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Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy

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Abstract

Vehicle-to-grid power (V2G) uses electric-drive vehicles (battery, fuel cell, or hybrid) to provide power for specific electric markets. This article examines the systems and processes needed to tap energy in vehicles and implement V2G. It quantitatively compares today's light vehicle fleet with the electric power system. The vehicle fleet has 20 times the power capacity, less than one-tenth the utilization, and one-tenth the capital cost per prime mover kW. Conversely, utility generators have 10–50 times longer operating life and lower operating costs per kWh. To tap V2G is to synergistically use these complementary strengths and to reconcile the complementary needs of the driver and grid manager. This article suggests strategies and business models for doing so, and the steps necessary for the implementation of V2G. After the initial high-value, V2G markets saturate and production costs drop, V2G can provide storage for renewable energy generation. Our calculations suggest that V2G could stabilize large-scale (one-half of US electricity) wind power with 3% of the fleet dedicated to regulation for wind, plus 8–38% of the fleet providing operating reserves or storage for wind. Jurisdictions more likely to take the lead in adopting V2G are identified.

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

1. Introduction

This article builds upon the article "Vehicle-to-grid power fundamentals (V2G): calculating capacity and net revenue" [1]. That companion article develops equations to calculate the power capacity and revenues for electric-drive vehicles used to provide power for several power markets. This article quantitatively places vehicle-to-grid power within the existing electric system, and covers implementation, business models, and the steps in the transition process. It calculates the amount of V2G necessary to stabilize large-scale solar electricity for peak power, and large-scale wind for baseload power.

2. Comparing the electric grid and vehicle fleet as power systems

During the 20th century, industrialized countries developed two massive but separate energy conversion systems—the electric utility system and the light vehicle fleet. In the United States, for example, there are over 9351 electric utility generators with a total power capacity of 602 GW (plus 209 GW from non-utility generators) [2]. These generators convert stored energy (chemical, mechanical, and nuclear) to electric current, which moves through an interconnected national transmission and distribution grid.

The second massive energy conversion system is the fleet of 176 million light vehicles (passenger cars, vans, and light trucks) [3], which convert petrochemical energy to rotary motion then to travel. With a shaft power capacity averaging 149 hp, or 111 $\mathrm{kW_m}$ per vehicle ($\mathrm{kW_m}$ is kW mechanical), the US fleet's 176 million light vehicles have a total power capacity of 19,500 $\mathrm{GW_m}$ or 19.5 $\mathrm{TW_m}$, which is 24

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Table 1
Electric utility generation compared with the light vehicle fleet (for the US)

Metric	Electric generation system	Current light vehicle fleet (mechanical power)	Hypothetical fleet with 25% EDVs
Number of units	9351[a]	176,000,000[f]	44,000,000
Average unit power (kW)	64,000	111[g]	15[k]
Total system power (GW)	602[b]	19,500[h]	660
In-use	57%[c]	4%[i]	4%
Response time (off to full power)	Minutes to hours[d]	Seconds	Milliseconds to seconds[l]
Design lifetime (h)	80,000–200,000[o]	3000	>3000
Capital cost (per kW)	US$ 1000+	US$ 60[j]	US$ 10–200[m]
Cost of electricity (US$/kWh)	.02–.09 average, .05–.80 peak[e]	n.a.	.05–.50[n]

[a] From [6]; this table uses utility generators only because those figures are more complete. Non-utility generation is approximately another 209 GW capacity.

[b] From [7].

[c] 3015×10^6 MWh/year [7] $\div$ (602,000 MW $\times$ 365 days $\times$ 24 h per day) = 0.57.

[d] Gas turbines about 10–15 min, large coal and nuclear several hours to 1 day.

[e] We approximate cost via wholesale electricity trading in 1999 regional markets (most recent tabulation by EIA in US$/MWh converted to US$/kWh here). Monthly average prices on the PJM spot market ranged from 1.7 to 9.0 ¢/kWh. Each month's peak hour ranged from US$ .047 to 1.08/kWh, with peak hourly prices above 80 ¢/kWh for 5 of the 12 months. California and New England exchanges were in similar ranges [7].

[f] From [3].

[g] kW of mechanical power, e.g., 149 hp (111 kW_m), based on average power of new light vehicles sold in 1993 [8]. The available sales-weighted horsepower figure for 1993 models is an imperfect approximation of the current fleet with an average age of 8 years.

[h] 176,000,000 units $\times$ 111 kW_m per unit.

[i] Average time spent driving per driver is 59.5 min/day, the ratio of licensed drivers to vehicles is 1.0 [3], so vehicle in-use fraction is $59.5/(24 \times 60) = 0.041$, about 4%.

[j] Cost per kWh_m of drive train only, not whole vehicle [9].

[k] Full-sized EDVs can generate bursts of 50–100 kW on-board, but we limit our analytical assumptions to just 15 kW due to limits on building wiring capacity. See Appendix A and [1].

[l] Milliseconds for battery EDV, 1–2 s for hybrid or fuel cell EDV.

[m] Incremental capital costs to add V2G to an EDV are given in [10], range reflects differences among battery, hybrid, and fuel cell vehicles. Formulae for calculating these figures are in [1]. Not included in this figure: capital cost of the vehicle itself is attributed to the transportation function; cost of additional wear on the vehicle due to V2G, which is calculated and included in the "cost of electricity" row of table.

[n] Calculated from fuel consumption, losses, wear on the vehicle, and/or battery depletion [1,11].

[o] A gas turbine peaking plant might have a 20-year design lifetime, intended to be run 4000 h/year for design life of 80,000 h. A large coal plant with a design lifetime of 30 years, operated at 75% capacity factor or approximately 8000 h/year would have a lifetime of about 200,000 h [12,7].

times the power capacity of the entire electric generation system.

Why is it relevant to compare the power of the light vehicle fleet with the power of the grid? The automotive industry is beginning its shift to electric-drive vehicles (EDVs) ("electric-drive vehicles" use an electric motor to drive the wheels—whether the vehicle's electricity comes from a battery, a fuel cell, or a hybrid combining a gasoline engine with a generator). The utility industry is beginning its shift to renewable energy. This article will argue that the economics and management of energy and power in the light vehicle and electric systems will make their convergence compelling in the early decades of the 21st century. We envision three forms of convergence: (1) the vehicle fleet will provide electricity storage and quick-response generation to the electric grid, (2) electricity will complement or displace liquid fuel as an energy carrier for a steadily increasing fraction of the vehicle fleet, and (3) automated controls will optimize power transfers between these two systems, taking into account their different but compatible needs for power by time-of-day [4,5].[1]

Table 1 compares the electric generation system with today's vehicle fleet, and with a hypothetical future fleet comprised of one-fourth EDVs (one-fourth is 44 million EDVs in a national fleet of 176 million light vehicles). The electric grid and the light vehicle fleet are rarely analyzed together, or even measured with the same metrics. Table 1 puts the current vehicle fleet in the second data column for comparison, although of course the current fleet's dispersed mechanical shaft power cannot be transmitted or aggregated in any practical way. A hypothetical future fleet consisting of one-fourth EDVs is compared in the rightmost column of Table 1. One-fourth is used for illustration, because it could provide electrical power approximately equal to all US utility generation; it is also a plausible intermediate-term fraction to be electric drive.

