The V2G Concept:

A New Model For Power?

Connecting utility infrastructure and automobiles.

By Steven E. Letendre, Ph.D., and Willett Kempton, Ph.D.

ELECTRIC-DRIVE VEHICLES CAN BE THOUGHT OF as mobile, self-contained, and—in the aggregate—highly reliable power resources. "Electric-drive vehicles" (EDVs) include three types: battery electric vehicles, the increasingly popular hybrids, and fuel-cell vehicles running on gasoline, natural gas, or hydrogen. All these vehicles have within them power electronics which generate clean, 60 Hz AC power, at power levels from 10kW (for the Honda Insight) to 100kW (for GM's EV1). When vehicle power is fed into the electric grid, we refer to it as "Vehicle-to-Grid" power, or V2G.

Electric utility planners and strategists, when they think about electric-drive vehicles at all, have seen battery vehicles as night-charge (valley-filling) load, and perhaps have seen fuel cell vehicles as possible generation resources for some distant future. In contrast, a recent study we conducted for the California Air Resources Board (CARB) and the Los Angeles Department of Water and Power, shows all three types of EDVs (battery, hybrid, and fuel cell) have potential roles to play as utility resources, and that ancillary services are the most lucrative use for vehicle power.

The electric power resource from vehicles is potentially quite large. In California alone, we calculate that CARB's zero emission vehicle mandates will provide 424 MW of power capacity by 2004, and 2.2 GW by 2008 (Kempton et al., 2001: 22). Looking further into the future, the Electric Power Research Institute (EPRI) predicts that power from electric-drive vehicles could reduce the global requirement for central station generation capacity by up to 20 percent by the year 2050 (EPRI 2001).

Our study assesses the technical requirements, electrical capacity, and economic value of V2G. We examined a range of EDVs to provide four types of power: baseload, peak, spinning reserves, and regulation (up and down). V2G for baseload power does not make sense, as the per-kWh cost is too high and drive train designs assume low operating time (average 1 hour/day). However, the economic value of other forms of V2G appears high, more than enough to offset the initially higher costs of electric-drive vehicles. To realize this potential, however, will require some minor design modifications to current vehicles, and some coordination of vehicle and infrastructure planning.

V2G: How it Would Work

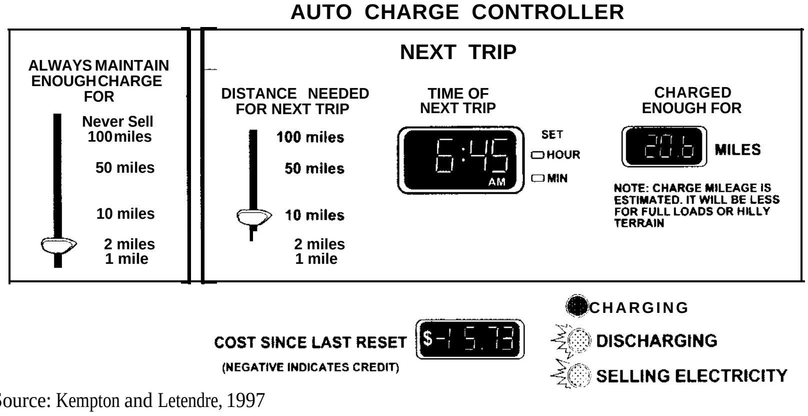
California, along with New York, Massachusetts, Vermont, and Maine, have embarked on policies to encourage the development and spread of electric-drive and low pollution vehicles. The goal is to reduce air pollution from mobile sources. These policy initiatives, advances in power electronics, and the opening of electricity markets across the country create opportunities for electric-drive vehicles 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 of battery vehicles, or the generation capacity of hybrid and fuel cell vehicles, for ancillary services and/or peak power.

Three elements are required for V2G: 1) power connection for electrical energy flow from vehicle to grid, 2) control or logical connection, needed for the grid operator to determine available capacity, request ancillary services or power from the vehicle, and to meter the result, and 3) precision certified metering on board the vehicle. For fueled vehicles (fuel cell and hybrid), a fourth element, a connection for gaseous fuel (natural gas or hydrogen), could be added so that on board fuel is not depleted.

