PC, the power capacity calculated from Equation 4.1 is based on on-board stored energy and time. Two additional limits to power output are considered after this number is calculated—the rated power of the internal vehicle power systems and the connection from the vehicle to the grid. These are restricted by physical limits such as wire size, heat dissipation rates of power electronics, circuit breakers, etc. As discussed in Section II.A, today's charging stations are limited to 6.6 kW, Level 3AC can be assumed to be between 16 and 19 kW, and connections on commercial sites could potentially handle as much as 40kW output from a fuel cell. Table IV.1 (following) will list as a vehicle characteristic the "maximum power to motor," which is the limit on power flow from the on-board power electronics to the vehicle electric motor, with values ranging from 27 to 150 kW. That is, the actual amount of power flow from vehicle to grid is the minimum of three values: PC per equation (4.1), connection from vehicle to grid, and maximum power to motor. In all but one vehicle we analyzed, *PC* or the connection to grid is the limiting factor and not the vehicle's maximum power to motor. Typically, for peak power and spinning reserves, *PC* is the limiting factor. Conversely, in the case of regulation (an auxiliary service), *DH* is very small so *PC* imposes few limits and regulation is limited by capacity of the connection lines. When the results are sensitive to these assumptions, we will discuss which is used as a limit to vehicle power.

<u>A.2 Cost of providing power to the grid from an EDV</u>

Equation (4.2) is used to calculate the per kWh cost to the EDV owner for providing power to the grid.

$$C_E = C_{PE} + C_D \tag{4.2}$$

C_E is the energy cost to owner which includes cost of purchased energy and cost of equipment degradation (*e.g.*, battery degradation) in \$/kWh. C_{PE} is cost of purchased energy to the owner in \$/kWh delivered. C_{PE} is based on the cost of electricity for recharging, or cost of hydrogen, natural gas, or gasoline, depending on the EDV type and it also may include conversion losses. C_D is the cost of equipment degradation due to the extra use for electricity generation, also in \$/kWh delivered. As we see below, when battery vehicles are discharged frequently, this cost often dominates the total cost, C_E, as extra cycling shortens most battery lifetimes.

The other cost component of delivering V2G power is C_{AC}, or the annualized capital cost for any additional equipment. One way to annualize this single capital cost is to multiply the cost by the capital recovery factor (CRF) as in equation (4.3)

$$C_{AC} = C_C \times CRF = C_C \times \frac{d}{1-(1+d)^{-n}} \tag{4.3}$$

where C_C is the capital cost (the one-time investment) in $, d is the discount rate, and n is the time during which the investment is amortized in years.

B. Battery EDVs

We analyze three battery-powered EDVs, with differing battery types: 1) a lead-acid prototype vehicles based on a design by AC Propulsion, 2) the Honda EV Plus, with nickel metal hydride batteries, and 3) the Th!nk City car, with nickel cadmium batteries. The first two vehicles are four-passenger sedans, while the Th!nk City is a smaller, two-passenger, shorter-range EV ("city type") produced for the European market and now owned by Ford. Table IV.1 lists the technical characteristics of the three batteries EDVs.

Table IV.1 Technical characteristics of the three battery EDVs.

Vehicle characteristics	Lead-acid prototype[a]	Honda EV Plus	Th!nk City
Battery type	Pb-acid, 66Ah, 30 modules 12V	NiMh, 95Ah, 24 modules 12 V	NiCd, 100Ah 19 modules 6 V
Energy stored (kWh)	23.8	27.4	11.5
Max Depth of Discharge (%)	90	90	90
Max power to motor (kW)	150	49	27
Eff_{veh} (Wh/mile)	200–250[b]	280–350[b]	217
Efficiency (%) (grid-battery-grid)	74 (93*85*93)	72 (93*83*93)	~80
Max range (miles)	80-100	80-100	53
Battery cycle life (cycles)[c]	1000	1000	1500
Battery calendar life (years)	3-4	5-6	5
Battery cost OEM[d] ($/kWh)	125	300-450	300 (600[e])
Replacement labor, h	10	10	8

[a]- based on prototype vehicles by AC Propulsion, Inc. b- In our calculations we use a median value, that is Effveh=225 Wh/mi for AC Propulsion vehicle and Effveh=315 Wh/mi for Honda EV Plus; c- at 80% depth of discharge; d-Original Equipment Manufacturer (Kalhammer 1995); e- retail cost that individual customers pay for replacing the battery pack (Schon 2001)

The lead-acid prototype and Honda EV Plus vehicles listed here fit CARB's definition of a full-function EV; they differ primarily in the type of battery. The lead-acid prototype is based on several vehicles assembled by AC Propulsion and assumes the Panasonic EV1260 batteries (these are 12V modules rated at 66 Ah, the number we use here, although 55 Ah may be more realistic for high-current applications). The Honda EV Plus has a NiMh battery and has somewhat greater energy capacity (27.4 vs. 23.7 kWh) and longer calendar life but also higher battery costs. The lead-acid prototype vehicle uses lead-acid batteries, which are much cheaper. The Th!nk City fits CARB's definition of a city EV and has under half the energy capacity (11.5 kWh) of the other two battery-powered EDVs. This vehicle is currently sold in Europe and will be introduced in the near future to the U.S. market although with some modifications. The Th!nk City uses NiCd batteries which have the highest number of lifecycles of the three batteries compared here.

B.1 Electrical power capacity: Battery EDVs

For the battery-powered vehicles, equation (4.1) is adapted slightly to include recommended depth of discharge (*DOD*) of the battery. This figure is the manufacturer's recommended limit on discharge, beyond which there are significant risks in reducing the battery life. Thus, for battery EDVs the term *ES* in equation (4.1) will be replaced by *ES**DOD* where *ES* is the energy capacity in kWh and *DOD* is set at 0.8 (80%). We use an average inverter efficiency (Eff_{inv}) of 0.93 for all three vehicles. Using equation (4.1), when we calculate *PC* for the lead-acid prototype vehicle and Honda EV Plus, we vary *RB* from 20 miles to 40 miles, and use *DD* of half the daily driving average of 32 miles, as stated earlier. For the Th!nk City we felt that these values were unreasonably high. The Th!nk is a smaller vehicle with a much smaller range (53 vs. 100 miles) and we anticipate that buyers of Th!nk will have shorter daily distance traveled, and lower required range buffer—otherwise they presumably would have purchased a fueled vehicle or a full-function battery EDV. Thus, for the Th!ink, we examine *RB* values of 10 to 30 miles and *DD* of 10 miles. The resulting power capacities for all three battery EDVs are listed in Table IV.2.

Table IV.2 Calculated electrical power capacity (*PC*) for battery EDVs, over a plausible range of discharge hours and range buffer values.

Discharge Hours (h)	Range Buffer (mi)	Power Capacity (PC) in kW_e		
		Lead-acid	Honda EV Plus	Th!nk City
1	10	-	-	4.5
1	20	10.2	9.8	2.5
1	30	8.1	6.9	0.5
1	40	6.0	4.0	-
2	10	-	-	2.3
2	20	4.0	4.9	1.3
2	30	3.0	3.4	0.2
2	40	2.5	2.0	-
4	10	-	-	1.1
4	20	2.5	2.5	0.6
4	30	2.0	1.7	0.1
4	40	1.5	1.0	-

In general, *PC* decreases with longer discharge times and greater required range buffers. The *PC* values in Table IV.2 illustrate a plausible range to use for peak power or spinning reserves. For regulation, *DH* is much lower and thus *PC* would be higher than the values in Table IV.2. The power capacity of the lead-acid prototype vehicle and the Honda EV Plus are nearly identical while that of the Th!nk City is considerably smaller.

B.2 Cost of providing power to the grid: Battery EDVs

A key parameter that determines the economic viability of V2G is the cost to the vehicle owner of delivering power to the grid. The cost of delivering power includes both the variable costs, stated in \$/kWh delivered (C_E from equation 4.2), and the annual fixed costs (C_{AC} from equation 4.3). Fixed costs reflect the cost of additional equipment needed to provide the functionality of V2G power. C_D from equation (4.2) are costs of equipment degradation due to the additional operating hours or cycling for V2G, expressed in \$/kWh delivered. For battery EDVs the cost of battery degradation dominates the result, as extra discharging shortens battery lifetime under most circumstances.

Fixed costs can be incurred on the vehicle's power electronics and connectors, and off-board due to charging station or wiring upgrades. Battery EDVs already must have electrical connections for charging that can be used also for discharging to the grid, but for other EDV types this is an incremental fixed cost. AC Propulsion's controller design allows discharging to the grid with no incremental cost and only small programming charge. Another fixed cost is that we assume the necessity of on-board metering of electrical flow for purposes of billing. We assume use of a chip available from Analog Devices, Inc with original equipment manufacturer (OEM) cost of \$3.00 (Collins and Koon, 2000). With additional parts we estimate that the total incremental costs for an on-board electric metering system is \$50. Thus, for the battery EDVs, the annualized fixed cost, C_{AC}, according to equation (4.3), is \$8.13 per year assuming a discount rate of 10% over a period of 10 years.

Cost of purchased energy (C_{PE}) and cost of equipment degradation (C_D), which comprise C_E defined by equation (4.2), are each in turn described for battery EDVs by equations (4.4) and (4.5).

$$C_{PE} = \frac{C_{el}}{Eff} \tag{4.4}$$

$$C_D = \frac{(ES \times C_B) + (C_L \times LH)}{ES_L} = \frac{(ES \times C_B) + (C_L \times LH)}{ES \times DOD \times B_C} \tag{4.5}$$

where C_{el} is cost of electricity for recharging in \$/kWh, and Eff is the two-way electrical efficiency (grid-battery-grid). ES_L is the total energy stored in the battery during its life cycle in kWh, C_B is cost of battery replacement in \$/kWh, C_L is cost of labor in \$/h, LH are labor time for battery replacement in hours, and B_C is battery life in cycles. We assume here that battery replacement is determined by its cycle life, not the calendar life of the battery. (For some batteries and driving cycles, calendar life would be reached first, in which case C_D should be zero rather than the values we calculate here.)

In these calculations, we use a cost of recharge electricity, C_{el} in equation (4.4), of \$0.045/kWh. This is the EV charging rate offered by Pacific Gas & Electric Company (Pacific Gas & Electric Company, 2000); several other California utilities offer similarly low night EV recharging rates. These rates reflect the lower cost of providing off-peak power (although rates may rise, presumably the peak rate would rise more than this off-peak rate, improving the final result of our economic calculations).

Table IV.3 compares the battery vehicles in cost to provide power, showing the major components of the per-kWh costs. Of the two per-kWh cost components, which make up C_E, the table shows the main two — cost of battery degradation C_D and cost of recharge electricity C_{el}. As Table IV.3 shows, battery degradation is the more important. As we shall see shortly, the costs in Table IV.3 apply to using battery EDVs to provide peak power or spinning reserves; cost calculations to provide regulation must be modified.

Table IV.3 Costs of power from battery EDVs for peak power or spinning reserves, showing major components of cost [9].

Costs	Lead-acid prototype	Honda EV Plus	Th!nk City
Total cost to owner per kWh, C_E ($/kWh)	0.229	0.446	0.322
Cost of battery degradation, C_D ($/kWh)	0.172	0.388[a]	0.267[a]
Cost of recharge electricity, C_{el} ($/kWh)	0.045	0.045	0.045
Annualized fixed costs, C_{AC} ($/year)	8.13	8.13	8.13

[a] based on battery capital cost of $300/kWh

For the lead-acid prototype vehicle, the cost of providing a kWh of energy to the grid is $0.229/kWh, for the Honda EV Plus $0.446/kWh and for the Th!nk City it is $0.322/kWh. While the cost of delivering power from battery EDVs may initially seem high, if compared to baseload power price around $0.10/kWh, in the electricity markets discussed in Section I, the value of a kWh often exceeds the cost of V2G power. These markets are analyzed in detail in the following sections where the costs of V2G, derived from these equations, are compared with potential revenue from selling this power.

Regulation, an ancillary service, requires two modifications to the general cost equations. The battery EDVs can participate in "regulation down" (decrease in power output or charging of battery) and "regulation up" (provide power to the grid). In both cases, revenue is generated to the owner for providing this service to the electricity market. The vehicle owner does not pay for the charging power in regulation down, leaving the owner to bear only the costs of energy losses that occur in the transaction. Thus, equation (4.4), used to calculate the cost of purchased energy C_{PE}, is modified to equation (4.6)

$$C_{PE} = \frac{1 - Eff}{Eff} \times C_{el} \qquad (4.6)$$

[9] Cost of purchased energy (C_{PE}) was calculated in Table IV.3 using only the electrical efficiency battery-grid (e.g. 0.79) instead of grid-battery-grid (e.g. 0.74). Being that C_{PE} is a much smaller number than C_D,

where *1-Eff* represents the energy losses from grid to battery.