Table 1 shows that when just one-fourth of the US light vehicle fleet has converted to electric drive, it would rival the electricity generation power capacity of the entire utility system. Capital costs to tap vehicle electricity are one to two orders of magnitude lower than building power plants. The average per kWh cost of vehicle electricity is considerably higher and design lifetimes are one to two orders of magnitude lower, but the critical insight of our analysis is that vehicle electricity is competitive in specific electricity markets.

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[1] The third form of integration, two-way flow of energy and information from distributed energy resources to the power grid, is envisioned by the EPRI "Roadmap" [4] and is already being standardized in IEC 61850 as part of the Distributed Energy Resources Object Model (DER-OM) by IEC [5].

In this article, we move beyond Table 1's gross comparison of the amount of electric services vehicles might provide to the grid, to develop an understanding of how vehicles would actually do so.

3. Types of vehicles and types of power markets

We review distinctions among EDV types and power markets very briefly in this section to make this article readable independently from the more detailed discussion of these in our companion article [1]. The three vehicle types are: (1) fuel cell, which produces electricity on-board from a fuel, such as hydrogen, (2) battery, which stores power from the electric grid in an electrochemical cell, and (3) hybrid, which produces electricity on-board from an internal combustion engine turning a generator. Most relevant to V2G among the many possible hybrid designs is the "plug-in hybrid", which has a grid connection, allowing recharge from the grid as well as from fuel, and larger electrical components to allow driving in electric-only mode [13–15]. Our companion article quantitatively analyzes the power capacity, and the economic costs and benefits, for each of the three vehicle types selling into four power markets.

The four power markets relevant to V2G, in very brief review, are baseload, peak, spinning reserves, and regulation. Baseload power is the "bulk" power generation that is running most of the time. Peak power is used during times of predictable highest demand, for example, on hot summer afternoons, when maximum air conditioning is running. The other two forms of power are less well known. Spinning reserves are supplied by generators set-up and ready to respond quickly in case of failures (whether equipment failure or failure of a power supplier to meet contract requirements). They would typically be called, say, 20 times per year; a typical duration is 10 min but must be able to last up to 1 h (spinning reserves are the fastest-response and highest-value component of the more general electric market for "operating reserves"). Regulation is used to keep the frequency and voltage steady, they are called for only one up to a few minutes at a time, but might be called 400 times per day (again, terminology and operating rules vary somewhat across jurisdictions); spinning reserves and regulation are paid in part for just being available, a 'capacity payment' per hour available; baseload and peak are paid only per kWh generated.

Our companion article presents example calculations suggesting, for the vehicle and power markets examined, that V2G (1) is not suitable for baseload power; (2) it may be suitable for peak power in some cases; (3) it is competitive for spinning reserves; (4) it is highly competitive for regulation. These example calculations, although needing replication across a wider range of markets, vehicles, and assumptions, are consistent with an inspection of Table 1. Continuous, bulk electricity can better be provided by large power plants because they last longer and cost less per kWh. But electric-drive vehicles, with their fast response and low capital costs, appear to be a better match for the quick-response, short-duration, electric services, such as spinning reserves and regulation. These constitute, for example, in the US, 5–10% of electric generation costs, or about US$ 10 billion/year [16].

A future form of electricity provision, not now formalized into separate markets, is storage and backup power for renewable energy. The needed storage differs depending on the type of renewable energy. Solar energy has a fairly regular diurnal cycle, and solar energy output peaks roughly 4 h before peak load demand. Wind energy is more erratic, less predictable, and more geographically determined; any one site may be low for several days, but a group of sites over a larger area is steadier. These renewable energy backup characteristics are analyzed in this article and matched to V2G.

4. Strategies to reconcile the needs of the driver and grid operator

Central to the viability of V2G are the needs and desired functions of the two human parties—the driver and the grid operator. The driver needs enough stored energy on-board (electric charge or fuel) for driving needs. The grid operator needs power generation to be turned on and off at precise times. Three strategies for V2G can resolve potential conflicts: (1) add extra energy storage to vehicle, (2) draw V2G from fleets with scheduled usage, and (3) use intelligent controls for complementary needs.

The first strategy, extra storage, is a "brute force" strategy. In this approach, the vehicle designer goes beyond the storage requirements for driving and adds on extra storage for grid support say more batteries or a larger H_2 tank. The problem is that extra storage on the vehicle increases cost and vehicle weight. Economically, the reason V2G makes sense is because the storage system is purchased for the transportation function, yet is idle 96% of the time [17]. If storage must be added for V2G, 100% of the cost of that storage must be attributed to grid management, leaving little economic advantage of V2G over centralized storage owned and managed by a power company. Thus, we do not further consider the brute force strategy of adding extra storage just for V2G.

The second strategy, fleet management, draws V2G only from vehicles with known, fixed schedules. For example, a fleet of delivery vehicles might be in use 9:00 a.m. to 5:00 p.m. They could then predictably be used for V2G most or all of the remaining 16 h of the day. For example, our preliminary investigation with the grid operator in the Mid-Atlantic US (PJM) suggests that a garage of 100 fleet vehicles with 15 kW V2G could meet PJM's requirements of a 1 MW provider of regulation, with minimal or no need for rule changes (discussed subsequently). Another example might be a warehouse with forklifts, again operating on a predictable schedule. Although some warehouses operate almost continuously (with battery swapping), many others run forklifts for a single 8-h shift, or only once every several days according to bulk delivery schedules. Fleets are good candidates for initial V2G installations, and our analysis suggests that their economics are very attractive [18]. We discuss fleets further in the sections on business models and transition steps.

Although the second strategy, using fleets, appears to be a good initial area for V2G, the combined markets for V2G are many times larger than total fleet vehicles. Thus, to realize the full potential of V2G, we need a third strategy so that non-fleet vehicles can also participate.

The third strategy, intelligent controls for complimentary needs, is the one we primarily investigate. One central insight of our work on V2G is that the needs of the light vehicle operator and the grid operator are complementary. Their needs differ in time, predictability, and in the fundamental difference between energy and power. The vehicle operator needs stored energy in one particular vehicle at one fairly predictable time—when a trip begins. The grid operator needs power (instantaneous flow from a source or sometimes, to a sink), possibly at multiple times, but does not care which power plant (or which V2G vehicles) that power comes from. Most driving times are fairly predictable, regulation and spinning reserves calls are unpredictable. How are these two reconciled?

