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Vehicle-to-grid power fundamentals: Calculating capacity and net revenue

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Abstract

As the light vehicle fleet moves to electric drive (hybrid, battery, and fuel cell vehicles), an opportunity opens for "vehicle-to-grid" (V2G) power. This article defines the three vehicle types that can produce V2G power, and the power markets they can sell into. V2G only makes sense if the vehicle and power market are matched. For example, V2G appears to be unsuitable for baseload power—the constant round-the-clock electricity supply—because baseload power can be provided more cheaply by large generators, as it is today. Rather, V2G's greatest near-term promise is for quick-response, high-value electric services. These quick-response electric services are purchased to balance constant fluctuations in load and to adapt to unexpected equipment failures; they account for 5–10% of electric cost—$ 12 billion per year in the US. This article develops equations to calculate the capacity for grid power from three types of electric drive vehicles. These equations are applied to evaluate revenue and costs for these vehicles to supply electricity to three electric markets (peak power, spinning reserves, and regulation). The results suggest that the engineering rationale and economic motivation for V2G power are compelling. The societal advantages of developing V2G include an additional revenue stream for cleaner vehicles, increased stability and reliability of the electric grid, lower electric system costs, and eventually, inexpensive storage and backup for renewable electricity.

Keywords: Electric vehicle; Fuel cell; Plug-in hybrid; Vehicle-to-grid power; Ancillary services; V2G

1. Introduction

The electric power grid and light vehicle fleet are exceptionally complementary as systems for managing energy and power. We compare these two systems briefly to introduce this article, and in more depth (with calculations and references) in a companion article [1]. The power grid has essentially no storage (other than its 2.2% capacity in pumped storage [2]), so generation and transmission must be continuously managed to match fluctuating customer load. This is now accomplished primarily by turning large generators on and off, or ramping them up and down, some on a minute-by-minute basis. By contrast, the light vehicle fleet inherently must have storage, since a vehicle's prime mover and fuel must be mobile. Vehicles are designed to have large and frequent power fluctuations, since that is in the nature of roadway driving. The high capital cost of large generators motivates high use (average 57% capacity factor). By contrast, personal vehicles are cheap per unit of power and are utilized only 4% of the time for transportation, making them potentially available the remaining 96% of time for a secondary function.

Our comparison of the electric system with the light vehicle fleet becomes of practical interest as society contemplates electric-drive vehicles (EDVs), that is, vehicles with an electric-drive motor powered by batteries, a fuel cell, or a hybrid drivetrain. EDVs can generate or store electricity when parked, and with appropriate connections can feed power to the grid—we call this vehicle-to-grid power or V2G power. The relatively lower capital costs of vehicle power systems and the low incremental costs to adapt EDVs to produce grid power suggest economic competitiveness with centralized

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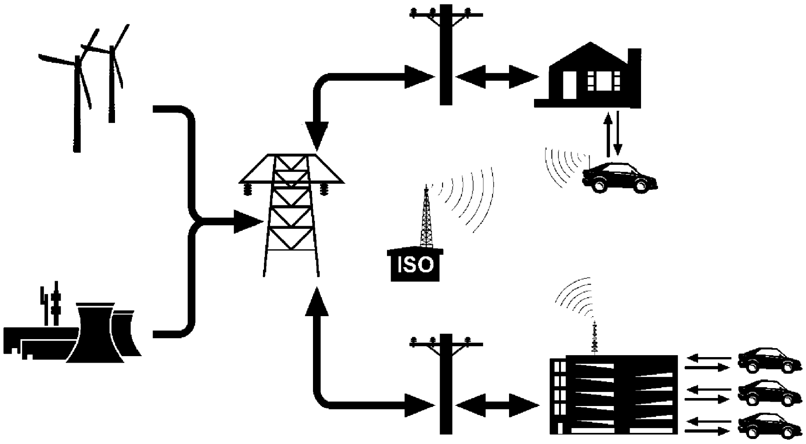

Fig. 1. Illustrative schematic of proposed power line and wireless control connections between vehicles and the electric power grid.

power generation. On the other hand, compared with large generators, vehicles have low durability (about 1/50 of the design operating hours) and high cost per kWh of electric energy, suggesting that V2G power should be sold only to high-value, short-duration power markets. As we'll describe shortly, these power markets include regulation, spinning reserves, and peak power.

We begin the article with a description of the V2G concept. Section 3 describes the three vehicle types, followed in Section 4 by a description of four electricity markets and their suitability to purchase V2G power. Finally, general equations are developed for capacity, cost, and revenue of electricity from EDVs. A companion article, "vehicle-to-grid power implementation" [1] more comprehensively compares the vehicle fleet and electric grid, proposes strategies to reconcile the differing needs of driver and grid operator, suggests business models, and outlines the steps to V2G implementation.

2. The concept of V2G

The basic concept of vehicle-to-grid power is that EDVs provide power to the grid while parked. The EDV can be a battery–electric vehicle, fuel cell vehicle, or a plug-in hybrid. Battery EDVs can charge during low demand times and discharge when power is needed. Fuel cell EDVs generate power from liquid or gaseous fuel. Plug-in hybrid EDVs can function in either mode.

Each vehicle must have three required elements: (1) a connection to the grid for electrical energy flow, (2) control or logical connection necessary for communication with the grid operator, and (3) controls and metering on-board the vehicle. These elements vary somewhat with the business model and are described in more detail in the companion article [1]. Fig. 1 schematically illustrates connections between vehicles and the electric power grid. Electricity flows one-way from generators through the grid to electricity users. Electricity flows back to the grid from EDVs, or with battery EDVs, the flow is two ways (shown in Fig. 1 as lines with two arrows). The control signal from the grid operator (labeled ISO, for Independent System Operator) could be a broadcast radio signal, or through a cell phone network, direct Internet connection, or power line carrier. In any case, the grid operator sends requests for power to a large number of vehicles. The signal may go directly to each individual vehicle, schematically in the upper right of Fig. 1, or to the office of a fleet operator, which in turn controls vehicles in a single parking lot, schematically shown in the lower right of Fig. 1, or through a third-party aggregator of dispersed individual vehicles' power (not shown). (The grid operator also dispatches power from traditional central-station generators using a voice telephone call or a T1 line, not shown in Fig. 1.)