The first V2G requirement is the power connection. Battery vehicles must already be connected to the grid in order to recharge their batteries; to add V2G capability requires little or no modification to the charging station and no modification to the cables or connectors, but on board power electronics must be designed for this purpose. AC Propulsion, Inc., a manufacturer of electric vehicle drive trains, tested the first vehicle power electronics built for this purpose in August 2000. They informally reported that designing in reverse power flow had "zero incremental cost." Propulsion's current V2G power electronics, though, with extensive control and safety to ensure no back feeding of power onto the grid during an outage, added $400 to the initial cost, assuming moderate production runs. Thus, the on board power connections and power control needed for V2G have already been demonstrated, and are now a standard feature of one company's vehicle-drive units. (The same company is currently testing demonstration vehicles that provide regulation up and regulation down in real time, controlled via a signal from the California Independent System Operator.) The ease of adapting on board conductive chargers (versus inductive chargers) to V2G was one reason CARB adopted, in June 2001, staff recommendation to make on board conductive the standard for all new EV charging stations in California. By providing V2G-capable charging stations today for battery EDVs, utilities are also building portals for V2G for future hybrid and fuel cell vehicles.

The second requirement for V2G is control, for the utility or system operator to request vehicle power exactly when needed. This is essential because vehicle power has value greater than the cost to produce it only if the buyer (the system operator) can determine the precise timing of dispatch. 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. Whether using built-in vehicle telematics, or in the interim using add-on communications, the

Figure 1: Suggested design of vehicle dashboard control, allowing driver to limit loss of range of vehicle and monitor power transactions.



Source: Kempton and Letendre, 1997

vehicle could receive a radio signal from the grid operator indicating when power is needed.

The third element of precision, certified, tamper-resistant metering, measures exactly how much power or ancillary services a vehicle did provide, and at which times. Such devices are currently available to manufacture for under $10. The telematics could again be used to transmit meter readings back to the buyer for credit to the vehicle owner's account.

Thinking about the metering of V2G expands our usual concept of a "utility meter." Electronic metering and telematics appear to have efficiency advantages in eliminating the meter reader, transfer of billing data to the central computer, and the monthly meter-read cycle. More unnerving, electronic metering and telematics also eliminates the service address! An onboard meter would transmit its own serial number or account number with its readings, via telematics, and presumably this would be billed in conjunction with a traditional metered account with a service address. A large-scale V2G system would automate accounting and reconciliation of potentially millions of small transactions, similar to the recording and billing of calls from millions of cellular phone customers. In the most refined system, the vehicle could use some form of positioning (either GPS or the cell-phone positioning now required for 911), or an electronic link like the Bluetooth system, in order to automatically determine which tied-down traditional meter it is plugged in to. Thus, the mobile-metered kWhs or ancillary services would be added or subtracted to the amount registered on the fixed-meter to reconcile both billing amounts. On board metering and verification of where the vehicle is plugged in 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. However, since the vehicle will often be plugged into the owner's building meter anyway, these are refinements that could be saved until second-generation V2G systems.

The system operator or local utility may not wish to do business with hundreds or thousands of small providers of peak power or ancillary services. In this case, a third party could aggregate EDVs into MW blocks to sell in bulk power and ancillary services markets. At 16 kW per vehicle, a 1 MW block is 63 vehicles. Potential businesses to serve as aggregators include energy service companies (ESCOs), cell-phone operators (accustomed to automated dispatch and billing of millions of individual transactions), telematics service providers working with automobile manufacturers or fleet operators, power marketers, or possibly even service-oriented local distribution companies.

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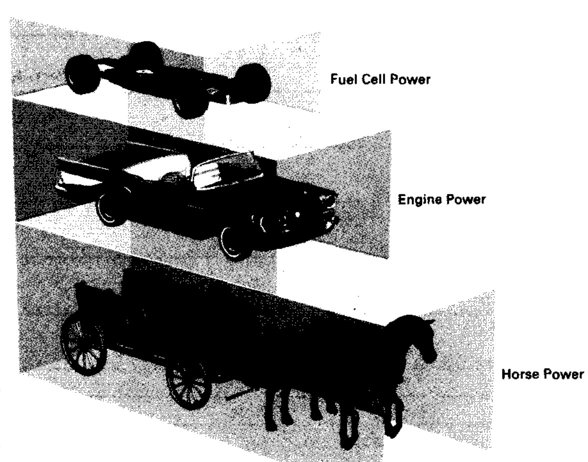
An initial concern often voiced about the V2G concept is that vehicle owners would not want to drain their vehicle's battery or an on board liquid fuel. To avoid V2G being seen as a threat to vehicle range, it is essential that the driver be able to limit any draw down so travel is not affected. Following Kempton and Letendre (1997), that can be done with a control that the driver sets according to driving needs. The power buyer must limit the degree of battery discharge or fuel tank rundown in accordance with the vehicle owners settings. An example control panel is shown in Figure 1. Whether the control is physical, on the dash, or on a Web

Evolution of Propulsion



Source: GM

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 1, 10 miles at 6:45 the next morning), and the minimum range that must always be maintained, e.g. for an emergency room trip, two miles. (As we will see in Figure 2, when providing regulation up and down rather than peak or spinning reserves, there is little impact on range.)