An early suggestion by Kempton and Letendre [17] for managing complementary needs was a dashboard control that the driver would set according to normal or anticipated driving time and distance. Then, the on-board V2G control system could run V2G when needed by the grid operator, as long as the vehicle storage is always sufficient for the driver-specified trip at the driver-specified time. Some drivers may find that the "next trip" settings require too much planning and attention. If so, an alternative would be for the vehicle to "learn" driving patterns for, say, a few weeks before beginning V2G service. Then, the user controls could be simplified to a single button: an override. For example, a driver expecting unusual trip times or expecting to drive longer than normal distances could push a 24-h override. In a fueled vehicle, the override would prohibit fuel use for V2G, while in a battery vehicle, it would charge at full speed whenever plugged in for the next 24 h. In either case, the override maximizes range at the cost of foregone V2G revenue for that 24 h time period.

Some additional flexibility is possible with plug-in hybrids as long as the fuel storage is sufficient to meet driver-specified minimum range—the battery could swing from full to empty, as the plug-in hybrid can still operate on fuel only.

A rather different type of complementary need is between the grid operator and the home resident (often the same individual as the driver, but we are analyzing roles and needs). When grid power is down, the grid has no need for regulation or spinning reserves, but the homeowner wants emergency backup power. A time lag before power restoration—even the time lag of driving back home from an errand—is tolerable (more tolerable in homes than businesses). Our back-of-the-envelope calculations comparing employee shifts, vehicle parking intervals at work and lags to backup suggest that vehicles in commercial lots could not be relied on to meet fast-response commercial-level "24–7" backup power reliability, because, depending on shifts, there might not be sufficient vehicles on-site when grid power fails (this merits more systematic analysis, since commercial power failures cost an estimated 1% of GDP or US$ 100 billion/year in the US [4]). Thus, we see the same equipment built for V2G as potentially also serving the home, but probably not commercial, emergency power. Any EDVs, battery or fueled, could serve a few hours of emergency power (or days if restricted to refrigeration and a few lights); for long outages, fuel cell, and plug-in hybrids have the advantage of being able to be driven out to refuel. The duration and power that vehicle emergency power would provide can be computed using the equations for spinning reserves from our companion paper [1]. Despite the expected merits of emergency power, we do not consider it further here.

Regarding V2G, the complementary-needs strategy—whether the driver sets a needed range or a smart vehicle learns driving patterns—results in the grid operator using aggregate V2G whenever needed, yet each vehicle is tapped only within the constraints of the driver's specified schedule and driving needs.

5. Business models

We now consider several business models that have been proposed for V2G [1,17,36]. The business models are overlays on the strategies above, specifying the types of institutions and financial transactions that would make V2G profitable for a business.

Under current rules, most large generators contract with the grid operators to provide spinning reserves or regulation, typically with a minimum of 1 MW quantities. During the time of that contract, the grid operator sends a signal when the electrical service is needed, and pays a single entity for the contract as well as for power actually generated (within vertically integrated utilities—which own generation, grid management and distribution—this power flows without market transactions, and often without any accounting of the true costs to provide it). With V2G operating under these rules, if each vehicle provided 15 kW, a 1 MW contract would require 67 vehicles available. To allow some vehicles being low on fuel or charge, being maintained, or being in use off hours, we use a rough multiplier of 1.5. Thus, a fleet of 100 vehicles, 15 kW each, should be able to bid 1 MW contracts during non-driving hours.

A first business model, corresponding to the "fleet management" strategy above, is that the fleet operator sells V2G—the same party both manages time availability of fleet use for transportation and sells ancillary services directly to the grid operator [18]. A single fleet in a single location simplifies the on-board electronics, and certified metering of power output would not be needed at the vehicle level, only for the fleet parking structure. To a grid operator accustomed to power plants feeding power into a single fixed location on the transmission network, a garage of vehicles looks more familiar and comfortable than dispersed vehicles. The fleet operator has a standard ancillary service contract and automatic generation control (AGC) controlled by the grid operator.

A second business model is to draw power from dispersed vehicles but within an existing business relationship. The obvious existing business relationship is with the retail power delivery company (the company known by consumers as "the electric utility"). This company could expand their business from selling retail electricity to also purchasing V2G power (a model first proposed in [17]). They would contract to buy V2G from hundreds or thousands of individual vehicle owners and sell 1 MW blocks to the regional power market. The aggregator would have no direct control over operating schedules of individual vehicles, but would provide financial incentives to stay plugged in when possible. Power availability would be highly reliable in the statistical aggregate. The retail power delivery company would incorporate payments for V2G into the existing electricity billing, resulting in lower net payments from customers to the power delivery company. Correspondingly, the power delivery company would charge the regional power market (e.g., the regional ISO) for the aggregated V2G (e.g., as regulation). Here, the existing relationships with the customer and with the regional power market are leveraged for the new V2G product.

A third business model derives from the second—an independent party rather than retail power delivery company serves as the aggregator of individual vehicles [1,36]. A number of parties might want to serve as aggregators: an automobile manufacturer or automotive service organization, who are increasingly using on-vehicle telematics to deliver information services between repairs; a battery manufacturer/distributor, who could provide "free battery replacement" for battery EDVs in exchange for reaping most or all of the profit from the V2G; a cell phone network provider, who might provide the communications functions and whose business expertise focuses on automated tracking and billing of many small transactions distributed over space and time—cell phone networking is a business similar to V2G in communications, control, value per transaction, and billing. Or, the aggregator could be a distributed generation manager, who today coordinates power from 5 to 10 small (100–500 kW) generators, and would extend this expertise to coordinate thousands of vehicles of 10–20 kW each. The former is now often coordinated via human-to-human telephone calls to 5 or 10 managers, whereas the switching on and off of individual vehicles for V2G, and commensurate billing, would of course be automated.

6. Dispatch of vehicles

Regardless of business model, if there is a complementary-needs strategy (either for a commercial fleet or for dispersed vehicles), we need to manage the vehicles' on-board storage. In management of power plants, "dispatch" refers to the timing and control of power plants, turning them on and off to match system needs. We extend the term here to refer to the same strategic control of vehicles in order to meet both driving needs and grid management needs.

6.1. Dispatch to match vehicle type

For power plants, dispatch is based on operating costs, time required to come on-line, etc. For V2G dispatch of vehicles, in addition to the consideration of driver needs (expected next trip, etc.), an aggregator would also dispatch individual vehicles to maximize efficiency and minimize wear on the vehicles. These considerations lead to opposite dispatch strategies for vehicles with combustion engines (hybrid running in motor-generator mode) versus vehicles with electrochemical power plants (battery vehicles, fuel cell vehicles, and hybrids that are running V2G from battery only).

For vehicles with combustion engines (i.e., a hybrid providing V2G via motor-generator), optimum dispatch would be with each vehicle running at maximum power (given vehicle limits, such as cooling when stationary, power line capacity, etc.). This is because of the overhead of operating the prime mover, e.g., one motor running near full load (e.g. 15–25 kW) is more efficient than two running at one-half load or three running at one-third load. Running near full load maximizes electrical output unit of fuel consumed, and minimizes wear per unit electricity produced. Operationally, minimizing the number of combustion engines turned on at any one time may also improve safety and convenience. In choosing which vehicles to dispatch, per the complementary-needs strategy, dispatch would be in order of vehicles with the fullest tank first, or more precisely, dispatch first vehicles with the most fuel above the driver-anticipated need.