3. Three EDVs: battery, fuel cell, and hybrid

Three types of EDVs are relevant to the V2G concept: (1) battery, (2) fuel cell, and (3) hybrid. All are EDVs, meaning that they use an electric motor to provide all or part of the mechanical drive power. All but the smallest EDV electric motors are driven by power electronics with sinusoidal AC at varying frequencies, with the capability of being set to the grid's 60 Hz. Thus, most of the power conditioning needed for grid power is already built-in and paid for as part of the transportation function. (Very small electric vehicles, such as a typical golf cart or neighborhood electric vehicle, typically use direct current motors and would require substantial additional power electronics to provide 60 Hz AC.)

3.1. Battery EDVs

Battery vehicles store energy electrochemically in the batteries, with lead-acid currently cheapest but with nickel metal-hydride (NiMH), lithium-ion, and lithium-metal-polymer batteries becoming more competitive due to longer cycle life, smaller size and lower weight. Operationally, they plug in to charge their batteries and unplug to drive. Battery vehicles must have grid connections for charging, so the incremental costs and operational adjustments to add V2G are minimal.

3.2. Fuel cell EDVs

Fuel cell EDVs typically store energy in molecular hydrogen (H_2), which feeds into a fuel cell along with atmospheric oxygen, producing electricity with heat and water as by-products. Multiple options for on-board storage or production of hydrogen are under development, including pressurizing the H_2 gas, binding it to metals, and on-board production of H_2 from natural gas, methanol, gasoline or another fuel. Currently, distribution infrastructure, on-board storage of hydrogen, and conversion losses are all substantial problems that leave open the question as to whether fuel cell light vehicles will be practical and cost-effective [3,4].

Fuel cell EDVs used for V2G would produce electricity from the fuel cell, converted to 60 Hz AC by the on-board power electronics and supplied to the grid. Any cost of grid connection is outside the transportation function, so in this analysis, the cost and driver inconvenience of plugging in a fuel cell vehicle are attributed to V2G costs.

3.3. Hybrid EDVs

Contemporary hybrid vehicles use an internal combustion (IC) engine whose shaft drives a generator. A small battery buffers the generator and absorbs regenerative braking. The battery and generator power one or more electric motors that drive the wheels, possibly in conjunction with direct shaft power from the IC engine. More conceptually, a hybrid has one power system with large energy storage—for range—and a second with high power output and discharge-recharge capability—for acceleration and regenerative braking. For simplicity, we discuss here only the contemporary hybrids with internal combustion engine and battery, although the principles and equations we develop apply to any hybrid type.

The hybrids being mass-produced at the time this article is being written (the Toyota Prius, Honda Insight, and Civic-hybrid) have much larger mechanical than electric drive power (approximately 75–25%), small batteries (1–2 kWh) and no electrical connection to the grid. This combination makes today's most-common hybrids impractical for V2G power. The coming "plug-in hybrid" makes two important additions: an enlarged battery and an electric plug to recharge [5], like the preproduction DaimlerChrysler Sprinter [6]. The larger battery (6 kWh or more) allows running in all-electric mode for at least 20 miles, a mode having advantages of lower fuel cost, home refueling convenience, and zero tailpipe emissions.

In relation to V2G, the plug-in hybrid has a grid connection for its transportation function and a large enough battery to provide V2G from the battery alone. In this article, our analysis of hybrids covers only the plug-in hybrid. The plug-in hybrid can provide V2G either as a battery vehicle (that is, not using the IC engine when doing V2G), or as a motor-generator (using fuel while parked to generate V2G electricity).

We next define the relevant power markets, and then develop the basic equations for V2G.

4. Power markets

Electricity is grouped in several different markets with correspondingly different control regimes. Here we discuss four of them—baseload power, peak power, spinning reserves, and regulation—which differ in control method, response time, duration of the power dispatch, contract terms, and price. We focus particularly on spinning reserves and regulation, which must deliver power within minutes or seconds of a request. All these electricity resources are controlled in real-time by either an integrated electric utility or an Independent System Operator —to refer to either of these parties here we use the simpler term "grid operator." Our companion article discusses an additional near future electricity market, storage of renewable energy, which can be approximated as combinations of the existing markets.

The terminology and specifics of grid control differ across countries and even across jurisdictions within federalized countries. Although we draw on US standards, markets, and terminology [7,8], the same basic types of control and power response are needed in any large power grid.

4.1. Baseload power

Baseload power is provided round-the-clock. In the US this typically comes from large nuclear or coal-fired plants that have low costs per kWh. Baseload power is typically sold via long term contracts for steady production at a relatively low per kW price. V2G has been studied across multiple markets [9–13], showing that EDVs cannot provide baseload power at a competitive price. This is because baseload power hits the weaknesses of EDVs—limited energy storage, short device lifetimes, and high energy costs per kWh—while not exploiting their strengths—quick response time, low standby costs, and low capital cost per kW.

4.2. Peak power

Peak power is generated or purchased at times of day when high levels of power consumption are expected—for example, on hot summer afternoons. Peak power is typically generated by power plants that can be switched on for shorter periods, such as gas turbines. Since peak power is typically needed only a few hundred hours per year, it is economically sensible to draw on generators that are low in capital cost, even if each kWh generated is more expensive. Our earlier studies have shown that V2G peak power may be economic under some circumstances [9,11,14,15]. The required duration of peaking units can be 3–5 h, which for V2G is possible but difficult due to on-board storage limitations. Vehicles could overcome this energy-storage limit if power was drawn sequentially from a series of vehicles, or if there were home refueling (say, with natural gas), options analyzed elsewhere [14] but not covered here.

4.3. Spinning reserves

Spinning reserves refers to additional generating capacity that can provide power quickly, say within 10 min, upon request from the grid operator. Generators providing spinning reserves run at low or partial speed and thus are already synchronized to the grid. (Spinning reserves are the fastest response, and thus most valuable, type of operating reserves; operating reserves are "extra generation available to serve load in case there is an unplanned event such as loss of generation" [16].)