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 p.m.). A supposition one might have from personal experience, that the majority of the vehicles are on the road during rush hour traffic, is false. Based on road use data, we have calculated that over 92 percent of vehicles are parked and thus potentially available to the grid during any given hour, including the peak traffic hours of 3-6 PM (Kempton et al. 2001).

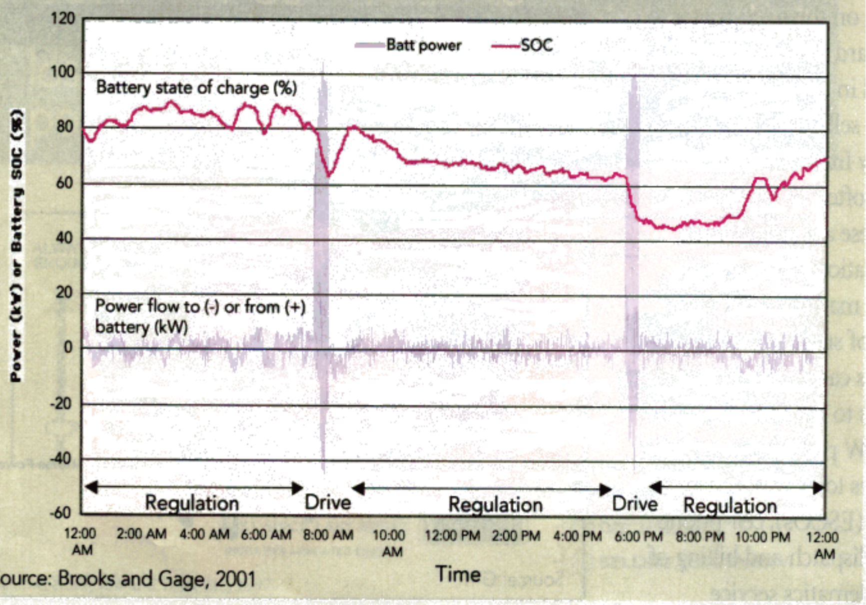
Economic Value of V2G

V2G opportunities and their financial value vary with the type of vehicle and the power market. Battery EDVs can store electricity, charging during low demand times and discharging when power is scarce and prices are high. Of potentially greater value, they can also provide ancillary services, notably regulation up, regulation down, and spinning reserves. Figure 2 illustrates power flow and battery state of charge for a battery EDV being used for regulation up and regulation down. The figure applies to a vehicle used for commuting and that is plugged in at home and work The two large spikes of power out of the battery at 8 a.m. and 5 p.m. are the commute trip (brief negative driving spikes result from regenerative braking). Since both regulation up and regulation down are provided, the net effect on battery charge is minimal, except after each commute, when regulation is controlled to provide a net charge.

Fuel cell and hybrid EDVs are a somewhat different case than battery powered EDVs in that they represent a new source of power generation. Our earlier analyses 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 values reported below derive from V2G in the day-ahead market for power (during peak periods), spinning reserves, and regulation. The values presented here were derived using market-clearing prices in California's competitive electricity markets (but do not rely on prices in the atypical year 2000).

Formulas were 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 piped gaseous fuel source is connected to the vehicle,

Figure 2: Power Flow and State of Charge
How an electric vehicle provides regulation services.



Source: Brooks and Gage, 2001

and other factors. All vehicle technical parameters were derived from production or prototype EDVs. 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 (Level 2), or near term standards that allow 16 kW (Level 3AC charger).

A key element regarding the economics of V2G is the cost of electricity generated by each EDV type. We calculate that 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 being due to the projected costs 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 vehicles, a fuel cell vehicle recharged from a natural gas reformer, and the hybrid vehicle. However, to understand the best niche for V2G power, the simple per kWh cost comparison is inadequate.