With electrochemical vehicles (battery and fuel cell), lower power levels both minimize wear and maximize efficiency. Battery wear is a function of kWh throughput, depth of discharge (as discussed in our companion article), and overheating (running high-current discharging or charging long enough to heat the battery, especially in hot weather) [19]. Fuel cell efficiency increases and wear decreases at lower current densities, although the latter is not yet fully investigated [20]. Each of these factors militates for dispatch of many battery or fuel cell vehicles at partial load, rather than fewer vehicles at full load.

6.2. Dispatch to match power market

Dispatch would be managed somewhat differently for regulation and spinning reserves, and differently again for storage of intermittent renewable energy. In all these cases, the level of storage in the vehicle is being managed to match the power market. For the fueled vehicles (fuel cell and hybrid running motor-generator), the best strategy is always to have as much fuel as possible and does not require further discussion. Here, we discuss dispatch for battery vehicles (including plug-in hybrids running V2G from battery only), which offer additional opportunities.

For spinning reserves, having the battery storage filled is always best. For regulation, assuming that both regulation up and regulation down are being sold, a partially charged state is best. Fully charged, the vehicle cannot sell regulation down; empty, it cannot sell regulation up. Thus, one dispatch strategy upon returning from driving at a mid-charged level is for the vehicle to sell regulation up and down initially and then shift to straight charging or regulation down only, to charge the battery to prepare for the next trip. In fact, a simplified variant of V2G is regulation down only, as a means of obtaining revenue while charging.[2] This charges at a substantially slower rate, specifically, at the ratio $R_{\mathrm{d-c}}$, which we estimate to be about 8% [1].

7. Renewable energy storage and backup

The most important role for V2G may ultimately be in emerging power markets to support renewable energy. The two largest renewable sources likely to be widely used in the near future, photovoltaic (PV) and wind turbines, are both intermittent.[3] At low levels of penetration, the intermittency of renewable energy can be handled by existing mechanisms for managing load and supply fluctuations. However, as renewable energy exceeds 10–30% of the power supply, additional resources are needed to match the fluctuating supply to the already fluctuating load [21]. Intermittency can be managed either by backup or storage. "Backup" refers to generators that can be turned on to provide power when the renewable source is insufficient. "Storage" has the advantage of additionally being able to absorb excess power, but adds the constraint that giving back power is duration-limited (as is absorbing it).

In terms of V2G, backup can be provided by the fueled vehicles (fuel cell and hybrid running motor-generator). Storage can be provided by the battery vehicle and the plug-in hybrid running V2G from its battery. Could hydrogen-powered fuel cell vehicles be considered electrical storage, if the hydrogen is produced by electrolysis? Because of round-trip losses of conversions in the path electricity–electrolysis–hydrogen-storage–small fuel cell–electricity, approximately 75% losses for electrolytic hydrogen versus 25% for battery [22], round-trip electrolytic hydrogen appears to be too inefficient to be practical as storage. The engineering distinction corresponds to relative economic advantage from shorter versus longer power flows and the difference between energy payment and capacity payment from Eq. (5) in [1].

Next, we perform calculations to quantitatively evaluate V2G's potential for supporting intermittent renewable electricity. For illustration, we assume very large penetrations, e.g., PV providing most US peak power, and wind providing one-half of total US electrical energy. We express the US results as percentages of the vehicle fleet required, so our percentage results would be approximately the same across OECD countries with similar proportions of electricity to vehicle fleet size.

For PV, the solar resource has a fairly predictable daily cycle. The daily solar cycle precedes the load peak by a few hours—PV peak power is at solar noon, load peak is mid- to late afternoon. Thus, a simple strategy to integrate PV into the grid is to meet peak load by storing from the solar peak to the load peak. The storage required for PV to be assured of meeting peak power needs is called the "minimum buffer storage requirement", or MBSR [23]. Current rules in California, for example, qualify PV as firm capacity, if there is MBSR of 0.75–1.0 h. Thus, to qualify a 1 MW solar PV plant as firm peak capacity would require 750 kWh to 1 MWh of V2G. Calculating vehicle power output (P_{vehicle}) from Eq. (3) and assumptions from our companion paper [1], a RAV4 EV could store or release 7 kW over a 1-h period. Thus, a 1 MW solar PV plant requiring 1.0 MSBR could be met with 143 RAV4s. At a national level, US electrical capacity is 811 GW (from Table 1, including utility and non-utility). Assuming that one-fifth were PV for peaking, at 1.0 MBSR, firm capacity credit would require 162 GW available from V2G. At 7 kW per vehicle, this could be met by 23 million V2G vehicles available, about 13% of the fleet; if we assume that only one-half of the contracted vehicles are available when needed, we would want 26% of the fleet under V2G contract.

Wind power is more complex. Wind fluctuates, and it cannot be turned up when electric demand increases. Some textbook treatments of wind describe storage as if it would be built and dedicated to match wind installations and their fluctuations [24]. But this mechanistic dedicated storage approach does not reflect the ways in which electrical grids are already set-up to handle intermittency problems (power plant failures, fluctuations in load, etc.). In Table 2, we map textbook wind "storage intervals" in the first three columns, to our suggested match of each interval with electric markets and strategies, in the rightmost column.

Table 2 illustrates that existing markets apply precisely to storage interval 1 (regulation, some spinning reserves or intrahour adjustments), storage interval 2 (operating reserves), and to part of interval 3. Our ordering of the utility strategies for interval 3 is deliberate, that is, we expect that storage at this interval is minimized most economically by more widely-spaced wind generation with transmission lines connecting them (discussed shortly), followed by operating reserves and load management (e.g., interruptible rates for industrial customers), followed by storage dedicated to the wind facilities

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[2] In electricity flow, regulation down only could be called "grid-to-vehicle" power, but the vehicle is in fact providing service to the grid. Thus, we refer to this case as V2G also.

[3] Another solar electric source, central-tower concentrating, is now more economically competitive than PV for utility-scale generation, but is more geographically limited. It contains inherent storage of 2–4 h in the transfer fluid's thermal mass, so additional storage from V2G would be less important to this technology.

Table 2
Meeting wind storage needs with electric markets and strategic management

Storage interval	Time range	Cause of fluctuation	Suggested electric market or strategy
1	Minute to hour	Gusts, weather	Regulation, some intrahour adjustments or spinning reserves
2	Hour to day	Weather and daily thermal cycles	Operating reserves (spinning and non-spinning reserves)
3	1–4 days	Movement of fronts	Dispersion of wind resources with transmission; operating reserves; load management; dedicated storage (in sequence—see text)
4	Seasonal	Seasonal thermal and weather cycles	Long-term match with of load (e.g., if wind is stronger in winter, move space heating toward electric heat pumps rather than fossil fuel)

only if needed after that point. Interval 4, seasonal mismatch between wind resources and load, would require huge purchases from operating reserve markets, or exceptionally large and cheap storage. A more practical way to meet seasonal mismatch would be to shift load over the multi-decade implementation period, for example, if planned wind power exceeds demand in winter, incentives should be created for new and replacement furnaces to be shifted from fuel-burning to electric heat pumps.