The other term that contributes to cost of energy (see equation 4.2) is the cost of battery degradation (C_D) which will also be different when a battery-powered EDV is providing regulation. It is expected that costs due to battery degradation will be lower when the battery is used for regulation due to much lower depth of discharge (*DOD*) and in turn greater number of cycles in the cycle life of the battery. However, the exact relationship between *DOD* and number of cycles is not clear and more study is needed. For regulation, we assume that C_D is half of the usual degradation costs. Table IV.4 lists the battery degradation costs and total energy costs when the battery-powered EDVs provide regulation of power for the ancillary services market. Cost of recharge electricity and fixed costs are the same as in the prior Table IV.3.

Table IV.4 Costs of providing power from battery EDVs, for regulation.

Costs	Lead-acid prototype	Honda EV Plus	Th!nk City
Total cost to owner per kWh, C_E ($/kWh)	0.099[b]	0.207[b]	0.145
Cost of battery degradation, C_D ($/kWh)	0.086	0.194[a]	0.134

[a] based on battery cost $300/kWh; [b] Eff from Table IV.1 refer to one way Eff from grid to battery.

Comparing costs in Table IV.3 and IV.4 we note that the total energy costs for regulation are much lower than total energy costs for providing power to the grid. This fact may prove to be crucial in determining the best opportunities for use of battery-powered EDVs in the current electricity markets.

C. Fuel cell EDVs

C.1 Generating directly from fuel cell with on-board compressed H_2

For analysis of fuel cell vehicles, we use a single built vehicle, the Ford's P2000 Prodigy. The Ford Prodigy P2000 is a fuel cell powered sedan, running on hydrogen. In this case we use the fuel cell (FC) for electricity. Water and heat are byproducts from the fuel cell and measures would have to be taken to ensure removal of these byproducts. The technical characteristics of this vehicle are given in Table IV.5.

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this does not affect significantly the resulting cost of energy (C_E). To be precise, this would affect the final values of C_E only by 2%.

Table IV.5 Technical characteristics of a fuel cell vehicle.

Vehicle Characteristics	Ford Prodigy P2000
Battery (V)	12
Hydrogen storage (kg)	2 (4)[a]
Max continuous power (kW)	30-40[b]
Efficiency - FC system (%)	40-48
Efficiency electrical (kWh/kg H_2)	13.5-16[c]
Inverter efficiency (%)	95
Efficiency vehicle (kWh/mile)	0.350
Maximum vehicle range (miles)	100

[a] Present models have 2 kg H_2 storage but 4 kg is currently under development; [b] larger capacity fuel cells can be installed but thermal management would probably limit output to about 40kW, or to 30kW on hot days; [c] based on 33.3 kWh/kg H_2 lower heating value (LHV).

C.1.1 Electrical power capacity

The electrical power capacity of a fuel cell vehicle is calculated for energy stored, defined by equation (4.7)

$$ES = Eff_{elec} \times C_{H_2} \tag{4.7}$$

where Eff_{elec} is the electrical efficiency in kWh/kg H_2 and C_{H2} is the capacity of hydrogen in kg. For H_2 capacity we use 4 kg which is not currently available but is expected in the near term forecast. We illustrate a reasonable range of power capacity of the FC vehicle in Table IV.6. Electric power capacity, PC, in calculated from equation (4.1), as given previously, based on a range of inputs of reserve buffer from 20-40 miles and discharge hours 1-4.

Table IV.6 Power capacity of FC vehicle depending on reserve miles and discharge hours.

Discharge Hours (h)	Range Buffer, (mi)	Power Capacity, (kW_e)
1	20	44.1
1	30	40.8
1	40	37.4
2	20	22.0
2	30	20.4
2	40	18.7
4	20	11.0
4	30	10.2
4	40	9.4

To simplify subsequent calculations, we use the power capacity of 22.04 kW defined by 2 discharge hours and range buffer of 20 miles.

C.1.2 Cost of providing power to the grid: Fuel cell on-board H_2.

The main factor contributing to the cost of a FC vehicle owner for providing power to the grid are the cost of hydrogen fuel and the incremental capital cost for an interface needed to enable V2G (see equation 4.2). We ignore degradation costs for the FC vehicle in the present calculations since the lifetime of the FC is expected to be typically longer than the life of the automobile chassis.

The cost of H_2 fuel is predicted from literature values for a number of different H_2 refueling stations. Estimates of H_2 production costs at a refueling station depend on the method of production and capacity of the production system. One estimate gives a range from \$12 – 40 per GJ (gigajoule) depending on the specific method of production (Ogden et al. 1999). This translates to \$ 1.7 – 5.6 per kg H_2. The least expensive method of production suggested is decentralized, local steam methane reforming from pipeline natural gas. Another study also recommends local steam methane reforming as the least expensive with the cost ranging from \$1.3 – 3.1 per kg H_2 where the lower cost is for 1000 stations each serving 1000 FC vehicles and the higher is for 100 stations each serving 50 FC vehicles (Thomas et al. 2000). The price of natural gas included in these cost estimates was \$3.79/GJ. Alternatively, H_2 can be produced using local electrolyzers at an estimated cost between \$3.0 – 4.2 per kg (Ogden et al. 1999) or 2.6 – 3.8 per kg H_2 (Thomas et al. 2000). The cost estimates by Thomas et al. (2000) were derived using electricity cost of \$0.03/kWh.

Based on these current literature studies, we use in our calculations a range from \$1.3–5.6 per kg H_2. Cost of electricity generated by the FC vehicle can be calculated using equation (4.2), which for the case of the FC becomes equation (4.8)

$$C_E = \frac{C_{PE}}{Eff_{elec}} \quad (4.8)$$

where C_{PE} is cost per kg of H_2 in $/kg and Eff_{elec} is the electrical efficiency of the FC in kWh/kg H_2 (median value is 14.75 kWh/kg H_2). With cost of H_2 at $1.3/kg, electricity generated by the vehicle would be $0.088/kWh and with cost of H_2 at $5.6/kg, electricity would be $0.380/kWh. This compares favorably to the price of power generated by the two battery-driven vehicles ($0.229 and $0.388/kWh) where the price was primarily dominated by the cost of battery degradation. In the case of the FC vehicle the price of output power is primarily defined by the cost of H_2 fuel under our current assumption that the FC degradation is not significant.

In determining the cost to the owner of providing power to the grid we have to include incremental capital costs of additional equipment necessary to permit V2G. This includes an on-board electric metering device (Analog Device, Inc.) and associated equipment with a total estimated cost of $50, a bi-directional charger with an estimated cost of $500 on the vehicle itself, a 20kW conductive charging station at the parking site or home with an estimated cost of $2000, plus $1000 for labor costs. Summing these figures, which are based on AC Propulsion's experience, the total capital cost for one FC vehicle is $3,550. This amount is annualized according to equation (4.3) using discount rate (*d*) of 10% for a period of 10 years (*n*). The annualized cost C_{AC} is equal to $578.

The cost to the vehicle owner for providing power to the grid is determined using equation (4.8) and the results are listed in Table IV.7.

Table IV.7 Per kWh cost and annual capital cost to vehicle owner for providing power to the grid from a Ford Prodigy P2000 with on-board H_2 at two different H_2 costs.

Costs	Cost of H_2 C_{H2} ($/kg) 1.3	5.6
C_E ($/kWh)	0.088	0.380
C_{AC} ($/year)	578	578

The cost of delivering power to the grid from FC vehicle with on-board H_2 is largely determined by the cost of H_2. The annual capital costs to vehicle owner for providing power to the grid at $578 is higher than that for providing power from battery EDVs. This is due largely to the fact that battery EDVs have much of the electronics on-board and take advantage of the charging infrastructure to deliver the power back to the grid when needed.

<u>C.2 Generating from fuel cell vehicle connected to a stationary reformer</u>

Instead of using on-board stored H_2, the FC vehicle could connect to a stationary small reformer that would supply a continuous flow of H_2. The reformer could be available at a parking lot (at work or at a public site) and could feed multiple vehicles at the same time. A small stationary natural gas reformer with a capacity of 48 kg of H_2 per day has a capital cost of $11,832 (Thomas et al. 1998). Alternatively, reformers could be connected to deliver independently H_2 to each vehicle. We estimate that a price of small reformers would be on the order of $2,000. The capital cost per vehicle is similar if we connect small reformers to each vehicle or use one larger reformer to feed 10 vehicles.

C.2.1 Electrical power capacity

The electrical power capacity is calculated from equation (4.1) with a modification that the range buffer (*RB*) and distance driven (*DD*) terms can be ignored since the H_2 fuel is not coming from on-board storage system. The available energy stored depends on the number of vehicles connected to the unit and is described by equation (4.9)

$$ES = Eff_{elec} \times \frac{M_{H_2}}{NV} \tag{4.9}$$

where Eff_{elec} is the electrical efficiency in kWh/kg H_2, M_{H2} is the mass of hydrogen in kg, and *NV* is the number of vehicles simultaneously connected. If we assume 10 vehicles, the electrical power capacity varies with discharge hours as shown in Table IV.8.

Table IV.8 Power capacity of a FC vehicle connected to a stationary natural gas reformer (assuming 10 vehicles simultaneously connected).

Discharge Hours (h)	Power Capacity, (kW_e)
1	67.3 (40) [a]
2	33.6
4	12.4

[a] Max rated continuous power output is 40 kW

C.2.2 Cost of providing power to the grid: Fuel cell with stationary natural gas reformer.

The main costs contributing to the cost to owner for providing V2G are the incremental capital cost of the reformer unit, cost of the interface for delivering power to the grid, and cost of H_2. In this case the cost of H_2 depends only on the cost of natural gas. Unless someone else incurs the reformer costs (*e.g.*, fueling company), the cost should be divided between the number of vehicles being served. The reformer capital cost per vehicle (assuming 10 vehicles would share the reformer) is equal to $1,183 and the interface equipment and labor costs, described in the previous section equal to $3,550. The total capital cost ($4,733) annualized using equation (4.3) at a 10% discount rate for a period of 10 years and is equal to $803 per vehicle per year.

The cost of H_2 is calculated assuming 70% efficiency of the reformer (Probstein and Hicks 1990), cost of natural gas at $8 per GJ and using the HHV (higher heating value) of natural gas (59,983 kJ/kg). The reformer will deliver 1.4 kmol of H_2 for each kmol of natural gas (2 kmol * 0.70). The cost of H_2 is $2.74/kg. Using equation (4.8) based on the cost of H_2 (which is also C_{PE}) we calculate the cost of generated electricity C_E to be $0.186/kWh.

The per kWh cost to vehicle owner for providing power to the grid is determined using equation (4.2) and presented in Table IV.9, along with C_{AC}, the annual capital costs of providing the infrastructure to allow V2G from the garaged fuel cell EDV.

Table IV.9 Energy cost and annual capital cost for providing power to the grid from a fuel cell vehicle with stationary reformer.

Costs	Ford Prodigy P2000 with stationary reformer
C_{H2} (\$/kg)	2.74
C_E (\$/kWh)	0.186
C_{AC} (\$/year)	803

Comparison of values from Table IV.9 and Table IV.7 for a FC vehicle with on-board H_2 and stationary reformer, we can evaluate the different H_2 delivery systems. The annual capital cost to establish the infrastructure for V2G is higher for the stationary reformer scenario. The cost of H_2 will in both cases depend largely on the cost of natural gas.

D. Hybrid EDVs

Hybrid vehicles combine the internal combustion engine with a battery and electric motor to power the vehicle. We analyze two hybrid vehicles that are currently available on the market; Toyota Prius and Honda Insight. Honda Insight is a parallel configuration hybrid, which means that the engine and the electric motor supply power simultaneously to the wheels while the Toyota Prius is a combination series/parallel. The technical characteristics of two hybrid vehicles are included in Table IV.10.

Table IV.10 Technical characteristics of hybrid vehicles.

Vehicle Characteristics	Toyota Prius	Honda Insight
Battery type	NiMh, 6.5 Ah 38 modules, 6 cells, 1.2V	NiMh, 6.5 Ah, 20 modules, 6 cells, 1.2 V
Battery Energy stored (kWh)	1.8	0.9
Battery cycle life (cycles)	1000	1000
Battery calendar life (years)	5-6	5-6
Maximum electrical power output to motor (kW)	30	10
Battery cost[c] ($/kWh)	843–1123	843–1123
Replacement labor (h)	2	2
Gasoline tank (gallon)	12	10
Efficiency – electrical (kWh/gal)	8.8	n.a.
Max range (miles)	600	650
Efficiency of vehicle (mi/gal)	50	65

For the hybrid vehicle we analyze three separate cases: 1) hybrid generating from stock battery, 2) hybrid generating from enlarged battery, and 3) hybrid generating from motor-generator a) fueled with gasoline and b) fueled with natural gas.