Spinning reserves are paid for by the amount of time they are available and ready. For example, a 1 MW generator kept "spinning" and ready during a 24-h period would be sold as 1 MW-day, even though no energy was actually produced. If the spinning reserve is called, the generator is paid an additional amount for the energy that is actually delivered (e.g., based on the market-clearing price of electricity at that time). The capacity of power available for 1 h has the unit MW-h (meaning 1 MW of capacity is available for 1 h) and should not be confused with MWh, an energy unit that means 1 MW is flowing for 1 h.

These contract arrangements are 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. Contracts for spinning reserves limit the number and duration of calls, with 20 calls per year and 1 h per call typical maxima [17]. As spinning reserves dispatch time lengthens, from the typical call of 10 min to the longest contract requirement, 2 h, fueled vehicles gain advantage over battery vehicles because they generally have more energy storage capacity and/or can be refueled quickly for driving if occasionally depleted by V2G.

Spinning reserves, along with regulation (discussed next), are forms of electric power referred to as "ancillary services" or A/S. Ancillary services account for 5–10% of electricity cost, or about $ 12 billion per year in the U.S. [18,19], with 80% of that cost going to regulation [20].

4.4. Regulation

Regulation, also referred to as automatic generation control (AGC) or frequency control, is used to fine-tune the frequency and voltage of the grid by matching generation to load demand. Regulation must be under direct real-time control of the grid operator, with the generating unit capable of receiving signals from the grid operator's computer and responding within a minute or less by increasing or decreasing the output of the generator. Depending on the electricity market and grid operator, regulation may overlap or be supplemented by slower adjustments, including "balancing service" (intrahour and hourly) and/or "load following." Here, we analyze only regulation, but V2G may be appropriate for some of these other services.

Some markets split regulation into two elements: one for the ability to increase power generation from a baseline level, and the other to decrease from a baseline. These are commonly referred to as "regulation up" and "regulation down", respectively. For example, if load exceeds generation, voltage and frequency drop, indicating that "regulation up" is needed. A generator can contract to provide either regulation up, or regulation down, or both over the same contract period, since the two will never be requested at the same time. Markets vary in allowed combinations of up and down, for example, PJM Interconnect requires contracts for an equal amount of regulation up and down together, whereas California Independent System Operator (CAISO) is more typical in allowing contracts for just one, or for asymmetrical amounts (e.g., 1 MW up and 2 MW down).

Regulation is controlled automatically, by a direct connection from the grid operator (thus the synonym "automatic generation control"). Compared to spinning reserves, it is called far more often (say 400 times per day), requires faster response (less than a minute), and is required to continue running for shorter durations (typically a few minutes at a time).

The actual energy dispatched for regulation is some fraction of the total power available and contracted for. We shall show that this ratio is important to the economics of V2G, so we define the "dispatch to contract" ratio as

$$R_{\mathrm{d-c}} = \frac{E_{\mathrm{disp}}}{P_{\mathrm{contr}}\, t_{\mathrm{contr}}} \tag{1}$$

where $R_{\mathrm{d-c}}$ is the dispatch to contract ratio (dimensionless), E_{disp} the total energy dispatched over the contract period (MWh), P_{contr} the contracted capacity (MW), and t_{contr} is the duration of the contract (h). $R_{\mathrm{d-c}}$ is calculated separately for regulation up or down.

We have found that this $R_{\mathrm{d-c}}$ ratio is not tracked or recorded. We requested information on it from six US utilities and grid operators, none of whom recorded it nor knew its approximate value; most could not easily provide the quantities needed for us to calculate it [14]. We therefore resorted to calculating this ratio ourselves from a short period of intensively monitored data. Using data from CAISO of frequency regulation needed during the course of 1 day (unpublished data from Alec Brooks) and modeling the response of one EDV, we obtained $R_{\mathrm{d-c}}$ of 0.08. We conservatively use 0.10 in our analysis ("conservative" because higher $R_{\mathrm{d-c}}$ increases the cost of V2G).

5. Power capacity of V2G

How much V2G power can a vehicle provide? Three independent factors limit V2G power: (1) the current-carrying capacity of the wires and other circuitry connecting the vehicle through the building to the grid, (2) the stored energy in the vehicle, divided by the time it is used, and (3) the rated maximum power of the vehicle's power electronics. The lowest of these three limits is the maximum power capability of the V2G configuration. We develop here analysis for factors 1 and 2, since they are generally much lower than 3.

We shall first develop equations to calculate the limit on V2G by line capacity. Second, we develop equations to calculate the limit on V2G power by the vehicle's stored energy, divided by the dispatch time. We then calculate several examples of limits, using two vehicles, across the markets of regulation services, spinning reserves, and peak power.

5.1. Power limited by line

Vehicle-internal circuits for full-function electric vehicles are typically upwards of 100 kW. For comparison, a US home maximum power capacity is typically 20–50 kW, with an average draw closer to 1 kW. To calculate the building-wiring maximum, one needs only the voltage and rated ampere capacity of the line:

$$P_{\text{line}} = VA \tag{2}$$

where P_{line} is power limit imposed by the line in watts (here usually expressed in kW), V the line voltage, and A is the maximum rated current in amperes. For example in the US, with home wiring at 240 V AC, and a typical 50 A circuit rating for a large-current appliance such as an electric range, the power at the appliance is 50 A × 240 V so Eq. (2) yields a line capacity of 12 kW maximum for this circuit. Based on typical US home circuits, some would be limited to 10 kW, others to 15 kW as the P_{line} limit. For a commercial building, or a residential building after a home electrical service upgrade (at additional capital cost), the limit could be 25 kW or higher. The assumptions behind these figures are discussed in detail in our companion article ([1], Appendices A.1 and A.2).

On the vehicle side, most existing (pre-V2G) battery vehicle chargers use the National Electrical Code (NEC) "Level 2" standard of 6.6 kW. The first automotive power electronics unit designed for V2G and in production, by AC Propulsion, provides 80 A in either direction, thus, by Eq. (2), 19.2 kW at a residence (240 V) or 16.6 kW at a commercial building (208 V). This V2G unit has been used in one prototype plug-in hybrid and several battery electric vehicles [20–22].