To quantitatively estimate the storage needs in terms of electric markets, we turn to the few existing studies of the impact of large-scale wind upon the grid, which consider regulation and operating reserves. Then, as a check on those calculations, we develop our own estimate of storage capacity needed for large-scale wind.[4]

For regulation, wind power increases the need over today's regulation needs. Hirst and Hild [26] simulate a large wind fraction (2.6 GW capacity in a 4.5 GW generation utility) in dispersed sites. They find the need for regulation to be 0.5% and for load following to be 7.3% of wind capacity (1.6 and 21% of average output, p. 32). Hudson et al. [27] estimate regulation need of 11% for small and 6% for large single wind installations. We use the Hudson et al. 6% figure to estimate regulation requirements, acknowledging that it may be high.

From Table 1, US electric utility capacity is 811 GW (utility plus non-utility) at 57% capacity factor. To generate half of the electrical energy from wind at 33% capacity factor [28,29] would require 700 GW of wind capacity (thus average wind output of 231 GW). Regulation at 6% would be 42 GW, which could be met by 2.8 million battery vehicles at 15 kW regulation per vehicle, or 1.6% of today's fleet (Table 1). Assuming only one-half of contracted vehicles are available for V2G at any one time, 3.2% of the light vehicle fleet would be on V2G contract for wind regulation.

Operating reserve needs for high-penetration wind include both spinning and non-spinning reserves, to cover all of interval 2 and part of interval 3 from Table 2. We find the most thorough analysis of these needs to be Milligan's [30], which uses the Strbac and Kirschen (SR) model [31]. The SR model is used by the electric industry to allocate the cost of operating reserves to specific generating plants within a mix of plants. In this model, the reserves are used to cover any shortfall between contracted generation and actual wind available—the storage needs are less stringent than those needed to guarantee constant baseload power from wind. Assuming dispersed wind generation and estimating some parameters not yet established for wind, Milligan uses the SR model to estimate reserves need, arriving at a maximum of 11% of wind capacity (with "less reasonable assumptions" the maximum reserve need would be 20%). Assuming as above one-half of US electric energy coming from wind generators with capacity of 700 GW, the 11% reserve need would be 77 GW. Milligan uses a 3 h rolling window, so we assume here that the maximum duration for the reserve requirement would be 3 h.

From the SR-operating reserve requirements (above), the number of EDVs to provide these operating reserves can be calculated. For the fuel cell vehicle described by Eq. (3) and Table 1 in [1], power output per vehicle (P_{vehicle}) is 12 kW over 3 h. At 12 kW per vehicle, the 77 GW reserve requirement could be met by 6.4 million fuel cell vehicles, or again assuming only one-half are available and adequately fueled when called, 12.8 million vehicles under V2G contract, or 8% of the US fleet. For the battery vehicle from [1], Eq. (3) yields 2.3 kW over a 3-h reserve requirement. Thus, to meet 77 GW would require 33.5 million battery vehicles or, assuming one-half available, 38% of the fleet needed under V2G contract. Assuming a charge maintaining mode,[5]

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[4] Apart from time intervals, some storage must be optimized according to geography and transmission capacity. Specifically, for remote wind sites that require dedicated transmission, storage may be optimal at the wind site, because storage there not only smoothes out wind power fluctuations but also improves capacity factor of the power lines [25]. V2G does not help with capacity of transmission lines from remote wind sites, as most vehicles are located close to loads.

[5] As shown in [1] (Eq. 3 and Table 2), the example plug-in hybrid would have too little battery charge left after a normal battery-depleting drive cycle to be useful. To illustrate possible hybrid use for wind backup, we assume that coming wind lulls would be forecast. Thus, 24-h before anticipated wind lulls, participating V2G hybrids would receive a control signal to drive in a "partial charge maintaining" mode, at the cost of burning more gasoline. We here assume that the partial charge minimum would be set at 60% battery capacity, which, after inverter losses, would be 7.8 kWh available from the 14.4 kWh battery.

the plug-in hybrid would provide 2.6 kW over 3 h [1]; similarly assuming one-half available when needed, this would be met by 34% of the fleet under V2G contract (the battery or plug-in hybrid vehicles would also be able to absorb the excess power that a 700 GW wind system would sometimes produce—assuming the same 33.5 million battery vehicles (38% of fleet), with one-half available and each absorbing 7.0 kWh, the fleet could absorb 235 GWh).

As a check on the SR model, an alternative approach is to estimate the size of storage needed to insure a given minimum firm capacity. This mechanistic approach sizes storage dedicated to wind, rather than using electricity markets (and existing generation) for operating reserves. Again, we assume that to meet our benchmark of one-half of US wind generation, multiple widely distributed sites would be required. We find only two analyses published on very large-scale, distributed wind.

Archer and co-workers sum wind speeds over a year from a distributed set of eight US Midwest sites in an ellipse approximately 500 km × 400 km. The sum of wind power from eight sites approaches a normal distribution rather than a Rayleigh distribution, and never goes below 3 m/s for any 4 h block during the entire year [32,33]. This study, and another one by DeCarolis and Keith with mid-continental wind sites separated by 1600 km [34], both suggest far less storage needed for widely distributed wind sites than for single or nearby sites. However, neither of them reports the type of data we need to calculate storage requirements.

Here, we use an unpublished data set from Archer, based on the same eight sites. These data are disaggregated to hourly and add calculation of energy at each site, based on actual wind turbine performance (a GE 1.5 MW turbine at 80 m hub height), summed to yield hourly total energy for all sites combined. These data allow us to calculate directly the amount of storage needed for a distributed wind resource, which yields a transparent calculation, and does not require the SR model's assumption of electricity markets using existing generators. We assume storage would be used to maintain a 20% firm capacity (this level would be set by the wind seller; higher firm capacity values require more storage but increase revenue and make wind viable for a larger fraction of the generation mix [35]). In the 6916 h of valid data, we find 1109 h in which the power was under 20% of rated capacity. Grouping contiguous hours, we find 342 low-power events and compute the shortage in total MWh for each event, as shown in Fig. 1; 60% of these events are 2 h or less and require only 3–10% of capacity (e.g., MSBR of 0.03–0.1 h), easily handled by V2G. Storage need is determined by the worst cases; in Fig. 1, the worst cases are the rightmost cluster of five events with MWh shortfalls of about 170% of the MW wind turbine capacity. These five range from 14 to 22 h duration. In the solar energy backup metric, 170% is 1.7 h MBSR.[6]

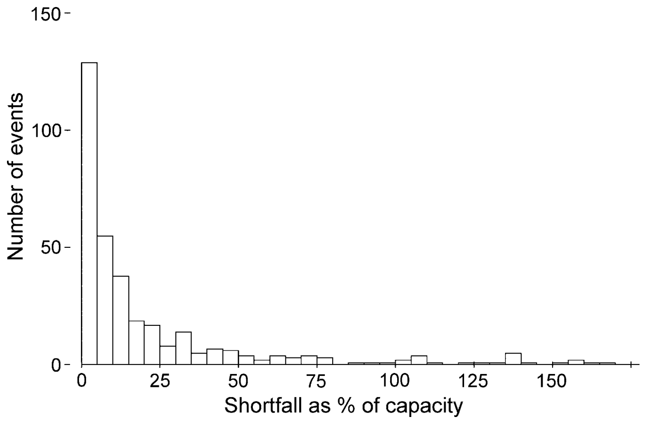

Fig. 1. Shortfall of energy as percent of wind capacity in 342 events during a year. We assume a contract for firm capacity at 20% of the wind turbines' rated capacity. Based on Archer data on eight connected wind sites (100% shortfall = 1 MWh/1 MW = 1 h MBSR).