D.1 Hybrid with stock battery

In this case we assume that all the available power is provided from the small battery packs available on the vehicle.

D.1.1 Electrical power capacity

This is calculated using equation (4.1) where the range buffer (*RB*) and distance driven (*DD*) terms are ignored and the energy stored (*ES*) is multiplied by 0.80 to take into account permissible depth of discharge of the battery pack.

Table IV.11 Electrical power capacity at different discharge hours from hybrid vehicles with stock batteries.

Discharge Hours (h)	Power Capacity, kW_e	
	Toyota Prius	Honda Insight
1	1.4	0.7
2	0.7	0.4
4	0.3	0.2

As expected, the electrical power capacity from the small batteries available on the hybrid vehicles is not significant. The range of values is from 1.4 kW to 0.2 kW and is too small to be considered as a significant source of power. The stock batteries in the current hybrid vehicles cannot be employed for V2G power.

D.2 Hybrid with enlarged battery

In this second scenario we propose a hybrid vehicle with an enlarged battery, which would satisfy the current California ARB recommendations of 20 miles battery-only range. Assuming 0.3 kWh/mile the size of the battery would be 6.0 kWh. This "enlarged" battery would still be smaller than many of the designs for plug-in hybrids, which we do not analyze.

D.2.1 Electrical power capacity

The electrical capacity for a hybrid with enlarged battery is listed in Table IV.12. In calculating the power capacity the range buffer and distance driven terms can be ignored.

Table IV.12 Electrical power capacity at different discharge hours from a hybrid vehicle with an enlarged battery

Discharge Hours (h)	Power Capacity, kW_e
1	4.6
2	2.8
4	1.1

D.2.2 Cost of providing power to the grid: Hybrid vehicle with enlarged battery.

Table IV.13 lists the costs of V2G power from a hybrid vehicle with enlarged battery. We also include the annualized capital cost for interconnecting equipment described earlier for the fuel cell vehicle (see Section C.1.2).

Table IV.13 Per kWh cost and annual capital cost to vehicle owner for providing power to the grid from hybrid vehicles with enlarged battery.

Costs	Toyota Prius or Honda Insight with enlarged battery (6 kWh)
C_E (\$/kWh)	1.34
C_D(\$/kWh)	1.29
C_{AC} (\$/year)	578

The electric energy cost of \$1.34/kWh is still relatively high even with an enlarged battery hybrid and would not likely be competitive in the various markets for distributed power analyzed in the proceeding sections. A plug-in hybrid with a larger and less expensive battery is not analyzed here, but would presumably perform V2G more like the city car we analyze.

D.3 Hybrid generating from motor-generator

D.3.1 Fueled with gasoline

This case assumes that power is generated from the motor-generator. This will involve certain problems regarding hot exhaust gases from a non-idle power setting as well as concerns regarding pollution at the source. It should be noted that the newest SULEV vehicles have very low emissions. The Prius NOx emissions are on the order of 0.02 g/kWh, which is nearly as good as the best combined-cycle power plants and approximately 10 times less than a small gas turbine (*e.g.*, Capstone). Nonetheless we consider it useful to evaluate this possibility especially if the presence of hybrids is expected to increase.

D.3.1.1 Electrical power capacity: Hybrid generating from motor-generator fueled with gasoline

In calculating the power capacity equation (4.1) is modified and can be described by equation (4.10).

$$PC = \frac{\left[ES - \dfrac{DD + RB}{Eff_{eng}} \right] \times Eff_{elec}}{DH} \tag{4.10}$$

where ES is the volume of the fuel in gallons, Eff_{veh} is the overall efficiency in miles/gallon, and Eff_{elec} is the electrical efficiency of the motor-generator in kWh/gallon.

The calculations indicate relatively high values ranging from 20–95 kW depending on the range buffer and discharge hours. However, the maximum power of the Honda Insight is limited to 10 kW due to the size of the motor-generator. For Toyota Prius the maximum power is limited by the Level 3AC connection which is 16.6 kW.

D.3.1.2 Cost of providing power to the grid: Hybrid vehicle generating from motor-generator fueled with gasoline.

The per kWh cost to vehicle owner for V2G power from a hybrid EDV generating electricity from the on-board motor-generator fueled with gasoline is calculated using equation (4.2). The annualized capital cost, C_{AC}, was previously described and estimated to have a value of \$578. Equation (4.2) describing total energy costs is for this case simplified to include only the cost of purchased energy, C_{PE}. Cost of purchased energy is defined by equation (4.11)

$$C_{PE} = \frac{C_{fuel}}{Eff_{elec}} \tag{4.11}$$

where C_{fuel} is cost of fuel (gasoline) and is equal to 1.5 \$/gallon, and Eff_{elec} is electrical efficiency in kWh/gallon. Degradation costs are based on total engine hours (or lifetime of engine) and the cost of rebuilding the engine. Cost of degradation is defined in this case by equation (4.12)

$$C_D = \frac{\dfrac{C_{Eng} + (C_L \times LH)}{EH}}{PC} \tag{4.12}$$

where C_{Eng} is cost of replacing the engine in \$, C_L is cost of labor in \$ and LH labor hours in h. PC is the power capacity, which is 16.6 kW for Toyota Prius and 10 kW for Honda Insight. We estimated that the C_{Eng} including the labor is \$2000 and that total engine hours are 3000 h. The 3000 h lifetime for an engine may be conservative as it is based on the lifetime of the current engine designs. It is likely though that engine life could easily be extended by the manufacturers to accommodate greater use of the engine required by V2G.

Table IV.14 Per kWh cost and annual capital cost to vehicle owner for V2G power from hybrid vehicles' motor-generator, fueled by gasoline.

Costs	Toyota Prius (16.6 kW)	Honda Insight (10kW)
C_E (\$/kWh)	0.21	0.23
C_D (\$/kWh)	0.04	0.06
C_{fuel} (\$/gallon)	1.50	1.50
C_{AC} (\$/year)	578	578

The cost of energy using motor-generation mode is on the order of \$0.20/kWh, which is similar to the cost of energy from the battery EDVs but higher than that from FC EDVs.

D.3.2 Fueled with natural gas

Alternatively, the hybrid vehicle can be fueled by natural gas instead of gasoline when it is parked. Costs of V2G power would then be dependent on the cost of natural gas and associated capital costs for any additional equipment.

D.3.2.1 Cost of providing power to the grid: Hybrid vehicle generating from motor-generator fueled with natural gas.

In this case the motor-generator is fueled by natural gas while the vehicle is parked. The natural gas would be delivered by a hose and valve with an estimated capital cost of $10. The capital cost would include all the costs described earlier for delivery of power to the grid ($3550) plus the $10. The annualized capital costs are slightly higher, or $580. In our calculations we use as power capacity 16.6 kW for the Toyota Prius and 10 kW for the Honda Insight. The energy cost is determined according to equation (4.11) where C_{fuel} is cost of natural gas ($8/GJ or 0.84/therm or $0.47/kg) and Eff_{elec} is electrical efficiency equal to 3.11 kWh/kg of natural gas. Cost of degradation was defined by equation (4.12).

Table IV.15 Per kWh cost and annual capital cost to vehicle owner for providing V2G from hybrid vehicles' motor-generator.

Costs	Toyota Prius (16.6 kW)	Honda Insight (10 kW)
C_E ($/kWh)	0.19	0.21
C_{fuel}($/kg)	0.47	0.47
C_D($/kWh)	0.04	0.06
C_{AC} ($/year)	580	580

The cost of energy using the motor-generator fueled with natural gas is $0.19-0.21 per kWh including the degradation of the motor-generator. This is by few cents less then the case when the motor-generator is fueled with gasoline.

E. Summary

We analyzed three types of electric-drive vehicles as sources of distributed power; battery-EDVs, fuel cell EDVs, and hybrids. First, we calculated the power capacity for each vehicle type. The capacity available to the grid varies based on the vehicle type, number of dispatch hours, distance driven, and range buffer. The maximum power capacities available from the battery EDVs for a RB of 20 miles and one hour discharge were on the order of 10 kW for the full function vehicles and 5 kW for the city car. Fuel cell vehicles have the ability to provide the highest power capacity to the grid, between 25-40 kW. The hybrid vehicles have very small batteries, which do not have significant power capacity to be useful for on-grid connection. The hybrid vehicles are interesting if they operate in the motor-generator mode while parked and fueled by either gasoline or natural gas, or if plug-in hybrids with larger batteries become available. The available power capacity from the two existing hybrid vehicles (Toyota Prius and Honda Insight) in motor-generator mode is 16.6 and 10 kW.

In addition, we calculated the per kWh cost of delivering a kWh of electricity to the grid for each of the vehicle configurations analyzed. The battery EDVs can provide electricity at a cost of \$0.23, \$0.32, and \$0.45 per kWh depending on the battery type. The lowest cost corresponds to the lead-acid battery followed by the nickel-cadmium and finally nickel-metal hydride. The annualized capital costs necessary for equipment to allow flow of electricity from the vehicle to the grid is only \$8.13 per year. A different cost was calculated when the battery EDVs provide regulation. The cost for this case is \$0.10, \$0.15, and \$0.21 per kWh for the three battery types. Fuel cell vehicles with on-board compressed H_2 can provide electricity at a cost of \$0.09 to \$0.38 per kWh. This range will depend on the cost of compressed H_2 and in turn on the cost of natural gas. The annualized capital costs for the fuel cell vehicle are \$578. If the fuel cell is connected to a stationary reformer, the cost of electricity is estimated at \$0.19 per kWh and the annualized capital costs at \$803. The hybrid vehicles can provide electricity generated by the motor-generator while parked. The cost of the electricity with current prices for natural gas is estimated at \$0.19 and for gasoline at \$0.21 per kWh. The annualized capital cost for connecting the hybrids to the grid is \$580.

In the next two sections of this report, we use these cost figures to analyze potential market opportunities for EDVs as distributed energy resources.

V. Value of V2G Power in California's Electricity Markets

In the previous section we developed a formula for power output from vehicles and calculated values for five vehicles under varying configurations. We use those values to calculate the value of V2G power in three current electricity markets. Table V.1 provides a summary of available power capacity from the vehicles analyzed in the previous section.

Table V.1 Available electrical power capacity from various EDV configurations (from Section IV)

Vehicle Type	Electrical Power Capacity (kW)	
	Peak Power and Spinning Reserves[a]	Regulation[b]
Battery Powered		
Lead-acid prototype	5.1	40.1
Honda EV Plus	4.9	39.0
Th!nk City[c]	2.3	10.0
Fuel Cell[d]		
On-board compressed H_2	22.0	40
Stationary natural gas reformer	33.6	40
Hybrid		
Stock battery[e]		
Toyota Prius	0.7	0.7
Honda Insight	0.4	0.4
Enlarged battery (Prius or Insight)	2.3	4.6
Gasoline /motor-generator		
Toyota Prius	15[f]	30
Honda Insight	10	10
Natural gas /motor-generator		
Toyota Prius	15[f]	30
Honda Insight	10	10

[a] Values presented assume 2 hour dispatch and 20 mile range buffer.

[b] These values assume 15 minute dispatch and 20 mile range buffer and the rated power output from the specific vehicle. These values or 16.6 kW (charging station and connection line capacity) are used for regulation.

[c] The values for Th!nk City assume 2 hour dispatch and 10 mile range buffer or 15 minutes dispatch and 10 miles range buffer for regulation.

[d] The values for the FC vehicle are higher than 16.6 kW but we use these values since a larger presence of FC vehicles is expected only in the longer term.

[e] This vehicle configuration is not analyzed further given the insignificant capacity available from hybrids with stock batteries.

[f] The power capacity for Toyota Prius was determined in Section IV as 16.6 kW but in the calculations in this section we use 15 kW.

There are two columns for power capacity in Table V.1. The first lists the power capacities assuming 2-hour dispatch and 20 mile range buffer. These values represent expected V2G power for peak power or spinning reserves. The second column lists power capacities assuming 15 minutes dispatch and 20 miles range buffer. These values are potential V2G power for regulation services. It should be noted that the values were constrained by the power capacity calculations and the rated power of the internal vehicle power system and represent the potential size of the V2G power from the different vehicle configurations. As mentioned in Section IV, we also have the third constraint imposed by the Level 3AC charging station and connection line capacities, which is 16.6 kW. If the value in Table V.1 is greater than the 16.6 kW, we usually base our calculations on both the 16.6 kW limit and the limit imposed by the vehicle configuration itself. An exception to this is the calculation for the FC vehicle where we used the values presented in Table V.1 (*i.e.*, 22 and 33.6 kW) directly because a wider presence of FC vehicles is expected only in the longer term, by which time the connection line capacities will most likely be higher as well.