5.2. Power limited by vehicle's stored energy

The previous section analyzed V2G power as limited by the line capacity. The other limit on V2G power is the energy stored on-board divided by the time it is drawn. More specifically, this limit is the onboard energy storage less energy used and needed for planned travel, times the efficiency of converting stored energy to grid power, all divided by the duration of time the energy is dispatched. This is calculated in Eq. (3)

$$P_{\text{vehicle}} = \frac{\left(E_{\text{s}} - \frac{d_{\text{d}}+d_{\text{rb}}}{\eta_{\text{veh}}}\right)\eta_{\text{inv}}}{t_{\text{disp}}} \tag{3}$$

where P_{vehicle} is maximum power from V2G in kW, E_{s} the stored energy available as DC kWh to the inverter, d_{d} the distance driven in miles since the energy storage was full, d_{rb} the distance in miles of the range buffer required by the driver (explained below), η_{veh} the vehicle driving efficiency in miles/kWh, η_{inv} the electrical conversion efficiency of the DC to AC inverter (dimensionless), and t_{disp} is time the vehicle's stored energy is dispatched in hours.

In a specific application of Eq. (3), d_{d} would depend on the driving pattern, the vehicle type (e.g., battery EDVs may be recharged at work), and the driver's strategies for being prepared to sell power. The value of d_{d} we use in examples here derives from the average daily vehicle miles traveled per US driver of 32 miles [23]. We assume here that half the average daily vehicle miles would have been depleted when the vehicle is parked and power is requested (i.e. $d_{\text{d}} = 16$ miles). The d_{rb} refers to the "range buffer," the minimum remaining range required by the driver. It is not an engineering measure of the vehicle but is specified by the driver or fleet operator who will determine d_{rb} based on, for example, the return commute or the distance reserved for an unanticipated trip to a convenience store or hospital. Based on interviews with California drivers, Kurani et al. [24] found that 20 miles was sufficient for most drivers. We use 20 miles for d_{rb} for battery and fuel cell vehicles; plug-in hybrids running V2G from their batteries can drain the battery and use fuel if driving is needed before recharge, so we assume $d_{\text{rb}} = 0$ for plug-in hybrids.

The time dispatched (t_{disp}) will depend on the electricity market. For peak power, a reasonable value for t_{disp} is 4 h. For spinning reserves, although typical dispatches are 10 min, we calculate based on $t_{\text{disp}} = 1$ h here to insure that a 1-h contract requirement can be met. For regulation up and down, power in a battery vehicle can flow both ways; although regulation dispatch is typically only 1–4 min, we use t_{disp} of 20 min to allow for the possibility of a long or repeated regulation up sequence.[1]

The fuel cell vehicle, or hybrid in motor-generator mode, can provide only regulation up (power flows from vehicle to grid), not regulation down (power from grid to vehicle), so it has no analogy to the battery EDV's recharge during regulation down.[2] Thus, for example, a fuel cell vehicle parked

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[1] Some ISOs require that power plants contracted for regulation also provide blocks of power, up to 30 min, via the regulation signal. V2G-supplied regulation (as well as some forms of power plant-supplied regulation) would be most effective if such blocks were not dispatched within regulation contracts, and we do not include such blocks in t_{disp} for regulation.

[2] In theory, fuel cells can be run in both directions, but no practical two-way cell can be built from current materials. A fuel cell vehicle parked at an electrolyzer could be configured for regulation down and regulation up, but this configuration is so inefficient in energy conversions compared to a

Table 1
Available power, P_{vehicle} from three EDV's at four dispatch times (t_{disp}), calculated from Eq. (3) and parameters in text

Vehicle type	Available power P_{vehicle} (kW)			
	Spin. res. (1 h)	Reg. up (1.4 h)	Reg. up + down (continuous per 0.33 h)[a]	Peak power (4 h)
RAV4 EV (battery)	7.0	5	21.0 + 21.4	1.75
Sprinter (hybrid, using battery only)	2.2	1.6	6.6 + 40.5	0.55
P2000 (fuel cell, added H_2 storage)	36.0	25.7	–	9.0

[a] Rather than Eq. (3), regulation down should be calculated as Eq. (3′): $P_{\mathrm{vehicle}} = (d_{\mathrm{d}}/\eta_{\mathrm{veh}} - E_{\mathrm{recharge}})/(\eta_{\mathrm{charger}}\, t_{\mathrm{disp}})$, where η_{charger} is efficiency of charger, and E_{recharge} is recharged kWh since plugging in. Here we assume $\eta_{\mathrm{charger}} = 0.9$ and $E_{\mathrm{recharge}} = 0$.

14 h and providing regulation up only, assuming $R_{\mathrm{d-c}}$ of 0.10, would have effective $t_{\mathrm{disp}} = 1.4$ h.

Power capacity of V2G is determined by the lower of the two limits, P_{line} or P_{vehicle}. We show how this is calculated for each type of vehicle: a battery EDV, the Toyota RAV4 EV, a plug-in hybrid, the preproduction DaimlerChrysler Sprinter, and a fuel cell EDV, the prototype Prodigy P2000. (There are newer examples of battery and fuel cell vehicles, e.g., the Volvo 3CC and Honda FCX, but our example vehicles are well documented and demonstrate the calculation methods.)

The Toyota RAV4 EV has a NiMH battery with 27.4 kWh capacity, only 21.9 kWh of which we consider available (E_{s} in Eq. (3)) because NiMH should not be discharged below 80% depth-of-discharge (DoD). The rated vehicle efficiency (η_{veh}) is 2.5 miles/kWh, and we assume an efficient inverter of η_{inv} of 0.93.

The plug-in hybrid is the Phase II preproduction DaimlerChrysler Sprinter, a 3.88-t panel van [6]. The hybrid Sprinter will have gasoline or diesel options for the internal-combustion engine, plus a 14.4 kWh Saft Li-Ion battery pack. This battery can be discharged 100% without excessive damage. From a specified all-electric range of 30 km [6], we calculate electric driving efficiency of 1.33 miles/kWh. Here we assume V2G from the battery only; another operational V2G mode not calculated here would be running the motor-generator to generate power while the car is parked and plugged-in.

The example fuel cell vehicle is the prototype Prodigy P2000. We assume the Ovonics metal hydride storage at 3.5 kg of H_2 rather than the Prodigy's 2 kg of compressed hydrogen. The 3.5 kg represent 116.5 kWh at the lower heating value, but with the P2000's 44% efficient fuel cell system E_{s} is equal to 51.3 kWh electricity available from storage. The vehicle efficiency (η_{veh}) is 2.86 miles/kWh.