Taking our scenario of 700 GW wind capacity, 1.7 MBSR is 1190 GWh storage needed. Using the numerator of Eq. (3) in our companion article [1], the example fuel cell vehicle has available energy of 36 kWh from stored hydrogen and the plug-in hybrid 7.8 kWh from battery only. We assume that over a 14–22 h wind shortfall period, most vehicles would be driven; so, the plug-in hybrid would recharge from fuel as part of normal driving, or the fuel cell vehicle could refill with H_2. Thus, we assume that three-fourths of the vehicles under V2G contract would be available over the 14–22 h shortfall period (rather than 50% assumed in prior examples). So, the storage need for 1190 GWh, would require 33 million fuel cell vehicles on-line (44 million on contract), or 152 million plug-in hybrids (203 million on contract). In a fleet of 176,000,000 vehicles, this becomes a need for V2G contracts with either 25% of the fleet of fuel cell vehicles or an impossible 116% fleet of plug-in hybrids (if the plug-in hybrid were allowed to run its motor-generator when parked during these long backup needs, the number of vehicles needed would be small, even less than for fuel cell vehicles, because of greater fuel storage). The battery vehicle is not suitable for these long storage intervals. Although these illustrative calculations give the fleet percentage for only a single vehicle type, our analysis above and in [1] suggest that optimum vehicle support for the pattern of shortfall events in Fig. 1 would be: (1) storage from battery or hybrid in battery mode for the most frequent and low-energy shortfalls and (2) backup from the fuel cell or hybrid in motor-generator mode, for the less frequent high energy shortfalls on the right of Fig. 1.

The results for PV and wind are summarized in Table 3. Note that the two "firm capacity" calculations are more

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[6] We define "valid data" as having wind data from at least seven of the eight weather stations. The number of shortfalls is exaggerated by missing data. When we examine only hours with all eight weather stations available, we find only 122 shortfall events rather than 342, and only one of the above-mentioned five largest shortfalls. Since one of the largest events remains, correction for missing weather data would substantially reduce the number of events but not significantly change the largest event, from which we calculate storage needs.

Table 3
V2G required to support large-scale renewable energy (see analysis in text)

Renewable type	Power type and fraction	Renewable capacity (GW)	Support criterion	Support quantity	Vehicle availability	Fleet % needed, vehicle type
Photo-voltaic	Peak (1/5 max load)	162	Firm capacity (MBSR)	162 GW	1/2	26% battery
Wind	Baseload (1/2 energy)	700	Regulation	42 GW	1/2	3.2% battery
			Operating reserves (SR)	77 GW	1/2	8% fuel cell, or 38% battery, or 34% plug-in hybrid
			Firm capacity at 20% (dedicated storage)	1190 GWh	3/4	23% fuel cell

stringent in requiring dedicated storage, whereas the operating reserves calculation assumes taking advantage of existing generation and markets.

This analysis, the above calculations summarized in Table 3, and indeed our opening Table 1, all suggest that V2G could play a role as storage for intermittent renewables, even when renewables become half (or more) of total electrical generation. V2G could be the critical missing piece of the system that enables intermittent renewable energy to provide much of society's energy needs, without large storage costs, while keeping the electric grid stable and reliable. In addition to the support of renewable energy, there are environmental and geopolitical benefits from operating the light vehicle fleet from domestic renewable energy—an understatement we do not quantitatively analyze here.

8. Transition path

Initial V2G proof-of-concept, prototyping and device-level testing has already been carried out and at least one V2G-capable controller for EDVs is commercially available [53]. A V2G-capable vehicle has been designed, developed, built, driven, and extensively shop-tested [36]. With an added wireless link to the grid operator, it has been tested, both driving and providing regulation up and down over several months [37]. This single-vehicle demo has proven complete on-board V2G equipment, including real-time control by the grid operator, and multiple-connection-point provision of regulation from a mobile source.[7] We outline below a possible set of subsequent steps to implementation. The first and second steps will not occur with market forces alone, so some policy intervention is likely to be needed. First, we consider what types of vehicles are likely to initially be appropriate and affordable for demonstration use.

8.1. Which vehicles to use for demonstration fleets

Of the three types of electric-drive vehicles we analyze, which might be available in the near term for demonstrations, at reasonable prices at small production volumes? We briefly compare startup or low-volume costs for these three vehicle types.

Although hybrids are already in mass production, a shift to plug-in hybrids with all-electric range would require a fundamental redesign, not just adding a plug (e.g., a shift in mechanical:electrical power ratio from the current 3:1 to a lower-emission and more V2G-useful 1:3). But the close integration of the mechanical and electrical components makes the hybrid expensive to design. As an indicator, to recoup the development costs of their already-existing Prius hybrid drive train, Toyota needs to sell 300,000 units per year [38]. Some design, development, and testing of plug-in hybrids has been done [15,13], but no vehicles are yet scheduled for production.

To compare costs of fuel cell and battery vehicles, we review small-production runs from major manufacturers. The Honda fuel cell FCX is being leased in Japan for US$ 87,600/year [39], and Toyota leased two fuel cell vehicles in California for US$ 120,000/year [40]. By comparison, 2 years earlier Toyota manufactured the battery-only RAV4 EV, providing it initially for fleets at US$ 5484/year lease or US$ 42,000 outright purchase. Subsequently, with production at 300 per year, it sold battery-electric RAV4s to the public, also at US$ 42,000 outright sale, including a home charging station. Approximately, the same price has been quoted from a small manufacturer for a battery electric vehicle planned for 2005, using Li-Ion batteries and with 80-A V2G (19 kW) already built in [41,42].

We conclude that in small production runs (100–1000 s per year), battery vehicles with V2G would be in the range of 2× the cost of mass-produced gasoline vehicles, whereas fuel cell vehicles have so far been closer to 10×, and suitable plug-in hybrids, when available, would fall in between. Since the V2G control and business models of all the three vehicle types are similar, it would be reasonable to begin demonstration of V2G fleets with battery vehicles, regardless of whether one of the other types predominates in later years.