Using our formula for costs, also developed in Section IV, we calculate the costs to vehicle owners for V2G. Costs are divided into per kWh costs and annualized equipment costs. Table V.2 summarizes the cost estimates presented in Section IV.

Table V.2 EDV owner kWh costs of delivering electricity to grid and annualized capital costs (from Section IV).

Vehicle Type	Energy Cost ($/kWh)	Capital Cost ($)
Battery Powered EDV		
Lead-acid prototype	0.23 (0.10)[a]	8.13
Honda EV Plus	0.45 (0.21)[a]	8.13
Th!nk City	0.32 (0.14)[a]	8.13
Fuel Cell EDV		
On-board compressed H_2	0.09 - 0.38[b]	578
Stationary natural gas reformer	0.19[c]	803
Hybrid EDV		
Enlarged battery	1.24	578
Gasoline using motor- generator	0.17 - 0.21	578
Natural gas using motor-generator	0.15 - 0.19	580

[a] Energy cost for providing regulation.
[b] The range results from different hydrogen cost assumptions from $1.3/kg to $5.6/kg.
[c] Assumes hydrogen production costs of $2.74/kg.

The value of V2G power is evaluated in three different markets: peak power, spinning reserves, and regulation services. During the time period of the analysis, through 2000, peak power was not labeled "peak" but was sold as kWh in the day-ahead and hour-ahead markets by the California Power Exchange (CalPX). The other two markets, spinning reserves and regulation services, are ancillary services markets operated by California Independent System Operator (CAISO). Historical data from these markets is analyzed to determine the potential market value of V2G power.

A. The market for peak power

The California Power Exchange (CalPX) was a non-profit corporation formed as part of the deregulation process to facilitate the purchase and sale of power in the state. CalPX operated the day-ahead and hour-ahead markets for power during the 1998-2000 period. Peak power is the power generated or purchased at times of day when high levels of power consumption are expected. Energy suppliers bid into the market to provide a specified amount of power at a specified time. Essentially, all bids were ranked from lowest to highest and the price at which power supplies satisfy power demands become the market-clearing price. As Figure 5.1 illustrates the market-clearing price of power fluctuates considerably from hour to hour.

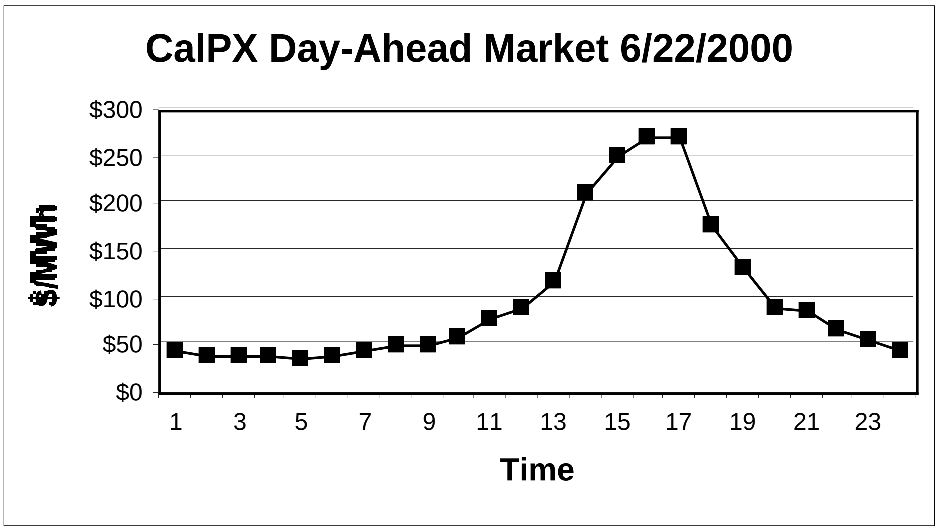


Figure 5.1. Market-clearing electricity prices on CalPX, June 22, 2000 (CalPX, 2000)

The value of V2G power for peak demand in California is analyzed using historical data from the CalPX on market clearing prices in the day-ahead market. As described earlier in this report, an aggregator of V2G power could market this power only when a prediction could be made that the market-clearing price of power will be greater than the cost of the V2G power.

A.1 Battery EDVs

In this section, the potential annual revenue to a battery EDV owner is calculated, along with the annual costs, from marketing the excess energy in EDVs in the CalPX day-ahead power market. Historical data from CalPX were obtained for the following years: 1998, 1999, and 2000 (UCEI 2001a). It is assumed that V2G power is sold only during those hours when the market-clearing price exceeds the EDV owner's costs of providing electricity, C_E (see table V.2 above).

The total potential annual revenues are calculated using equation (5.1)

$$AR = PC * \sum MC \tag{5.1}$$

where AR stands for annual revenue in \$, PC is the electric power capacity in kW and $\sum MC$ equals the summation of hourly market-clearing prices that are equal to or greater than the costs to the EDV owner for providing power to the grid (C_E). This is the revenue that would accrue from selling power into the CalPX day-ahead market only during those hours when the market-clearing price is equal to or greater than the cost to the EDV owner of delivering the electricity to the grid.

Equation (5.2) is used to calculate the yearly costs to the EDV owner for providing peak power

$$\left(CY_{owner}\right)_Y = \left(PC \times DH_Y \times C_E\right) + C_{AC} \tag{5.2}$$

where $(CY_{owner})_Y$ is the yearly cost to provide peak power in \$, PC is the electric power capacity in kW defined in Section IV, DH_Y represents the number of discharge hours in one calendar year (in hours). C_E is the variable energy cost to owner which includes cost of purchased energy and cost of equipment degradation (*e.g.*, battery degradation) in \$/kWh, and C_{AC} is annualized capital cost for any additional equipment in \$ (see Table V.2). C_E will determine the number of hours in a year that the EDV can be used to provide peak power (DH_Y). The actual value of DH_Y is based on the electricity prices from the CalPX as the number of hours in a particular year when the market price of peak power is greater or equal to C_E.

Table V.3 presents the potential revenues and costs for an EDV owner who was participating in CalPX's day-ahead markets for the three years for which the Power Exchange was in operation. We recognize that past market prices may not be a perfect predictor of future market prices, however it provides a good frame of reference for assessing the value of using battery EDVs as a source of power for the grid. Table V.3 assumes that the vehicle owner has a 20-mile range requirement and that the energy is dispatched over a two-hour period (see Table IV.2 in Section IV) during all hours when the market-clearing price for the day-ahead market exceeds the variable costs to the vehicle owner. In addition to costs based on actual market-clearing prices for the last three calendar years, we also include estimates of revenues and costs based on a utilities' "internal rule of thumb" for the cost of peak power. This estimate of cost assumes 200 hours of peak power during one year at a cost of \$0.50/kWh and is commonly used by utilities in forecasting costs and needs of peak power (Savidge 2000).

Table V.3 Day-Ahead Market: Revenues and costs for battery EDVs (CalPX 2000)

Revenue & Cost	Lead-acid prototype (5.1 kW)	Honda EV Plus (4.9 kW)	Th!nk City (2.3 kW)
Utility Rule of Thumb [a]			
Revenue	\$510	\$490	\$230
Costs	\$243	\$449	\$155
1998 [b]			
Revenue	\$0.0	\$0.0	\$0.0
Costs	\$8.13	\$8.13	\$8.13
1999 [b]			
Revenue	\$0.0	\$0.0	\$0.0
Costs	\$8.13	\$8.13	\$8.13
2000			
Revenue	\$993	\$300	\$211
Costs	\$715	\$255	\$147

[a] Using utilities' "internal rule of thumb" peak power estimates for 200 hour per year at \$0.50/kWh.
[b] Revenue is zero because in 1998 and 1999 there were no hours for which market exceeded hourly cost to sell power.

The figures in Table V.3 represent annual revenue and annual costs. Out of the three years that we evaluated value of V2G power for peak power, we found that only in year 2000 could the vehicle owner provide peak power at a net profit. Because peak power prices have been highly variable in the three years that data was available for, it is hard to make firm conclusions on the future value of V2G for peak power. A better measure is using the "utility rule of thumb" which indicates that all three battery EDVs could sell peak power at a net profit. The margin of profit depends on the vehicle type and is mostly dependent on the battery replacement costs. Of the three battery vehicles we found that the lead-acid prototype battery EDV would have the largest profit margin.

A.2 Fuel cell EDVs

Equations 5.1 and 5.2 above can also be used to calculate the potential annual revenue and owner costs for fuel cell vehicles selling power. Again, the annual revenue estimates assume that the power is sold only during those periods when the market-clearing price is greater than the kWh cost of delivering power to the grid from the fuel cell vehicle. Thus, this determines the number of hours each year that the vehicle would be dispatched, which in turn determines the annual cost to the vehicle owner. Table V.4 summarizes the results based on the historical data from 1998, 1999, and 2000 (UCEI 2001a).

Table V.4 Day-Ahead Market: Revenues and costs for fuel cell EDV, Ford P2000 vehicle (CalPX 2000).

Revenue & Cost	On-board compressed H_2[a] (22 kW)	Stationary natural gas reformer (33.6 kW)
Utility Rule of Thumb[b]		
Revenue	\$2,200	\$3,360
Costs	\$974 - \$2,250	\$2,080
1998		
Revenue	\$336 - \$0	\$0
Costs	\$804 - \$578	\$803
1999		
Revenue	\$247 - \$0	\$0
Costs	\$760 - \$578	\$803
2000		
Revenue	\$10,082 - \$1,774	\$8,450
Costs	\$5,609 - \$1,891	\$6,402

[a] The ranges are based on the fact that two different hydrogen costs estimates were used (\$1.31/kg and \$5.6/kg respectively).
[b] Using utilities' "internal rule of thumb" peak power estimates for 200 hour per year at \$0.50/kWh.

The lowest cost to the fuel cell EDV owner for providing peak power is from the on-board H_2 when the H_2 cost is \$1.3/kg. At this price of compressed H_2 the FC vehicle owner would not be motivated to have a stationary reformer. However it should be noted that that cost of compressed H_2 was derived assuming 1000 reformer stations each serving 1000 FC vehicles and is more realistic for a later stage of FC vehicle market introduction. Our design with a stationary reformer serves only 10 vehicles at a time. This comparison leads us to predict that in the near term the more economical option for providing power from FC vehicles would be the combination with the stationary reformer rather than with the on-board compressed H_2.

A.3 Hybrid EDVs

Table V.5 contains the results using the same methods utilized above to calculate the potential revenues and costs of using different hybrid vehicle configurations to participate in California's wholesale power market.

Table V.5 Day-Ahead Market: Revenues and costs for hybrid EDVs -Toyota Prius and Honda Insight (CalPX 2000)

Revenue & cost	Enlarged Battery (2.3 kW)	Gasoline motor-generator (15 kW & 10 kW)[a]	Natural gas motor-generator (15 kW & 10 kW)[b]
Utility Rule of Thumb			
Revenue	$0.0	$1,500 - $1,000	$1,500 - $1,000
Costs	$578	$1,178 - $978	$1,090 - $920
1998			
Revenue	$0.0	$0.0	$33 - $22
Costs	$578	$578	$611 - $600
1999			
Revenue	$0.0	$0.0[c]	$24 - $16
Costs	$578	$578	$600 - $594
2000			
Revenue	$0.0	$3,465 - $2,310	$4,237 - $2,825
Costs	$578	$2,891 - $2,120	$3,260 - $2,367

[a] Cost of electricity using the gasoline motor-generator used in the calculation is $0.20/kWh.

[b] Cost of electricity using natural gas motor-generator used in the calculation is $0.17/kWh, the mid-range of values given in Table 5.2

[c] There were only five hours during 1999 when the market clearing price of power exceeds $0.20/kWh, thus the potential revenue is insignificant.

B. The market for ancillary services

The second market for V2G power we analyzed is the market for ancillary services. According to Hirst and Kirby (1997) ancillary services are all the functions performed by electrical generating, transmission, system-control, and distribution equipment and personnel. The CAISO is charged with maintaining the reliability of the transmission grid. It buys and provides ancillary services as required and controls the dispatch of generation accepted to procure ancillary services. The CAISO operates a day-ahead and hour-ahead market for ancillary services where services are procured daily based on competitive mechanisms.

Ancillary services are used to continually maintain the balance between load and generation and to maintain the system frequency at 60 Hz. Ancillary services include: a) operating reserves, b) regulation, c) adjustment reserves, and d) replacement reserves. Of these various types of services we find the greatest opportunity for use of V2G power for certain operating reserves (*i.e.,* spinning reserves) and regulation. Operating reserves have traditionally been supplied by electricity generating units that can be called upon in response to sudden and unanticipated loss of electricity supply (Hirst and Kirby 1997). Operating reserves can be further broken down into spinning reserves and supplemental reserves. Spinning reserves are generated by equipment that is on-line and ready to respond immediately.