The values for P_{vehicle} for different electricity markets for the two EDVs are calculated using Eq. (3) and listed in Table 1. For all vehicles, we assume d_{d} of 16 miles and an efficient inverter of $\eta_{\mathrm{inv}} = 0.93$.

Several observations can be made from Table 1. The fuel cell vehicle can provide more power for spinning reserves and peak, whereas the battery and plug hybrid vehicles can provide more for regulation because they provide both regulation up and down. For example, the RAV4 provides 21 kW regulation up plus 21 kW down, that is 42 kW of revenue from regulation; the P2000 provides 25.7 kW regulation up only. Comparing the battery and plug-in hybrid, note that our assumed 16 miles of electric-mode driving almost exhaust the Sprinter's smaller battery capacity (given lower η_{veh}, and despite assuming $d_{\mathrm{rb}} = 0$). This leaves only 2.2 kW for 1 h spinning reserve. In some situations, such as V2G being used for wind backup, it is reasonable to assume advance notice on need for spinning reserves, so that hybrid driving could be done in constant-recharge mode, leaving full battery capacity available.

Available V2G power is the lesser of P_{vehicle}, from Table 1, and P_{line}, from Eq. (2). If we assume a residential line limit of 15 kW, Table 1 shows that these battery and hybrid vehicles are limited by storage (P_{vehicle}) for spinning reserves and peak power, and by P_{line} for regulation services. By contrast, the fuel cell vehicle has high P_{vehicle} values, as shown in Table 1, thus the assumed 15 kW P_{line} would limit it for two of the three markets. (These limits in turn might motivate upgrade to a 20 or 25 kW line connection.)

6. Revenue versus cost of V2G

The economic value of V2G is the revenue minus the cost. Equations for each are derived in the next two sections, followed by examples.

6.1. Revenue equations

The formulas for calculating revenue depend on the market that the V2G power is sold into. For markets that pay only for energy, such as peak power and baseload power, revenue is simply the product of price and energy dispatched. This can also be expanded, since energy is $P\,t$,

$$r = p_{\mathrm{el}}\, E_{\mathrm{disp}} = p_{\mathrm{el}}\, P_{\mathrm{disp}}\, t_{\mathrm{disp}} \tag{4}$$

where r is the total revenue in any national currency (we use \$ as a shorthand for the appropriate currency), p_{el} the market rate of electricity in \$/kWh, P_{disp} the power dispatched in kW (for peak power P_{disp} is equal to P, the power available for V2G), and t_{disp} is the total time the power is dispatched

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battery [25] that it would not be economically feasible for a high-throughput service like regulation.

in hours. (Throughout, we shall use capital P for power and lower-case p for price.) On an annual basis, peak power revenue is computed by summing up the revenue for only those hours that the market rate (p_{el}) is higher than the cost of energy from V2G (c_{en}, discussed later).

For spinning reserves and regulation services the revenue derives from two sources: a "capacity payment" and an "energy payment." The capacity payment is for the maximum capacity contracted for the time duration (regardless of whether used or not). For V2G, capacity is paid only if vehicles are parked and available (e.g., plugged-in, enough fuel or charge, and contract for this hour has been confirmed). The energy payment is for the actual kWh produced; this term is equivalent to Eq. (4). Eq. (5) calculates revenue from either spinning reserves or regulation services, with the first term being the capacity payment and the second term the energy payment.

$$r = (p_{\mathrm{cap}}\, P\, t_{\mathrm{plug}}) + (p_{\mathrm{el}}\, E_{\mathrm{disp}}) \tag{5}$$

where p_{cap} is the capacity price in \$/kW-h, p_{el} is the electricity price in \$/kWh, P is the contracted capacity available (the lower of P_{vehicle} and P_{line}), t_{plug} is the time in hours the EDV is plugged in and available, and E_{disp} is the energy dispatched in kWh. (Note that the capacity price unit, \$/kW-h, means \$ per kW capacity available during 1 h—whether used or not—whereas energy price units are the more familiar \$/kWh.)

For spinning reserves, E_{disp} can be calculated as the sum of dispatches,

$$E_{\mathrm{disp}} = \sum_{i=1}^{N_{\mathrm{disp}}} P_{\mathrm{disp}}\, t_{\mathrm{disp}} \tag{6}$$

where N_{disp} is the number of dispatches, P_{disp} the power of each (presumably equal to the vehicle capacity P), and t_{disp} is the duration of each dispatch in hours. A typical spinning reserves contract sets a maximum of 20 dispatches per year and a typical dispatch is 10 min long, so the total E_{disp} will be rather small.

For regulation services, there can be 400 dispatches per day, varying in power (P_{disp}). In production, these would likely be metered as net energy over the metered time period, E_{disp} in Eq. (5). For this article, to estimate revenue we approximate the sum of P_{disp} by using the average dispatch to contract ratio ($R_{\mathrm{d\text{–}c}}$) defined by Eq. (1), and rearrange Eq. (6) as Eq. (7)

$$E_{\mathrm{disp}} = R_{\mathrm{d\text{–}c}}\, P\, t_{\mathrm{plug}} \tag{7}$$

Thus, for forecasting regulation services revenue (in a forecast, energy is estimated, not metered), Eq. (7) is substituted into Eq. (5), becoming Eq. (8),

$$r = p_{\mathrm{cap}}\, P\, t_{\mathrm{plug}} + p_{\mathrm{el}}\, R_{\mathrm{d\text{–}c}}\, P\, t_{\mathrm{plug}} \tag{8}$$

6.2. *Cost equations*

The cost of V2G is computed from purchased energy, wear, and capital cost. The energy and wear for V2G are those incurred above energy and wear for the primary function of the vehicle, transportation. Similarly, the capital cost is that of additional equipment needed for V2G but not for driving. Assuming an annual basis, the general formula for cost is

$$c = c_{\mathrm{en}}\, E_{\mathrm{disp}} + c_{\mathrm{ac}} \tag{9}$$

where c is the total cost per year, c_{en} the cost per energy unit produced (calculated below), E_{disp} the electric energy dispatched in the year, and c_{ac} is the annualized capital cost (calculated below).

For spinning reserves, again E_{disp} would be computed by Eq. (6) and used in Eq. (9) to obtain annual cost.