8.2. Step 1, demonstration fleets

V2G will be unfamiliar to both electric system managers and to vehicle users. It will require full-scale, market-

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[7] As of fall 2004, several other companies have bid or advertised V2G capabilities; at the time of this writing, the only public reports of testing built V2G hardware are those cited above.

participating demonstrations in order to work out problems and to educate the institutions and analysts involved. Since the technology development and above-mentioned single vehicle demo have been done already, what we describe as the first implementation step is implementation of demonstration fleets. A sufficiently sized fleet would allow real participation in grid management (by providing regulation or spinning reserves) and substantial revenue flows over a period of time. This will give fully real-world experience to both fleet managers and grid operators.

Initial fleets can draw from fabrication of V2G-capable EDVs in modest volumes, say, 100s to 1000s of vehicles per year. These volumes would be possible for a small company, by replacing the drive train of a mass-marketed vehicle (if a major auto manufacturer does assembly at this step, they too would likely produce 100s of vehicles in the same way, by refitting one of their mass-produced vehicles in a separate, smaller facility; this was how Toyota produced RAV4 EVs in multi-100 per year quantities).

What types of fleet would be reasonable for a Step 1 demonstration project? A company-owned fleet operated primarily during a single shift would typically be parked in one parking area the remaining 16 h of the day. This would simplify management and control for V2G. A fleet of 100 vehicles at 15 kW each, even assuming only two-thirds available, could provide the 1 MW minimum of many current power supply contracts. Presuming exclusively battery electric vehicles at this stage (per cost and availability noted above), the regulation market would be the likely primary market. Regulation is needed 24 h per day, and unlike peak power is often needed as much overnight as during higher load hours [43].

In these small production volumes, selling even high-value regulation would not cover the cost of vehicles. Nevertheless, a company and/or government might implement demonstration fleet(s) for the sake of: (1) technology leadership, (2) economic development, (3) to meet requirements on emissions, CO_2 limitation, or clean fuels, or (4) for strategic reasons (e.g., to develop expertise in this area, to prepare for high fractions of renewable energy, to provide a local source of uninterruptible power, etc.).

As more fleets adapt V2G-capable vehicles, prices would be reduced with larger production volumes. Delucchi and Lipman [44], using a gasoline Taurus as a base, estimate costs of several comparable battery electric vehicles. For a then–current (in 2001) NiMH battery with 90 miles range, they estimate retail cost of US$ 44,920 in limited production or US$ 28,034 in volume production. The volume price is still above the US$ 20,085 cost of the gasoline model. Given lower driving cost (electricity is cheaper than gasoline), they estimate that it would break even if gasoline reached US$ 4.19/gal (with then–current battery technology). With a more advanced Li-Ion battery with 140-mile range, and assuming longer shelf life than today's Li-Ion, Delucchi and Lipman [44] estimated in 2001 that the battery vehicle would have lower costs once gasoline exceeds US$ 1.27/gal (a price already surpassed as of this writing). They do not consider V2G payments, which, at over US$ 2000/year [1] tip the economics for the fleet operator further toward electric drive over gasoline.

In short, initial fleet adopters will pay a cost premium over gasoline vehicles, which the V2G payments would reduce but probably not eliminate. However, as the vehicles move to volume production and battery technology improvements continue, V2G payments shift the fleet operator's cost to breakeven with gasoline vehicles, then to lower costs.

8.3. Step 2, cost breakeven and below; aggregation of individual vehicles

Once fleets demonstrate viability and vehicle production volumes bring down cost, the V2G revenues may stimulate aggregators. They would aggregate smaller fleets and individual vehicles in the same utility control area. Because the number of vehicles is still relatively limited at this stage, getting enough in one grid "control area" may require local marketing or incentives (or a region with very high numbers of early adopters). Electricity markets served at this point might be predominantly regulation and spinning reserves, with peak power only in a few areas. Here, vehicle production might be expected to be 10s of 1000s of vehicles per year.

Step 2 begins at the point that costs drop below breakeven (with V2G revenue and fuel savings included) until the point that the high-value V2G markets of regulation and spinning reserves are saturated. We provide here the method for estimating saturation point, with representative calculations from one US state, California, which is comparable in size to a number of OECD countries. Assume vehicles with 15 kW capacity for V2G, and that on average only one-half are parked, plugged in, sufficiently charged, and participating in the program. A mid level of regulation of 1200 MW [45,11] would be fully met by a fleet of $(1200\ \mathrm{MW}/15\ \mathrm{kW}) \times 2 = 160{,}000$ vehicles, or 0.9% of the California light fleet of 18,000,000 registered vehicles [46]. To meet California's maximum regulation plus maximum spinning reserves contracts, totaling 4100 MW, again assuming 15 kW vehicles with one-half available at any one time, would be 547,000 vehicles, or 3% of California's fleet. As we approach 3% of the fleet under V2G contracts, the very high-value regulation market begins to saturate and the price of V2G drops.

8.4. Step 3, saturation of high-value markets; expand V2G to store renewable energy

As the implementation process approaches the time of saturation of the regulation and spinning reserves markets, the capital cost of electric-drive vehicles would be expected to be at or near parity with conventional internal combustion vehicles (on lifecycle cost), the revenue from selling V2G should be quite a bit lower per kWh than it was initially, and the total installed capacity of V2G, even in just one of the larger US states or OECD nations, would be in the GW.

The high volumes of electric-drive vehicles will push vehicle prices down and permit a wider variety of vehicles, including plug-in hybrids and eventually perhaps fuel cell vehicles. The fraction of these three vehicle types will be determined by market forces in the vehicle market, and the V2G market should be prepared to utilize all three, whatever the fraction of each.[8]

Higher volumes of V2G capable vehicles and a more efficient aggregation industry have the benefits of making electric grid management cheaper, and making power more reliable and stable. They would also lead to the power plants now used for regulation and spinning reserves being freed up for base load, peak generation, renewable backup, or retirement. However, these conditions will put pressure on prices for V2G, lowering V2G rewards to drivers and profit margins to aggregators, thus, leading to a smaller proportion of V2G-capable vehicle owners opting to participate in V2G markets, and fewer being careful to stay plugged in. The large aggregate capacity and low unit cost of V2G at this phase is essential to the last market—storage for renewable energy.

9. Jurisdictions well-suited to adopt V2G

Which jurisdictions (that is, nations, states, or provinces) might be expected to have earlier and greater interest in V2G implementation? Below we describe characteristics of jurisdictions that we would expect might motivate earlier V2G development. Such jurisdictions would:

1. Want electric grid improvements, higher reliability, and more frequency stability, but prefer to avoid construction of new power plants and transmission lines.
2. Be in geographic areas where a population of automobiles (e.g., a city or several fleets) is located on a peninsula with transmission constraints (e.g., Long Island, Delaware), a grid-isolated island (e.g., Ireland), or an area with a fragmented grid (e.g., Australia).
3. Have high or moderate costs for regulation and spinning reserves. This includes most areas of the world, but not areas where hydropower provides most of the electricity, e.g., Brazil, Norway, or Washington (state in US).
4. Have competitive markets for regulation and spinning reserves, or alternatively, have some non-market ability to recognize or justify the value of providing these ancillary services.
5. Have policies or other encouragement for development of new industry, technology, or employment. For example, Step 1 of the suggested transition path involves small production facilities that provide local jobs immediately, although the vehicle costs would initially be above market.
6. Have a single or coordinated government units (state, nation, and ministry) with jurisdiction over both transportation and electricity.