Regulation refers to maintenance of the system frequency around 60 Hz by adding or subtracting power in response to slight changes in frequency. Regulation represents contracts for power generation that are under direct real–time control of the ISO for increasing or decreasing output. We analyze in more detail the costs and revenues for each type of EDV providing power for spinning reserves and for regulation.

B.1 Spinning reserves market

Spinning reserves are provided by electrical generating equipment that is online and synchronized to the grid, which can begin to supply electricity to the grid immediately in response to changes in interconnection frequency (Hirst and Kirby 1997). Spinning reserves can be supplied by generators, which are literally kept in readiness by spinning at low power, or by an ultra-fast response device such as a battery.

Historical data on the market-clearing price in the day-ahead market for spinning reserves is used to estimate the value of V2G power to serve as spinning reserves (UCEI, 2001b). The value of spinning reserves is calculated for a kW-year. Essentially, we sum across all 8,760 hours of market-clearing prices for spinning reserves in the day-ahead market to obtain a $/kW-year value for spinning reserves. This value is used to assign a market value to the capacity available in EDVs serving the spinning reserves market (Note:the capacity values for each vehicle assume 2 hour dispatch and 20 mile range buffer). To account for the fact that the vehicle is not 100 % available to provide spinning reserves, we discount the annual $/kW-year value of spinning reserves by 10 %.

Equations 5.1 and 5.2 are used to calculate the annual cost to the vehicle owner for supplying spinning reserves. The key unknown variable here is the number of hours (DH_Y) each year that the CAISO would access energy in EDVs for spinning reserves. This variable determines the annual cost to the vehicle owner. We assume three different scenarios regarding the number of times each year the EDVs are accessed to provide emergency power: 10, 20, and 30 times. Table V.6 contains the results of this analysis.

Table V.6 The revenue and costs of using EDVs as spinning reserves

Vehicle Type	Annual Revenue[a]			Annual Costs (number of dispatches/year)		
	1998	1999	2000	10	20	30
Battery						
Lead-acid prototype	\$775	\$225	\$891	\$32	\$55	\$79
Honda EV Plus	\$744	\$217	\$856	\$52	\$96	\$140
Th!nk City	\$349	\$102	\$402	\$23	\$38	\$52
Fuel Cell						
On-board compressed H_2	\$3,342	\$972	\$3,841	\$618–\$745	\$657–\$912	\$697–\$1,080
Stationary reformer	\$5,105	\$1,485	\$5,867	\$931	\$1,058	\$1,186
Hybrid						
Enlarged battery	\$346	\$101	\$398	\$634	\$691	\$748
Gasoline/ motor-generator	\$2,279[b]	\$663[b]	\$2,619[b]	\$638[b]	\$698[b]	\$758[b]
Natural gas/ motor-generator	\$2,279[b]	\$663[b]	\$2,619[b]	\$631[b]	\$682[b]	\$733[b]

[a] These annual revenue numbers can be considered conservative, payments are made to the owner of the generating unit for the energy delivered. Payments are made based on the market-clearing price of electricity at the time when the reserves were dispatched. In addition, day-ahead market clearing prices for spinning reserves were used for the zone referred to by the CAISO as SP15.
[b] Based on a 15 kW motor-generator (Toyota Prius).

Based on the values presented in Table V.6 it seems that spinning reserves are a potentially profitable power market for V2G power. Most of the EDVs that we analyzed could provide spinning reserves at a net profit to the vehicle owner. Although the net profit varies with the particular year analyzed, in two of the three years the net profit to owner is significant. The battery EDVs can provide spinning reserves at the average annual profit ranging from tens of dollars to \$700. The fuel cell EDVs profit range is from tens of dollars to \$2,000. The hybrid vehicles in motor-generation mode can provide spinning reserves at a net profit close to \$2,000.

B.2 Regulation services market

Another ancillary service, regulation, appears to be an especially good application of V2G power. In California regulation services represent about 80% of the total ancillary service expenditures by the ISO. Regulation of power is used to fine-tune the frequency of the grid by matching generation with load demand (*i.e,* electricity consumption). The main objective is to maintain the system frequency around 60 Hz. This is achieved by adding or subtracting power in response to slight changes of frequency. The frequency is regulated so that the number of power cycles in an hour is always the same, even if there are minor fluctuations during the hour.

Regulation services are split into two elements for the market: one for the ability to increase power generation from a baseline level, and the other to reduce it. These are commonly referred to as "regulation up" and "regulation down," respectively. Traditionally, regulation is provided by generators that increase or decrease their power output in response to a signal from the generation control equipment within a control area[10]. They provide regulation up by increasing output and regulation down by decreasing it.

The CAISO typically procures 1,600 MW of regulation every hour and spends on the order of 1 – 3 million dollars each day on these services. For V2G, regulation up is equivalent to power flowing from the vehicle to the grid and "regulation down" for decreased power output or power flowing from the grid to the vehicle (battery charging). Regulation services are sold on an hour-by-hour basis. The way current contracts are written, if the EDV has insufficient energy to participate in regulation (*e.g.,* not enough stored energy in the battery or fuel in the tank), the EDV can simply opt-out with no penalties.

The method presented above for calculating the potential annual revenue for providing spinning reserves is adopted to determine the potential annual revenue for using EDVs to provide regulation. Historical market-clearing data was analyzed to determine a $/kW-year value of regulation in CAISO's competitive market for ancillary services (UCEI 2001b). The electrical power capacities of the vehicles assume 15 minutes discharge and 20 miles range buffer (see Table V.1). The 15 minutes is an approximate figure, based on "eyeballing" typical calls for regulation. Also, to account for the fact that the vehicle is not 100 % available to provide regulation, we discount the annual $/kW-year value of regulation by 10 % assuming that it would not be plugged in 10% of the time.

The actual regulation dispatched is some fraction of the total power available and contracted for regulation. To be exact, the ratio needed is:

$$\frac{\text{Energy dispatched for regulation (MWh)}}{\text{Contracted (MW) * Hours of contract (h)}} \tag{5.3}$$

In an attempt to obtain the data on energy dispatched for regulation we contacted multiple utilities and energy companies such as: Austin Energy, Sacramento Municipal Utility, New York Power Authority, Pacific Gas & Electric, PJM Interconnect, Electric Power Research Institute. Remarkably, none had the quantities needed for us to calculate the fraction describe by equation (5.3). In discussions with CAISO we were unable to get an exact figure for this fraction of regulation dispatched over regulation contracted. We therefore resorted to calculating this ratio ourselves from the frequency fluctuations, which already contain the correction.

We obtained data from CAISO of the frequency change during the course of one day (as an example). We further assumed and modeled the response of one EDV with power output set at 7 kW during the course of that day. The results indicated that the total energy dispatched from the EDV is equal to 27 kWh (the numerator in equation 5.3) if the vehicle was used for regulation up and down. This would mean that a total of 14 kW were available for regulation in the 24 hours; 7 kW for regulation up and 7 kW for

[10] Control area is an electrical region bounded by interconnection metering and centrally controlled to maintain balance between its load and generation, and maintain its interchange schedule with other control areas.

regulation down. Using these values in expression (5.1) we obtain that the ratio for regulation used is 0.08. Estimating that there is about 20% error in this calculation, for conservatism we use 0.10 in our analysis.

Table V.7 contains the results of the calculations of the value of regulation. The cost to the vehicle owner for providing regulation is based on degradation of the equipment due to cycling and energy costs to cover the losses in the transaction. For the battery vehicles, we assume that the vehicle would be providing 22 hours of regulation up plus 22 hours of regulation-down per day. This is because the vehicle can be contracted simultaneously for regulation up and regulation down since only one is called at a time. The battery EDVs are a special case that can provide regulation down while recharging the battery (*i.e.*, power flowing from the grid to the battery). In the case of fuel cell and hybrid vehicles, we only calculate the potential for regulation up since it is presumably more profitable to generate power at a maximum power capacity (*e.g.*, 15 kW) than to operate continuously at some lower capacity (*e.g.*, 5 kW) in order to sell both up and down.

Table V.7 Revenue and costs of using EDVs for regulation: power capacity limited by the near-term charging station capacities (Level 3AC).

Vehicle Type	Power (kW)	Annual Revenue			Annual Costs
		1998	*1999*	*2000* [a]	
Battery					
Lead-acid prototype	16.6	$4,479	$4,688	$9,813	$1,317
Honda EV Plus	16.6	$4,479	$4,688	$9,813	$2,756
Th!nk	16.6	$4,479	$4,688	$9,813	$1,906
Fuel Cell [b]					
On-board compressed H_2	16.6	$2,567	$2,671	$7,796	$1,756–$5,551 [c]
Stationary reformer	16.6	$2,567	$2,671	$7,796	$3,290
Hybrid					
Enlarged battery	4.6	$2,391	$1,299	$2,719	$2,391
Gasoline/ motor-generator [d]	16.6	$2,567	$2,671	$7,796	$3,326
Natural gas/ motor-generator [d]	16.6	$2,567	$2,671	$7,796	$3,067

[a] In August of 1999, the CAISO began to operate separate markets for regulation down and regulation up.
[b] Providing only regulation-up (from vehicle to grid). The revenue will be only for regulation-up.
[c] For a range of energy cost (0.09-0.38) depending on the range of H_2 costs.
[d] Based on the Toyota Prius motor-generator nominal power 30 kW; V2G power 16.6 kW.

The values in Table V.7 were calculated using 16.6 kW as the V2G power capacity. This is the limit imposed by the Level 3AC charging stations and line connections. There is, however, no technical barrier to charging stations and connection lines that can allow flow of V2G higher than 16.6 kW. Thus, in Table V.8 we present results for regulation using power capacities that are not limited by the 16.6 kW of the line connections but rather by the internal vehicle power system. These values are much higher and would not apply in the short term but might in the mid-term. For example, for the fuel cell vehicle the maximum power output is 40 kW and for the hybrid EDV the power output depends on the nominal size of the motor-generator.

Table V.8 Revenue and costs of using EDVs for regulation: power capacity limited only by the internal vehicle power system.

Vehicle Type	Power (kW)	Annual Revenue *1998*	*1999*	*2000* [a]	Annual Costs
Battery					
Lead-acid prototype	40.7	$10,982	$11,494	$26,059	$3,217
Honda EV Plus	39.4	$10,631	$11,127	$23,290	$6,531
Th!nk	18.1	$4,884	$5,112	$10,699	$2,077
Fuel Cell [b]					
On-board compressed H_2	40.0	$6,185	$6,437	$18,785	$3,416–$12,562 [c]
Stationary reformer	40.0	$6,185	$6,437	$18,785	$6,795
Hybrid					
Enlarged battery	4.6	$1,241	$1,299	$2,719	$2,391
Gasoline/ motor-generator [d]	30.0	$4,639	$4,828	$14,089	$5,545
Natural gas/ motor-generator [d]	30.0	$4,639[d]	$4,828	$14,089	$5,074

[a] In August of 1999, the CAISO began to operate markets for both regulation down and regulation up.
[b] Providing only regulation-up (from vehicle to grid). The revenue will be only for regulation-up.
[c] For a range of energy cost (0.09-0.38) depending on the range of H_2 costs.
[d] Based on the Toyota Prius motor-generator nominal power 30 kW; V2G power 16.6 kW.

B.2.1 Battery EDVs for regulation

The battery vehicles are particularly well suited for regulation. The ISO tries to balance the amount of energy every hour so the EDV could provide this service continuously as long as it is plugged-in. There are losses in the battery and inverter system that should be covered over time. This can be accomplished by contracting slightly asymmetric amounts of up and down regulation, or by setting the nominal power point at a low power consumption level.

In another form, the EDV could provide just regulation down service, giving the ISO direct control over reducing power from a nominal point. If the nominal point is zero, then regulation down amounts to recharging the battery. With direct ISO control of recharging, the process of recharging the vehicle becomes a valued grid stabilization service rather than just another load.

Our calculations of costs and revenue for the three battery EDVs presented in Table V.7 indicate that the lead-acid battery prototype vehicle would have a net annual profit of $8,442, $3,382 and $3,162 in year 2000, 1999, and 1998, respectively for providing regulation up and down 22 h each day. For the NiMh battery type the annual calculated profits are smaller; $7,057, $1,932 and $1,723 in 2000, 1999, and 1998, respectively. And last for the Th!nk City vehicle the profits are $7,907, $2,782 and $2,573 in those three years. The greater overall costs for this battery type are due to the higher battery costs (and battery-degradation costs) and hence the energy costs. This indicates that while battery EDVs are in principle well suited for regulation, the economics are nonetheless governed by degradation (*i.e.*, replacement) costs of the specific battery type. More research and testing needs to be done on actual battery degradation during regulation improve the calculations of actual costs caused by battery degradation.