For regulation, substituting Eq. (7) for E_{disp} into Eq. (9), the total annual cost to provide regulation is

$$c = c_{\mathrm{en}}\, R_{\mathrm{d\text{–}c}}\, P\, t_{\mathrm{plug}} + c_{\mathrm{ac}} \tag{10}$$

where c_{en} is the per kWh cost to produce electricity (also used in Eq. (9)). The equation for c_{en} includes a purchased energy term and an equipment degradation term

$$c_{\mathrm{en}} = \frac{c_{\mathrm{pe}}}{\eta_{\mathrm{conv}}} + c_{\mathrm{d}} \tag{11}$$

where c_{pe} is the purchased energy cost, and c_{d} is the cost of equipment degradation (wear) due to the extra use for V2G, in \$/kWh of delivered electricity. The purchased energy cost c_{pe} is the cost of electricity, hydrogen, natural gas, or gasoline, expressed in the native fuel cost units (e.g., \$/kg H_2), and η_{conv} is the efficiency of the vehicle's conversion of fuel to electricity (or conversion of electricity through storage back to electricity). The units of η_{conv} are units of electricity per unit of purchased fuel. Thus Eq. (11)'s computed c_{en}, the cost of delivering a unit of electricity, is expressed in \$/kWh regardless of the vehicle's fuel.

Degradation cost, c_{d}, is calculated as wear for V2G due to extra running time on a hybrid engine or fuel cell, or extra cycling of a battery. For a fuel cell vehicle or hybrid running in motor-generator mode, degradation cost is

$$c_{\mathrm{d}} = \frac{c_{\mathrm{engine}}}{L_{\mathrm{h}}} \tag{12}$$

where c_{engine} is the capital cost per kW of the engine or fuel cell, including replacement labor in \$/kWh, and L_{h} is the engine or fuel cell lifetime in hours. The degradation cost, c_{d} is thus expressed in \$/kWh. For a battery vehicle, c_{d} is

$$c_{\mathrm{d}} = \frac{c_{\mathrm{bat}}}{L_{\mathrm{ET}}} \tag{13}$$

where c_{bat} is battery capital cost in \$ (including replacement labor), and L_{ET} is battery lifetime throughput energy in kWh for the particular cycling regime (discussed below).

The cost of degradation is zero if the vehicle life is less than the engine, fuel cell, or battery life due to driving plus V2G degradation, or if the battery's shelf life is reached before the degradation/wear life,

$$c_{\mathrm{d}} = 0 \tag{14}$$

Table 2
Calculation of revenue from a RAV4 EV providing regulation

Revenue parameters	Value	Comments
P (kW)	15	Use P_{line} because $P_{\text{line}} < P_{\text{vehicle}}$ (Table 1)
p_{cap} ($/kW-h)	0.04	CAISO 2003 market prices [28]: $ 0.02/kW-h for regulation up capacity plus the same for regulation down
p_{el} ($/kWh)	0.10	Retail electricity price[a]
t_{plug} (h/year)	6570	Assume vehicle plugged in 18 h daily, so t_{plug} = 18 h/day × 365 day/year
$R_{\text{d-c}}$	0.10	See text with Eq. (1)
r ($)	4928	Revenue, result by Eq. (8)

[a] Retail electric rates are used on the RAV4 for revenue and subsequently for cost, so the net effect is paying retail for round-trip electrical losses.

Battery lifetime is often expressed in cycles, measured at a specific depth-of-discharge. For Eq. (13), we express battery life in energy throughput, L_{ET}, defined as

$$L_{\text{ET}} = L_{\text{c}}\, E_{\text{s}}\, \text{DoD} \tag{15}$$

where L_{c} is lifetime in cycles, E_{s} the total energy storage of the battery, and DoD is the depth-of-discharge for which L_{c} was determined.

Shallow cycling has less impact on battery lifetime than the more commonly reported deep cycling. For example, test data on a Saft lithium-ion battery show a 3000-cycle lifetime at 100% discharge, and a 1,000,000-cycle lifetime for cycling at 3% discharge [26]. Using Eq. (15), the 3% cycle achieves 10 times the lifetime kWh throughput. For lead-acid and NiMH batteries, Miller and Brost [27] present similar results; their Fig. 8 suggests that batteries at 3% DoD yield about 28 times the throughput as they do at 80% DoD.

Deep cycling approximates V2G battery use for peak power or spinning reserves at longer dispatches, whereas the 3% cycling is closer to that of regulation services. Here we base battery life parameters on 80% discharge test cycle for peak power or spinning reserves, and approximate lifetime energy throughput at three times that amount when V2G is used for regulation services. The three times approximation is conservative—the above data suggest a 10 times or greater increase in lifetime throughput at the low DoD cycling regimes.

To make financial decisions, calculations are typically made on a yearly basis and capital cost is annualized. One way to annualize a single capital cost is to multiply it by the capital recovery factor (CRF) as expanded in Eq. (16)

$$c_{\text{ac}} = c_{\text{c}}\,\text{CRF} = c_{\text{c}}\frac{d}{1-(1+d)^{-n}} \tag{16}$$

Where c$_{\text{ac}}$ is the annualized capital cost in $/year, c_{c} the total capital cost in $, d the discount rate, and n is the number of years the device will last.

6.3. *Example: battery EDV providing regulation services*

For a sample calculation of revenue and cost, we use the same RAV4 EV discussed earlier, providing regulation for the 2003 CAISO market. Revenue is calculated with Eq. (8). This vehicle's parameters for Eq. (8) are listed in Table 2 and described under "comments." The last entry is the resulting computed revenue. The total annual revenue calculated by Eq. (8) then for the RAV4 is $ 4928, with $ 3942 from capacity payments and $ 986 from energy payments.

Next we calculate costs for the RAV4 to provide regulation services, using the cost parameters in Table 3 and Eq. (10). As shown in Table 3, the annual cost for RAV4-provided regulation is $ 2374.