The cost of electricity from the EDVs noted above is too high to be competitive with baseload power. However, EDV power could be competitive in three other markets: peak power, 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. Grid operators maintain reserve generating capacity available for immediate power production. The term "spinning" reserves refers to generators spinning and synchronized with the grid, ready for immediate power feed into the grid. Typically, these reserves are called upon when a power plant drops off-line unexpectedly due to equipment failure. By contrast, regulation is needed throughout the day and night. Grid operators must continuously match the generation of power to the consumption. Regulation requires a generating facility that can ramp power up or down under real time control of the grid operator.

In California and a few other power markets, this function, called regulation or automatic generation control (AGC), is unbundled from power generation, and is sold separately. Even when provided internally to a company, regulation has costs—at a minimum, generators must be kept at idle or partial speed.

For each combination of vehicle and power market, we calculate the value of the power in California's electricity markets 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, increased reliability of the electric system, and other distributed benefits (i.e., reduced line losses and avoidance of transmission and distribution upgrades) 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

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Table 1: Vehicle owner's annual net profit from V2G

These are representative mid-range figures extracted from full analysis in the report.

	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)

Source: Kempton et al, 2001

Key: Net profit
(revenue - cost)

combustion engine lifetime due to additional use.

Some key V2G economic results are summarized in Table 1. From Table 1, one notices that some vehicles are better suited than others for individual power markets. 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 during off-peak hours when 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 market prices from California's now defunct Power Exchange, we find that the price was never high enough to justify selling electricity in the bulk power market during peak price periods.

Spinning reserves shows economic viability for most vehicles we analyzed, and for all those shown in Table 1. Net revenues for the spinning reserve market is particularly large for the fueled vehicles and is relatively insensitive to fuel prices because a large portion of the revenue stream is from contract payments for time available, rather than for power generated.

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. This is because regulation demands shallower cycling than peak or spinning reserves, thus causing less battery degradation. Also, batteries experience very little net discharge when providing both regulation up and regulation down. The estimated net value of regulation services from battery EDVs is several thousand dollars per year. Fuel cell vehicles and hybrids in motor-generator mode could provide only regulation up, not down, and the economics are not attractive.

Vehicles can provide ancillary services of a higher quality than currently available—fast response, available in small increments, and distributed. In a recent presentation, California Independent System Operator (ISO) staff described several possible advantages of V2G over current methods: Fast response to AGC signals, improved frequency control, less wear and tear on generators, and the possibility of frequency response service and line overload relief (Hawkins 2001). Possible concerns to study include the impact on distribution systems, making V2G visible to the EMS system, and generally, the lack of experience of system operators with distributed resources. An additional consideration by the Califonia IS0 is that V2G appears to be "an ideal complement to wind generation," since the regulation function of battery EDVs can be used to smooth out small or unexpected fluctuations in wind power production (Hawkins 2001). Thus, the demand for and value of V2G grid services may increase in the future as intermittent, renewable energy resources become a larger fraction of electric generation.

Over just a decade or two, V2G could revolutionize the ancillary services market, improve grid stability and reliability, and support increased generation from intermittent renewables.

As the V2G-capable EDV fleet grows, it will begin to saturate existing ancillary service markets. We estimate that in California the 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 we currently project. These vehicle saturation 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.

Conclusions

Overall, we conclude that all three types of EDVs—battery, hybrid, and fuel cell—could become a significant component of the nation's 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 modeling approach presented here. Also, some policy review would be helpful now. From the electric industry side, it would be appropriate to review rate structures and interconnect and safety standards in order to assess changes or additions appropriate for V2G power. Interconnection standards are currently being addressed to accommodate emerging distributed energy technologies (e.g., photovoltaics, stationary fuel cells, and micro-turbines). Charging station infrastructure planning should similarly be reviewed for its application to V2G power (as CARB has already done for California).

Individual utilities acquiring electric-drive vehicle fleets might start by reviewing their buying specifications. With the low incremental cost of adding V2G at the design stage—and with products already on the market—now may be the time to add V2G as a specification for new purchases. Utilities may start to ask, why not have our fleet of customer service or meter-reader vehicles providing regulation services while parked? If experience with utility-fleet vehicles providing V2G is positive, the next questions might be: How much vehicle ancillary service do we want to acquire in total? Do we want an aggregator to sell us MW blocks, or is aggregation an interesting opportunity for one of our business units?

Over just a decade or two, V2G could revolutionize the ancillary services market, improve grid stability and reliability, and support increased generation from intermittent renewables. The associated revenue stream could make electric-drive vehicles more attractive to buyers. These synergistic developments could have substantial benefits to the electric industry, to the environment, and to society as a whole. F

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