B.2.2 Other EDVs for regulation

For the hybrid vehicle with an enlarged battery there seems to be no opportunity for providing regulation at a profit to the owner. The reason is the very high battery costs (and battery-degradation costs) of these small batteries. But in this case as well better understanding on actual depth of discharge during regulation would improve our calculations.

For all of the other EDVs we estimated the costs and revenues only for regulation up at the maximum power available from the vehicle configuration. This is because it would be unpractical to have to operate round the clock a fuel cell or hybrid vehicle at a low power output for regulation down. According to the values shown in Table V.7 the other EDVs could not consistently profitably provide power for regulation in the three years evaluated, but rather only in year 2000. An exception is the fuel cell vehicle with on-board H_2 at a very low cost of $1.3/kg. This low H_2 cost, however, is not very likely until later stages of fuel cell market penetration and is thus considered an option only in the longer term.

Caution should be used in interpreting and drawing conclusions based on the costs and revenues in year 2000 because the electricity market was very unusual during this period. However, these results do show that the potential for the other vehicles to provide regulation exists and depends on the future market value.

B.3 Other ancillary services

In discussions with the ISO we learned that there are potentially other ancillary services where use of EDVs would be of great interest. One value that EDV power could bring is to provide a new service balancing the area control error (ACE). Further research needs to be done to evaluate how EDVs could contribute to reducing ACE and to determine the value by looking at what fraction of all regulation this represents. Schedule Coordinators, such as local distribution companies (*e.g.*, SoCalEd) can self provide ancillary services, which may make the transactions simpler.

C. Summary

We found that battery EDVs had economic potential to sell peak power, at CalPX market prices, only in the year 2000. Using the "utility rule of thumb" to compare the three vehicles, the vehicle with the lead-acid battery is economically the most attractive (has the highest net profit) followed by the city car with the NiCd battery and finally the Honda EV Plus with the NiMH battery. Fuel cell vehicles offer economic potential as a resource for participating in the day-ahead power market, selling power during peak price periods in all three years analyzed if the price of H_2 is less than $2/kg. In year 2000 power could have been provided economically from fuel cell vehicles with either method of H_2 delivery (on-board H_2 or stationary reformer). Hybrid vehicles are not economically viable for V2G in battery mode; we expect that plug-in hybrids with enlarged batteries would have the economic viability of the city car we did analyze.

In general, the market for ancillary services is significantly more attractive for V2G. Over the three-year period, the value of V2G for spinning reserves is more consistent than the value as peak power. Regulation seems to be a very promising market especially for V2G power from battery EDVs. Actual testing would be helpful to improve two numbers that are not well established—the degradation costs of regulation-driven battery cycling and the ratio of regulation contracted to regulation dispatched.

VI. Value of V2G Power on the Customer's Side of the Meter

In Section IV, formulas for calculating the available energy and capacity of EDVs were derived. Section V investigated the value of V2G in power markets currently being operated in California. The revenue from providing V2G power was then compared to the costs to the EDV owner. The analysis presented in section V can be thought of as a utility-side of the meter analysis. The electricity that flows from the vehicle must be metered to reconcile the purchase and sale of the V2G power with the quantities recorded on the traditional building meter.

In contrast, this section of the report presents a customer-side of the meter analysis. The electricity from the vehicle is assumed to flow directly into the customer's building wiring, reducing the electricity consumption registered on the building meter. Thus the value of this power is exactly the retail value of electricity. If utility rate structures reflect the fact that the cost of generating and delivering power varies by time of day and date or month, power from EDVs can effectively be used to reduce end-use customers' monthly electric utility bills. This represents a near-term opportunity for utilizing EDVs as a distributed energy resource, given that no rate changes, metering or other institutional changes are required to exploit these opportunities. In this section, we begin with a review of the California utility rate structures. Next, specific utility rates are used to estimate the potential annual electric bill savings from each of the vehicles analyzed above. These potential bill savings are compared to the costs to the EDV owner. Finally, an assessment is presented regarding which business types have load profiles that will likely result in the greatest potential bill savings.

A. Utility rate structures

Energy providers have developed different rate schedules based on customer classes. In general, electric rates are categorized into residential and commercial and industrial (C&I) rate schedules. Typical, residential rates are simply an energy charge stated in $/kWh. For example, Pacific Gas & Electric's E-1 Residential Service charges customers approximately $0.12/kWh for all energy consumed (Pacific Gas & Electric 2000). Most utilities also offer what are termed time-of-use rates, in which the energy charge varies by time of day and month of year. Southern California Edison's Domestic, Time-Of-Use (TOU-D-1) rate includes energy charges that range from a high of $0.49/kWh during the summer months from 10:00 am to 6:00 pm to a low of $.08/kWh during off-peak periods (Southern California Edison 2000). The opportunity for bill savings to residential customers is limited, but is analyzed below.

C&I customers offer greater opportunities for electricity bill savings as compared to residential customers. Most C&I customers' rate schedules include an energy charge like residential customers and an additional demand charge. Energy charges are stated in $/kWh and are applied to the monthly kWhs consumed. Demand charges apply to the monthly maximum kW demand as measured by a fifteen-minute demand meter. The demand charge component of a C&I customer's bill is often the largest part of the overall bill. As a result, substantial bill savings are possible for some C&I customers, as analyzed in detail below.

B. Residential customer-side analysis

This section analyzes residential V2G based on rates from four California utilities: Pacific Gas and Electric (PG&E), Southern California Edison (SoCalEd), Los Angeles Department of Water and Power (LADWP), and the Sacramento Municipal Utility District (SMUD). Although EDVs with V2G capabilities could also provide value to their owners as a source of emergency backup power, this option requires grid isolation for safety, and is not analyzed here.

Residential owners of battery EDVs can buy power during low-cost periods and store it for use during high-cost periods. Fueled EDVs can produce power when vehicle power is cheaper than their retail rate to purchase power from the utility. These two opportunities are discussed separately below.

Bill savings can be achieved only for those customers who have rates that vary over time because V2G power is more expensive than levelized retail energy charges. Table VI.1 presents the maximum rate differential and the cost to the EDV owner for using the stored energy to satisfy a portion of their household's energy consumption. For battery EDVs it only makes sense to use the stored energy when the storage cost is less than the spread between non-peak periods and during peak price periods.

Table VI.1 Sample Residential Time-Of-Use (TOU) Rates

Utility Rate Schedule[a]	Peak Rate ($/kWh)	EV Charging Rate ($/kWh)	Rate Spread, ($/kWh) (peak. – EV rate)
PG&E E-7	0.32	0.04	0.28
SoCalEd TOU-D-1	0.49	0.04	0.45
LADWP Rate B	0.14	0.01	0.13
SMUD Rate R Optional TOU	0.16	0.04	0.12

[a] All rate structures can be found at each of the utility's web pages (see references cited).

Only those rate structures with peak rates above the cost of providing EDV power offer opportunity for an economic advantage for residential customers. Referring to the battery EDVs in Table V.2, we find that the cost of V2G power from the lead-acid prototype vehicle is $0.23/kWh, which is less than the peak rate for both PG&E's E-7 rate and Southern California Edison's TOU-D-1 rate. The cost of V2G from the Ford Th!nk City is $0.32/kWh, which is less than SoCalEd's rate. The $0.45/kWh cost of providing power from the Honda EV Plus is higher than all peak residential energy rates presented above. For example, if a residential owner of a lead-acid battery vehicle, like the one we analyze, could exploit the above differential for 10% of their annual energy consumption of 9,000 kWh, the net savings to the customer would be approximately $234 per year. Although this figure is smaller than the value of regulation, it can be done today with no changes in rate structures and can also be used in the future when the regulation market is saturated.

For the fuel cell and hybrid vehicles, the residential customer determines whether the cost of generating vehicle power is less than purchasing power from their utility. Table VI.2 contains several California residential utility rates. These values can be compared to the cost of generating power from the various vehicle configurations analyzed, from Table V.2 in the previous section.

Table VI.2 Sampling of California Residential Electricity Rates

Utility/Rate Structure	Peak Summer Rate ($/kWh)	Peak Winter Rate ($/kWh)
PG&E		
Schedule E-1	0.13	0.13
Schedule E-7	0.32	0.12
SoCalEd		
Schedule D	0.12	0.12
Schedule TOU-D-1	0.49	0.14
Schedule TOU-D-2	0.40	0.11
LADWP		
Rate A	0.07	0.07
Rate B	0.14	0.14
SMUD		
Schedule R	0.08	0.07
Schedule R TOU option	0.16	0.16

Comparing Table V.2 with VI.2, EDVs that generate electricity from fuel can generally compete with the residential electricity rates on a cost per kWh basis only with same summer time-of-use rates. For example, regardless of whether a fuel cell EDV uses compressed hydrogen or a stationary reformer, the costs to provide power of $0.09kWh - $0.38/kWh and $0.19/kWh respectively is less than Southern California Edison's TOU-D-1 rate. Other than SoCalEd rate and possibly PG&E's E-7, the other peak rates are lower than the cost of V2G. Eventually V2G may be cheaper for fuel cell vehicles, when hydrogen costs are in the $1.3/kg cost range.

C. Commercial and industrial customer-side analysis

In this section, the opportunity to reduce C&I electric bills is analyzed based on rate structures from four California utilities. It is assumed that the owner/operator of the C&I building has access to fleet or employees' parked EDVs, and that they can dispatch the energy as needed to reduce the peak demand of the building. Furthermore, it is assumed that the building operator compensates the EDV owner (whether employee or fleet manager) for costs incurred on the vehicle side.

The results of the C&I analysis are presented in three separate tables based on vehicle types: battery, fuel cell, and hybrid. Tables VI.4 – VI.6 presents the results of the analysis respectively, drawing from the values in Table IV.2, which assumes a 20-mile range buffer and a 2-hour dispatch period.

Given that the peak demand savings from the lead-acid prototype and Honda EV Plus are approximately equal, demand charge savings would be essentially the same for both vehicles. We take the middle value of 5 kW for calculating demand charge savings for these vehicles. Demand charges for the Ford Th!nk City are calculated separately.

However, Table VI.4 does provide the calculated costs to the EDV owner for peak-shaving purposes for all three vehicle types. Furthermore, the costs to the EDV owner are calculated based on two different assumptions regarding the number of days each month the building operator must access V2G for peak-shaving purposes. For this analysis, we assume that the building operator would call for V2G for two hours, either 10 or 20 times per month. Table VI.3 summarizes the demand charges utilized in the analysis presented in Tables VI.4 – VI.6.

Table VI.3 Demand Charges for Utility C&I Tariffs Analyzed

Utility Rate Schedule	Summer Demand Charge ($/kW)	Winter Demand Charge ($/kW)
PG&E A-10	6.70 (May – Oct.)	1.65 (Nov. – April)
PG&E E-19	13.35 (May – Oct.)	0.00 (Nov. – April)
SolCalEd GS-2	7.75 (June – Sept.)	0.00 (Oct. – May)
SoCalEd TOU-GS-2 Option B	16.40 (June – Sept.)	0.00 (Oct. – May)
SoCalEd TOU-8	17.55 (June – Sept.)	0.00 (Oct. – May)
LADWP A-3	8.52 (June – Oct.)	7.80 (Nov. – May)
SMUD GS-TOU	9.4 (June – Sept.)	6.90 (Oct. – May)

Table VI.4 C&I Customer –side Analysis: Battery EDVs

Utility Rate Schedule	Annual Demand Charge Savings ($/year)		Annual Cost to Vehicle Owner based on Number of Dispatches ($/year)					
			10 Dispatches / Month			20 Dispatches / Month		
	Lead-acid/ Honda	Th!nk	Lead-acid	Honda	Th!nk	Lead-acid	Honda	Th!nk
PG&E A-10[a]	$251	$115	$284	$548	$185	$560	$908	$361
PG&E E-19	$401	$184	$146	$278	$97	$284	$458	$185
SolCalEd GS-2[b]	$155	$71	$100	$188	$67	$192	$368	$126
SoCalEd TOU-GS-2 Option B[b]	$328	$151	$100	$188	$67	$192	$368	$126
SoCalEd TOU-8	$351	$161	$100	$188	$67	$192	$368	$126
LADWP A-3[c]	$486	$224	$284	$548	$185	$560	$908	$361
SMUD GS-TOU[d]	$464	$213	$284	$548	$185	$560	$908	$361

[a] Assumes secondary voltage level and customer peak demand < 500 kW.
[b] Rates apply to customers with peak demand < 500 kW.
[c] Rate applies to customers with peak demand > 500 kW.
[d] Rate applies to customers with peak demand > 1,000 kW.