The net profit (revenue in Table 2 minus cost in Table 3) is $ 4928 − 2374 or $ 2554 a year. If we assume a 10 kW

Table 3
Calculation of cost of RAV4 EV providing regulation

Cost parameters	Value	Comments
c_{pe} ($/kWh)	0.10	Assume purchase at retail electric cost
η_{sys} (%)	73	Round-trip electrical efficiency, grid–battery–grid
c_{bat} ($)	9890	350 ($/kWh)[a] × 27.4 $/kWh + 10 h replacement labor × 30 ($/h)
c_{d} ($/kWh)	0.075	By Eq. (13)
c_{en} ($/kWh)	0.21	Result by Eq. (11)
L_{ET} (kWh)	131520	This NiMH battery achieves 2000 cycles under deep cycle testing (EPRI 2003). By Eq. (11), L_{ET} = 43840 kWh; for shallow DoD, we assume 3 × L_{ET} (see text).
c_{c} ($)	1900	On-board incremental costs $ 400 [29]; wiring upgrade $ 1500[b]
c_{ac} ($/year)	304	Result by Eq. (16), assuming d = 10%; n = 10 years, thus CRF = 0.16
c ($)	2374	Cost, result by Eq. (10), assuming as before P = 15 kW and t_{plug} = 6570 h

[a] Assuming annual production of 100,000 batteries per year, EPRI estimates $ 350/kWh [30].

[b] If the plug capacity in a residence is to be greater than 6.6 kW, we assume wiring costs of $ 650 for 10 kW and $ 1500 for 15 kW. We assume custom, single-home costs and attribute the additional wiring costs to V2G costs, even though there would be transportation benefits such as fast charging. Wiring upgrades to a series of plugs in a parking structure or fleet lot would be far less, as would installation in new residences.

Table 4
Revenue from fuel cell vehicle providing spinning reserves

Revenue parameters	Value	Comments
P (kW)	15	Assume $P = P_{line} = P_{disp}$
p_{cap} ($/kW-h)	0.007	CAISO spinning reserves market price average for 2003 [28]
p_{el} ($/kWh)	0.03	Assumed average spot energy price
t_{plug} (h/year)	6570	Plugged in daily, 18 (h/day) × 365 (day/year)
E_{disp} (kWh)	300	Assume 20 calls a year, each 15 kW for 1 h, per Eq. (6)
r ($)	699	Revenue, result by Eq. (5)

Table 5
Cost of fuel cell vehicle providing spinning reserves

Cost parameters	Value	Comments
c_{pe} ($/kg H_2)	5.6	High of projected hydrogen cost range [31]
c_{pe} ($/kg H_2)	1.7	Low of projected hydrogen cost range [31]
η_{conv} (kWh/kg H_2)	13.57	For fuel cell, $\eta_{conv} = \eta_{FC}\ \eta_{inv}$; $\eta_{FC} = 14.75$ kWh/kg H_2; $\eta_{inv} = 0.92$
c_d ($/kWh)	0.0025	Mid-range of degradation estimates: 33% over 10000 h, thus $L_h = 30000$ h; capital cost $c_{engine} = 75$ $/kW (both per [32]); Eq. (12)
c_{en} ($/kWh)	0.42	Per Eq. (11), high H_2 cost
c_{en} ($/kWh)	0.13	Per Eq. (11), low H_2 cost
c_{ac} ($/year)	399	c_c = $ 2450 (see text); d = 10%; n = 10 years; CRF = 0.16; Eq. (16)
c ($ (high))	525	Cost, result by Eq. (9)
c ($ (low))	438	Cost, result by Eq. (9)

line rather than 15 kW (at $ 650 incremental capital cost for wiring upgrade rather than $ 1500 ([1], Appendix A.2), the revenue is $ 3285, cost is $ 1554, and the net is $ 1731. Thus, the more expensive 15 kW wiring upgrade pays off quickly.

6.4. Example: fuel cell EDV providing spinning reserves

The second net revenue example is the fuel cell vehicle selling spinning reserves. We use the fuel cell vehicle in these examples because, as suggested in Table 1 and our earlier work [14,29], the fuel cell vehicle is better matched to spinning reserves and peak power, the battery vehicle better matched to regulation. Values of the parameters in Eq. (5) are listed in Table 4 for this particular example. As shown in Table 4, the revenue for fuel cell vehicles selling spinning reserves is $ 699.

To calculate the annual costs for providing spinning reserves for the FC vehicles we use the values shown in Table 5, with Eqs. (9) and (11).

The capital costs are higher in this case because we assume that the transportation function of our example fuel cell vehicle would not require grid connection, thus the plug, wiring, and on-board connections must be charged entirely to the capital cost of V2G. We assume capital costs of $ 2450.[3] Amortized as shown by Eq. (12) this gives an annual value of c_{ac} = $ 399. The total annual cost based on Eq. (5) and the values in Table 5, using the high estimate for hydrogen, is $ 525. Thus, given the above assumptions, the net annual revenue is $ 174. At low H_2 costs, the total annual cost is $ 438 and the net is $ 262. These figures illustrate that this result is not very sensitive to projected hydrogen prices, nor to energy payments ($/kWh), because spinning reserves involve very little energy transfer. However, the result is very sensitive to the capacity price for spinning reserves. For example, the ERCOT market is one of the higher US prices for spinning reserves—at 2003 ERCOT price of $ 23/MW-h [33] and again assuming the high end range of H_2 prices, the gross revenue is $ 2276 and the net annual revenue is $ 1751. More generally, fuel cell spinning reserves is economically viable only with a combination of good market prices and moderate capital costs; it is not sensitive to hydrogen costs.

6.5. Example: fuel cell EDV providing peak power

In Table 5, the values of the parameter c_{en} range from $ 0.13 to 0.42/kWh, depending on the assumed price of hydrogen. Since bulk power production is below $ 0.05/kWh, under our assumptions the fuel cell vehicle cannot compete with bulk power production from centralized plants. However, since peak power can be much more expensive per kWh, selling peak power may be economically viable despite its lack of a capacity payment.

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[3] Incremental capital costs of V2G for a fuel cell vehicle include on-board power electronics to synchronize the AC motor drive to 60 Hz and provide protection ($ 450), and wires and plug for grid connection ($ 200). On the building side, a 70 A, 240 V (16.8 kW) connection with ground fault interrupt but not NEC 625 compliant (only flow to grid, not charging, is contemplated) could range $ 50–5000 at a residence, probably closer to $ 800 in a fleet garage. Here we assume $ 1800 on the building side, plus $450 on-board, for a total of $ 2450. This cost analysis, drawing from our companion article ([1], Appendix), is refined from our earlier analysis ([14], p. 39).