Table VI.5 C&I Customer-side Analysis: Fuel Cell Vehicles

Utility Rate Schedule	Annual Demand Charge Savings ($/year)		Annual Cost to Vehicle Owner based on Number of Dispatches ($/year)			
			10 Dispatches / Month		20 Dispatches / Month	
	On-board H_2	Reformer	On-board H_2	Reformer	On-board H_2	Reformer
PG&E A-10[a]	$1,102	$1,684	$1,053–2,584[e]	$2,335	$1,528–4,591[e]	$3,867
PG&E E-19	$1,762	$2,691	$816 - 1,581[e]	$1,569	$1,053–2,584[e]	$2,335
SolCalEd GS-2[b]	$682	$1,042	$736 - 1,247[e]	$1,314	$895–1,916[e]	$1,824
SoCalEd TOU-GS-2 Option B[b]	$1,443	$2,204	$736 - 1,247[e]	$1,314	$895–1,916[e]	$1,824
SoCalEd TOU-8	$1,544	$2,359	$736 - 1,247[e]	$1,314	$895–1,916[e]	$1,824
LADWP A-3[c]	$2,138	$3,266	$1,053–2,584[e]	$2,335	$1,528–4,591[e]	$3,867
SMUD GS-TOU[d]	$2,042	$3,118	$1,053–2,584[e]	$2,335	$1,528–4,591[e]	$3,867

[a] Assumes secondary voltage level and customer peak demand < 500 kW.
[b] Rates apply to customers with peak demand < 500 kW.
[c] Rate applies to customers with peak demand > 500 kW.
[d] Rate applies to customers with peak demand > 1,000 kW.
[e] The range is based on different H_2 cost assumptions.

Table VI.6 C&I Customer-side Analysis: Hybrid Vehicles

Utility Rate Schedule	Annual Demand Charge Savings ($/year)		Annual Cost to Vehicle Owner based on Number of Dispatches ($/year)			
			10 Dispatches / Month		20 Dispatches / Month	
	15 kW	10 kW	15 kW	10 kW	15 kW	10 kW
PG&E A-10[a]	$752	$501	$1,298–1,192[e]	$1,058–988[e]	$2,018–1,804[e]	$1,538–1,396[e]
PG&E E-19	$1,202	$801	$938–886[e]	$818–784[e]	$1,298–1,192[e]	$1,058–988[e]
SolCalEd GS-2[b]	$465	$310	$818–784[e]	$738–716[e]	$1,058–988[e]	$898–852[e]
SoCalEd TOU-GS-2 Option B[b]	$984	$656	$818–784[e]	$738–716[e]	$1,058–988[e]	$898–852[e]
SoCalEd TOU-8	$1,053	$702	$818–784[e]	$738–716[e]	$1,058–988[e]	$898–852[e]
LADWP A-3[c]	$1,458	$972	$1,298–1,192[e]	$1,058–988[e]	$2,018–1,804[e]	$1,538–1,396[e]
SMUD GS-TOU[d]	$1,392	$928	$1,298–1,192[e]	$1,058–988[e]	$2,018–1,804[e]	$1,538–1,396[e]

[a] Assumes secondary voltage level and customer peak demand < 500 kW.
[b] Rates apply to customers with peak demand < 500 kW.
[c] Rate applies to customers with peak demand > 500 kW.
[d] Rate applies to customers with peak demand > 1,000 kW.
[e] The range represents costs of generating power on-board for gasoline and natural gas respectively.

The analysis presented in Tables VI.4 – VI.6 suggests that demand charge savings can be achieved, especially for 10 or fewer dispatches per month, for the right combinations of vehicles and rate schedules. Looking at battery EDVs (Table VI.4), we see that potential demand charge savings from PG&E's E-19 rate are $401 annually for the lead-acid prototype and Honda EV Plus and $184 for the Ford Th!nk. These benefits exceed the costs for all vehicles analyzed assuming 10 monthly dispatches. However, looking at the costs assuming 20 dispatches per month the potential demand charge savings are higher then the associated costs for only one of the vehicles ($284 for the lead-acid prototype EDV). This pattern is generally applicable to the other rate structures –fewer and/or shorter dispatches improve the economics.

Turning to the fuel cell and the hybrid vehicles, we draw similar conclusions. Even with greater dispatch requirements certain fuel cell vehicles still create benefits that exceed the costs, especially with a low-cost hydrogen source. For example, the fuel cell vehicle with a stationary reformer could achieve annual demand charge savings under SoCalEd's TOU-8 of $2,359, which is greater than the costs to the EDV owner assuming either 10 monthly 2-hour dispatches ($1,314) or 20 monthly dispatches ($1,824).

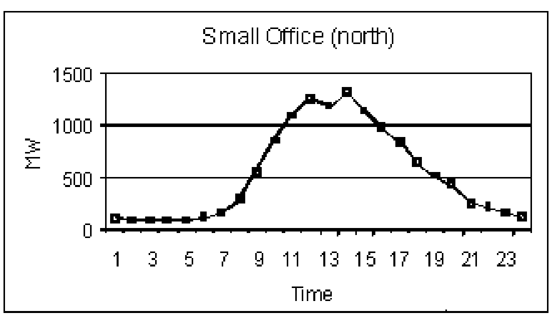
D. C&I building load profile assessment

The rate structures analyzed above apply to a variety of different business types, from offices to manufacturing facilities. The potential demand charge savings calculated above assume that the full capacity from the EDVs being discharged over two hours results in firm peak shaving. However, the best opportunity for V2G demand charge reductions is in buildings with short periods of relatively high spikes in energy demand. Next, data provided by the California Energy Commission (CEC) is evaluated to identify those building types that offer the greatest demand reduction opportunities.

D.1 Business type aggregate load profile analysis

The California Energy Commission supplied aggregate hourly load data for 17 different business types in northern California and 21 in southern California (CEC, 2000). The data are hourly, that is separate load number for all 24 hours. They are aggregated into business types, so that a single load value under "small office" is the aggregate load of all small offices. The data provided for each business type is given for the utility's one peak day for each month. We reviewed this data to determine which business types offer the greatest likelihood of achieving demand charge savings.

We consider first commercial businesses, then industrial. Commercial businesses range from small offices to colleges. We searched for business types with relatively short peak load periods, for which EDVs could provide practical demand reductions. The demand charge analysis presented above assumes a two-hour dispatch period. Thus, only those buildings with peak-load duration of two or less hours would realize the demand charge reductions calculated above. Based on this analysis, several commercial building types emerge as likely candidates for further analysis. Of those commercial business types analyzed, small offices, retail establishments, restaurants, warehouses, schools, and hospitals exhibit load profiles characterized by relatively short peak demand periods between two and three hours. Since these types comprise a large number of buildings, relative to the near-term size of the EDV fleet, commercial buildings appear to represent ample opportunity for customer-side V2G power. Figures 6.1 – 6.6 graph the peak day during the peak month from the aggregate commercial building data.



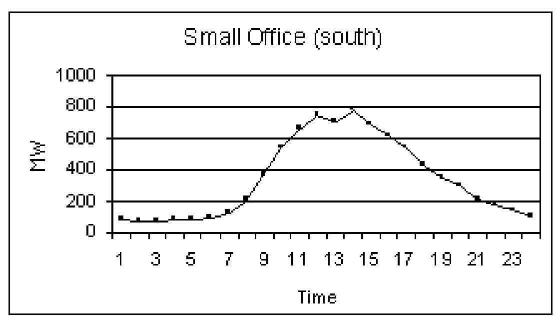


Figure 6.1. Load profiles during a peak day for small offices; Northern and Southern California

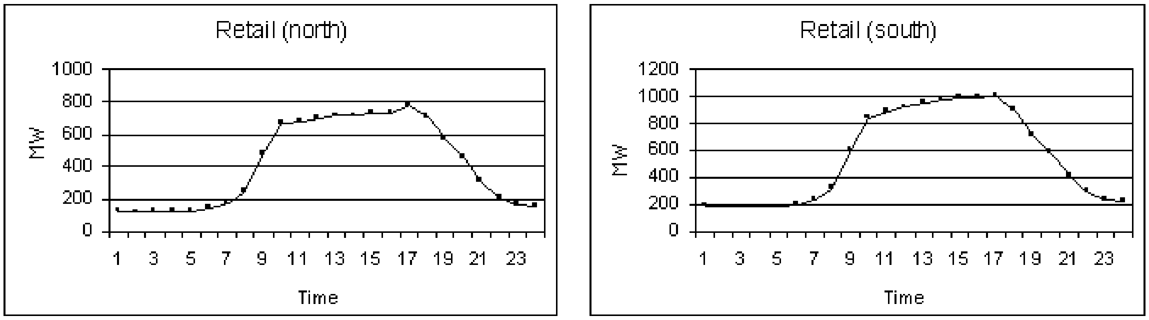


Figure 6.2. Load profiles during a peak day for retail locations; Northern and Southern California

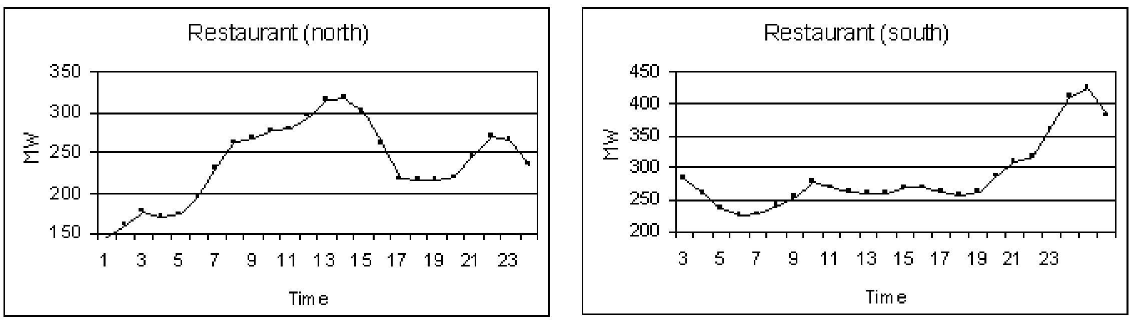


Figure 6.3. Load profiles during a peak day for restaurants; Northern and Southern California

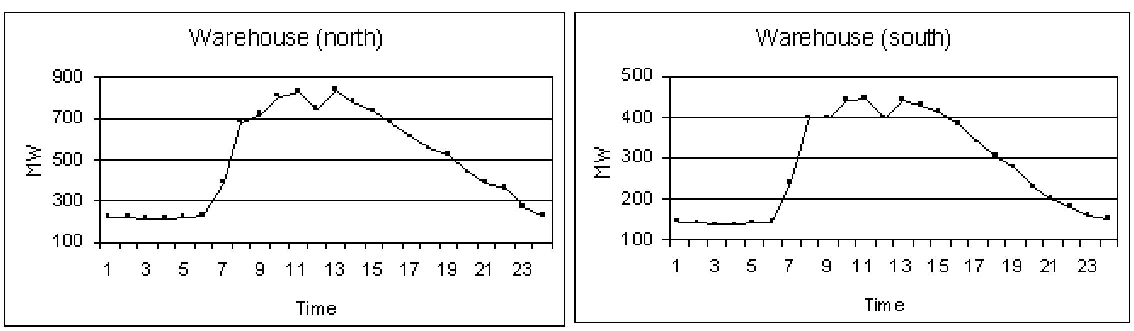


Figure 6.4. Load profiles during a peak day for warehouses; Northern and Southern California

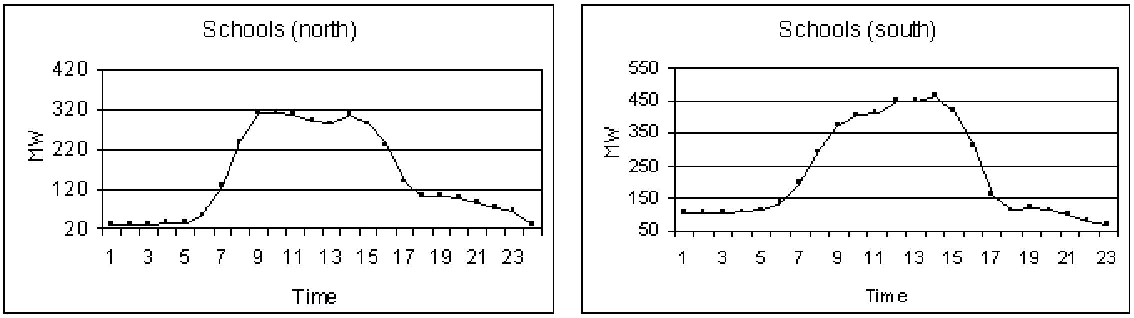


Figure 6.5. Load profiles during a peak day for schools; Northern and Southern California

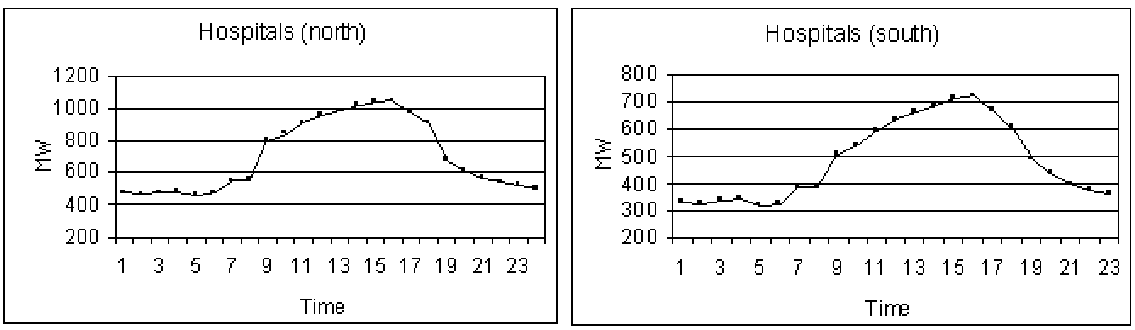


Figure 6.6. Load profiles during a peak day for hospitals; Northern and Southern California

Now, we do the same analysis for the industrial business types. The types of industries analyzed range from the Standard Industrial Classification codes (SIC) 35 (industrial machinery and equipment) to SIC code 50 (wholesale trade: durable goods). Most of the industries analyzed exhibit relatively flat load profiles, which make V2G peak-shaving costly and thus impractical. However, the SIC code 20 (food and kindred products) exhibits a load profile characterized by relatively short peak periods occurring in the late afternoon. These types of facilities may offer opportunities for demand charge savings from EDVs, however this is a relatively small fraction of industrial electricity users. Figures 6.7 and 6.8 present load graphs for two specific industries within SIC code 20: the meat and dairy products, and preserved fruits and vegetables.

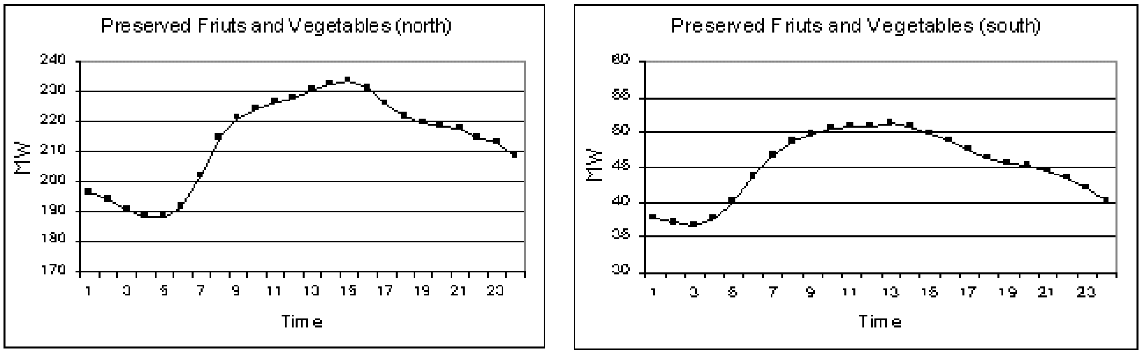


Figure 6.7. Load profiles during a peak day for the preserved fruits and vegetable industry; Northern and Southern California

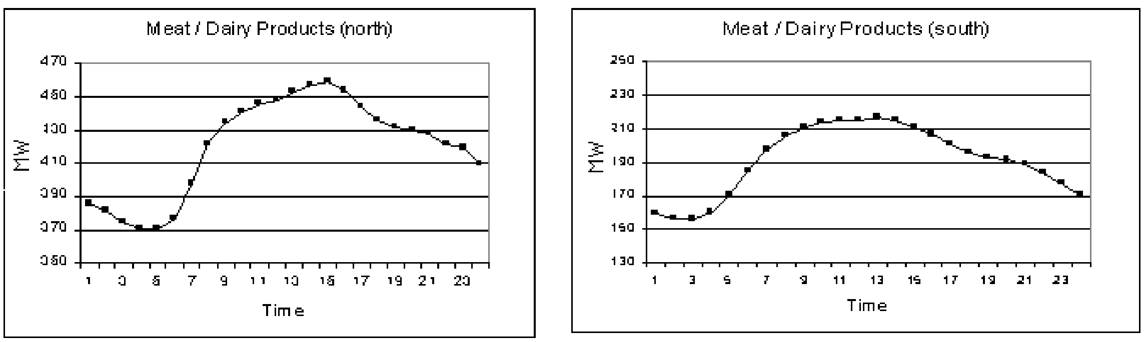


Figure 6.8. Load profiles during a peak day for a meat/dairy industry; Northern and Southern California

E. Summary

This section analyzed the potential for V2G on the customers' side of the meter. The economic question from a customer-side analysis is: Can V2G power be provided at a cost lower than the retail bill savings? Based on existing residential and C&I rates, with the right combination of California utility rate schedules and vehicles, the answer to this question is “yes.” However, the analysis of residential rates suggests that potential bill savings are small and may not be sufficient to cover transaction and management costs. For commercial and industrial customers, V2G could offer some opportunities to reduce demand charges. In addition, an analysis of different C&I business types suggested which business types have load characteristics more likely to have demand savings opportunities. There were several potential building types in the commercial sector, but only one (food and kindred products) in the industrial sector. These are the business types that should be investigated if demonstration projects were carried out on customer-side V2G.

Based on this analysis, we suggest the role of customer-side V2G in the overall picture. The value of customer-side V2G is generally lower than transactions with the utility, especially regulation. However, customer-side V2G can be implemented immediately, without new tariffs or utility control technology. Also, the more modest savings may become more attractive in a decade or two, offering a potentially very large market when V2G is mature and the high value utility V2G markets are becoming saturated.

VII. Policy Discussion

The technical and economic analysis in this report suggests that V2G power is feasible and will have very high economic value. For example, the first hundred thousand or so battery and plug-in hybrid EDVs signing up to sell regulation in California could potentially earn a net of several thousand dollars per year. Spinning reserves and peak power are additional markets.

In addition to private benefits to producers and consumers in both the electricity and automotive industries, development of V2G appears to have substantial public benefits. Public benefits include more rapid introduction of zero-pollution and low-pollution vehicles, increased reliability of the electric system, and deploying storage and generation infrastructure on-grid to allow higher proportions of renewable electricity in the future (renewable sources such as wind and solar are clean but intermittent). Several implications for policy have been mentioned within the report. In this concluding section, we summarize and elaborate the major policy points made within the report. We do not here recommend specific policies but rather identify important areas for attention.

A. Allowing for V2G power on the grid side

Choices among today's alternatives for charging infrastructure will have implications for V2G power. As noted in Section II, on-board conductive charging seems to be more easily and more economically adapted for flow of power from the vehicle back to the grid. In fact, current conductive charging stations permit V2G power without any technical modifications at all.

With several automobile manufacturers already considering V2G capabilities, now is the time to start reviewing codes and standards that would apply to V2G. As noted in Section II, the National Electrical Code, and California's Rule 21, have sections that could be interpreted as prohibiting V2G power. For example, Rule 21, designed for home renewable power, requires a mechanical switch on the outside of the residence to allow line workers to disconnect the source of home power from the grid. A building-mounted switch makes less sense for power producing equipment that moves from one location to another. For EDVs, this line-worker safety need can probably be met as well, and at far lower cost, by electronically detecting loss of grid power, shutting down any V2G, and transmitting verification of shutdown via on-board telematics.

If some utilities will be interacting with individual customers as V2G suppliers, tariffs would also need to be established. If an aggregator is to sell V2G power in blocks, they may fall within current contracts and rates for power producers. Nevertheless, even in the case of aggregators, some adjustments to contracts and tariffs would probably be helpful. For example, the fast response, distributed location and the possibility of autonomously responding to the need for regulation may make battery EDVs more valuable for regulation than traditional generators. This higher quality may make grid operators willing to pay more, and/or to accept V2G's shortcomings: smaller contract sizes and probabilistic availability.

To simplify billing, it may be desirable to add an electronic serial number to charging stations. The local distribution company would use this to identify which fixed meter should be adjusted by the consumption (or production) registered on the vehicle meter. Level 2 and Level 3AC charging stations could transmits a serial number using the existing pilot signal wire, but this will require agreement within the industry as to standard signals, and would require some motivation for charger manufacturers to add this capability. V2G can proceed without charging stations that identify themselves, using an alternative method of confirming what meter the vehicle is plugged into such as on-board GPS or cell-phone positioning. To keep all V2G capabilities on the vehicle, an alternative to a serial number would be a more accurate positioning system. Nevertheless, a serial number from the charger would simply and definitively establish the bill-to (or credit-to) party.

In the long term, utility grid operators and local distribution companies will need to think through the model of supplementing their existing set of fixed-location meters with a new set of mobile meters. The vehicles on those mobile meters may either draw or produce power. In either case the fixed meter amount would be reconciled accordingly. Even without any V2G, on-board vehicle power meters provide options to better deal with current battery EDV arrangements such as separate EV charging rates on fixed meter, and public charging stations.

B. Building V2G capacity on the vehicle side

On the vehicle side, the most obvious requirement is that grid connections must be planned to be suitable to V2G. For battery and plug-in hybrids, this probably means conductive charging as noted earlier, but on the vehicle it also means that the power electronics must be designed for two-way flow. For fuel cell and no-plug hybrids, it means adding a high power electrical connection from the existing high-power circuitry driving the motor to an external connection.

A more subtle design consideration on the vehicle side is that electrical efficiency becomes more important. For example, in a battery EDV fuel costs (electricity) are quite low compared to gasoline and compared to the cost of battery wear. Thus, design criteria for such vehicles in the pre-V2G world do not necessarily prioritize efficiencies of charging. In the V2G world, 93% versus 80% one-way electrical efficiency means 86% versus 64% round-trip electrical efficiency—a difference important in price-sensitive electricity markets.

As the report has pointed out, a number of other features in the vehicle are important. These include on-board certified metering of power flow to and from the grid; using planned vehicle telematics to communicate with to the on-board power metering and power control, and interlock safety to detect loss of line power and shut off V2G for safety reasons.

C. Interagency, inter-industry coordination

The very concept of V2G is predicated on interconnecting two heretofore distinct industries (electricity grids and automotive manufacturing) with distinct business models and separate regulatory bodies. Some working groups or interagency coordinating bodies would seem appropriate. On the agency side, in California, coordination would be helpful across some or all of the Air Resources Board, the California Energy Commission, the Independent System Operator, and/or the California Public Utilities

Commission. Across industries, coordination would have to include at least the automobile manufacturers (OEMs), the component manufacturers and technology development firms, and the electric power industry. Industry coordination, at least for the automotive industry, would necessarily be at the national or international level. Coordination on the agency side would primarily be at the state level, since the US Federal government is not taking an active role in development of this industry, leaving California providing the only serious guidance toward the future.

D. Demonstration projects and developing businesses

A number of questions could not be answered by this study, which was based on obtaining specifications from vehicle manufacturers and tracking existing power markets. Some important numbers were not available, or were not reliable from this paper study.

Several examples of unavailable information can be seen by looking at the case of regulation. The MWh of regulation called, as a fraction of contracted MW per hour, is important to the economics of regulation but is not tabulated by any of the half-dozen large utilities and grid operators we contacted (we estimated it by analyzing a small sample of raw dispatch data). Also we did not have a measure of the impact of very shallow cycling on battery life. We estimated it to be half the degradation of deep cycling, but that is probably high (so our estimated cost of V2G regulation is probably high and our estimate of the net profit to vehicle owner is thus too low). Finally, the value of V2G regulation can probably be handled in different ways from traditional generators; it may have higher value and may be controlled by more automated mechanisms which would have to be designed and tested.

Another area of needed research involves driver reactions. Although our suggested control panel in Section II is based on studies of driver range requirements, it has not been tested on drivers. It would be helpful, for both technology development and marketing of V2G contracts, to know if the controls we recommend are adequate and convenient enough to encourage V2G participation by drivers. Demonstration projects would provide an empirical basis for the missing quantities, allow testing of driver requirements and reactions, and allow developing and testing new ways for grid operators to use V2G resources.

The potential public benefits of V2G, and the challenge for two industries to develop products that coordinate with each other, suggest that both industry coordination and public incentives would be helpful. Incentives might take the form of technology development grants, insuring that contracts are available for the first generation of V2G-capable vehicles, nurturing bridge industries such as V2G aggregators, or setting standards for developments each industry must provide to enable the other to participate in V2G.

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