Table 6
Revenue and cost of fuel cell vehicle providing peak power

Cost parameters	Value	Comments
c_{pe} (\$/kg H_2)	3.65	Mid-range of hydrogen cost [31]
c_{en} (\$/kWh)	0.27	Per Eq. (11), with parameters from Table 5
t_{disp} (h/year)	200	Rule of thumb: 200 h at $ 0.50/kWh
E_{disp} (kWh)	3000	200 h at 15 kW, Eq. (6)
r (\$)	1500	Revenue result, per Eq. (4)
c (\$)	1210	Cost result, per Eq. (9)

The term “peak power” does not refer to a specific power market. Rather, it is used to refer to the highest cost hours of the year, when most or all generators are on-line and additional power is costly. A full analysis of the value of peak power requires stepping through hourly market values, assuming sales of V2G whenever the market value is above the cost of V2G and the vehicle is available, and summing the annual revenue (see [14]). To provide a simpler calculation here as an example, we use an industry rule of thumb from central California [14], that there are 200 h in an average year when additional generation costs $ 0.50/kWh. Based on this and the data in Table 5, we give in Table 6 parameters for calculating the revenue and cost of a fuel cell vehicle providing peak power.

Thus the net revenue, based on Table 6, is $ 1500–1210, or $ 290, a positive annual net, but perhaps too small to justify transaction costs. This calculation is given only as an illustration. This result is highly dependent upon the cost of hydrogen (a mid-range projection was used here), the actual market prices for a representative year rather than the rule of thumb used here, and the match of peak time to vehicle availability. More complete analyses of V2G for peak power have been performed by Nagata and Kubo [15] and Lipman et al. [32].

7. Conclusions

We conducted technical analysis to understand the capacity of vehicles to provide power with minimal compromise of their primary function, transportation. We also investigated four major electricity markets, to find the best match of vehicle types to electric markets. To investigate these quantitatively, we developed equations to describe the available power and duration, and the costs and market value of these forms of power.

The result we offer is a quantitative understanding of how electric drive vehicles can become part of the electrical grid, and methods for estimating the expected revenue and costs. Our conclusions suggest that vehicles probably will not generate bulk power, both because of their fundamental engineering characteristics and because our calculated per kWh cost of energy from vehicles is higher than bulk electricity from centralized generators. V2G most strongly competes for electricity when there is a capacity payment to be on line and available, with an added energy payment when power is actually dispatched. This is the case for the ancillary service markets of spinning reserves and regulation. For these markets, even if V2G power loses money on each kWh sold, it can more than make up for that with the capacity payment. V2G may be able to compete when paid only for energy, but only when electricity prices are unusually high, as in some peak power markets.

Existing electricity markets have been the focus of this article, because their prices are known and they offer a multi-billion dollar annual revenue stream to help move V2G innovations forward. In the process, V2G would improve the reliability and reduce the costs of the electric system. As described in our companion article [1], as V2G begins to saturate these high value markets, it will be positioned to play a more fundamental role—storage for the emerging 21st century electric system based primarily on intermittent renewable energy sources.

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Appendix A. Nomenclature and worksheet

This appendix lists the symbols, names, and units from the equations of this article. Table A.1 lists the primary data needed as inputs and Table A.2 names the resulting computed values. In Table A.1, the “vehicle/market” column indicates parameters needed for only a certain vehicle type or power market; if this column is blank, the same parameter applies to all vehicles or power markets. The empty “value” column allows a copy of this page to be used as a worksheet for parameters needed to make calculations for new vehicles or markets. Miles, gallons, and $ values can be replaced with appropriate national units, as long as all instances are substituted.

Table A.2 gives the values calculated by the equations in this article, along with the equations used to calculate them.

Table A.1
Data needed for equations in this article

Parameter description	Symbol	Vehicle/market	Units	Value
Line connection parameters				
Rated maximum circuit	A		Amperes	
Line voltage	V		Volts	
Vehicle parameters				
Stored energy (available to inverter)	E_s		kWh	
Vehicle efficiency	η_{veh}		Miles/kWh	
Efficiency of line AC to battery charge	$\eta_{charger}$		Dimensionless	
Efficiency of inverter from DC to line AC	η_{inv}		Dimensionless	
Efficiency of converting fuel to electricity	η_{conv}	Fuel cell	kWh/kg H_2	
		Battery	kWh_{out}/kWh_{in} (dimensionless)	
		Hybrid	kWh/gal	
Lifetime	L_h	Fuel cell or hybrid	h	
	L_C	Battery vehicle	Cycles (at given DoD)	
Capital cost of prime mover	c_{engine}	Fuel cell or hybrid running motor-generator	\$/kW	
	c_{batt}	Battery	\$	
Vehicle operational parameters				
Time plugged-in	t_{plug}		h	
Recharge since plugged in	$E_{recharge}$		kWh	
Distance driven	d_d		Miles	
Range buffer	d_{rb}		Miles	
Market parameters				
Dispatch to contract ratio	$R_{d–c}$	Regulation	Dimensionless	
Time for one dispatch[a]	t_{disp}		h	
Price to sell V2G energy	p_{el}		\$/kWh	
Capacity price	p_{cap}	Regulation, spin	\$/kW-h	
Cost for EDV to buy energy	c_{pe}		\$/kWh, \$/kg H_2, \$/gal	

[a] Maximum dispatch time for computing $P_{vehicle}$; average for computing E_{disp}.

Table A.2
Variables calculated by the equations in this article

Description	Symbol	Units	Equation
Dispatch to contract ratio	$R_{d–c}$	Dimensionless	(1)
Power limit of line connection	P_{line}	W (or kW)	(2)
Power limit of vehicle's stored energy	$P_{vehicle}$	kW	(3) (3′)
Total revenue	r	\$	(4), (5), (8)
Dispatched energy	E_{disp}	kWh	(6), (7)
Total cost per year	c	\$/year	(9), (10)
Cost per energy unit produced	c_{en}	\$/kW	(11)
Degradation cost	c_d	\$/kWh	(12)–(14)
Battery lifetime, in throughput	L_{ET}	kWh	(15)
Annualized capital cost	c_{ac}	\$/year	(16)

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