Additionally, jurisdictions with the following characteristics are more likely to see V2G as highly synergistic with wind development:

7. Have committed to growth of renewable energy and/or reduction of carbon dioxide emissions, and want to prepare for wind generation surpassing 20%.
8. Be in geographic areas where large auto fleets are located close to large wind resources. For example, such areas include the US East Coast, the United Kingdom or other western states of Europe. This criterion militates against regions whose wind resources are distant from population centers, such as the wind of Central Asia or the US Midwest.

Jurisdictions with several of these characteristics are more likely to adopt V2G earlier.

10. Conclusions

This article began with a broad comparison of two immense energy conversion systems, finding them surprisingly complementary. The electric grid has high capital costs and low production costs; the automobile fleet is the reverse. Electric generators are in use 57% of the time, automobiles only 4%. The electric grid has no storage; the automobile fleet inherently must have storage to meet its transportation function. Based on the contrasts between these systems, we lay out management strategies, business models, and three steps for a transition to V2G.

We suggest that in the short-term, electric-drive vehicles should be tapped for high-value, time critical services—regulation and spinning reserves—which can be served by about 3% of the fleet. As those markets are saturated, V2G can begin to serve markets for peak power and storage for renewable electric generation. Envisioning a longer-term role for V2G, with perhaps one-fourth to one-half of the fleet serving as backup generation and storage for renewable energy, leads us to the following reconceptualization of the entire energy system.

The fossil-fueled vehicle fleet and the mostly fossil-fueled electric power system, today taken for granted, increasingly appear circumscribed by the assumptions of the 20th century. For environmental and resource reasons, and eventually for economic ones as well, we expect that the 21st century will see fossil fuels displaced by intermittent renewable energy. Intermittent renewable resources will prove cheap and abundant, but present the problems of variation in strength through time and not being matched to load variation.

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[8] Rather than a shift to one vehicle drive type, we expect that the market may shift to a diversity. Based on the new lithium battery technologies, the battery vehicles should have low operating cost and very low maintenance costs; the plug-in hybrid has the advantage of dual-fuel, electricity for low cost and home refuel convenience, or liquid fuel for fast-refueling and thus long-range trips. Market research conducted under contract by a consortium organized by EPRI suggests that there is a significant market for vehicles that can plug-in and have all-electric driving range, a feature absent from today's fuel-only hybrids [14].

Contemplating a future based primarily on intermittent renewable resources forces us to recognize that fossil fuels have been not only an energy source, but also a high-density energy storage medium. Whether an automobile's US$ 50 sheet metal tank storing 300 miles of range, or a coal plant's piles to be burned only when electricity is needed, energy storage has been practically free. Storage has been a side benefit of our habit of carrying energy as molecules rather than electrons. We believe that those days are numbered. While future vehicles will always require storage to perform their function, future electric generation will no longer come with free storage.

The long-term case for V2G boils down to a choice. We can keep the electric system and vehicle fleet separate, in which case we substantially increase the cost of renewable energy because we have to build storage to match intermittent capacity. Or, we can connect the vehicle and electric power systems intelligently, using the vast untapped storage of an emerging electric-drive vehicle fleet to serve the electric grid. We predict that the latter alternative will be compelling. It offers a path to reliable high-penetration renewable electricity as well a path to a low pollution vehicle fleet independent from petroleum. The prospect of V2G is to carry us along both these paths together, more quickly and economically than has been thought possible when planning either system in isolation.

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Appendix A. Requirements for electric power connection and telecommunications

This appendix lays out specifications of the power and communications requirements for V2G. The current standards for power connection to vehicles were formulated with one-way flow in mind and are being updated to allow for V2G [47,48].[9] This appendix also develops cost estimates for adding V2G capability.

A.1. Electrical power connections

To evaluate power connections, it is useful to begin by comparing the desirable connections for V2G with the existing connections for battery electric vehicles (current, hybrid, and fuel cell vehicles do not have electrical connections). Most of the chargers for battery EDVs installed in the first California EV boomlet (through year 2002) are 7.7 kW (6.6 kW at commercial locations). The revised EV-charging standard by SAE allows up to 96 kW [49,50],[10] vehicle connectors rated 20 kW are now commercially available [51], and V2G offers a substantial revenue increase if that original 7.7 kW maximum can be increased to the range around 15–20 kW. The following section analyzes plug connections in the 15 kW range, because typical house wiring, practicalities of grid-to-vehicle connections, and heating during continuous output from vehicles make 15 kW a reasonable upper limit to consider for analysis (for fuel cell vehicles, a little more, say 20 or 25 kW may be appropriate; higher values may be more likely at commercial locations than residences).

It is also illustrative to compare V2G connections with home electrical connections for generation, for example, home PV systems and emergency power. Both types of generation should be designed to consider utility worker safety. The danger is that line workers turn off the power source from the main power lines, but can receive a shock from electricity coming from a home PV or generator. Many local jurisdictions require that home power systems have approved safety interconnections [52]. These include 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. The approach to home power to date has been to have the interlock on the building. For vehicles, if they are to recharge at several locations, interlocks might more efficiently be incorporated into on-board electronics instead, as one manufacturer has already done [53]. Here, we calculate cost based on this approach.

A.2. Line capacity and upgrade costs

V2G requires electrical service to the parking site. Some locations would require electrical service upgrades to the residential or commercial building site (a higher capacity breaker box and possibly larger line to the power pole). In cost accounting, here we assume that a 6.6 or 7.7 kW line would be provided for a battery electric or plug-in hybrid, and no

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[9] The 1999 National Electrical Code, article 625, requires that "upon loss of voltage from the utility or other electric system(s), energy cannot be backfed" [47]. Since this could be interpreted as prohibiting V2G, NEC 625 was revised in 2002 to allow feeding the grid "when intended" and more comprehensive standards for V2G are currently under discussion for NEC 625 as well as for SAE J2293 and IEEE P1547 [48].

[10] The above discussion covers conductive chargers with power conditioning on-board the vehicle. We believe that a competing approach, inductive charging, is more costly to modify for V2G [11]. The advantage of conductive charging in simplifying 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. Nevertheless, at least one company says they are building V2G into an inductive link [50].

plug for a fuel cell vehicle. Thus, the V2G line upgrade costs would be 0, if the 6.6 kW line for BEV or plug-in hybrid were also used for V2G. In all other cases, costs are attributed to V2G; the entire costs of plugs on any fuel cell vehicle, or the incremental costs if a BEV or plug-in hybrid connection were upgraded from 6.6 to 15 kW or more. If an upgrade is being contemplated, our analysis is used to answer the question of whether the service upgrade would be justified based on the revenue from V2G. These cost estimates assume retrofit of a residential building, the highest cost situation. Costs would be dramatically lower if the V2G wiring were built into homes and commercial buildings from the start.

The initial step we suggest for V2G is for fleet vehicles. With commercial voltage at 208 V, 15 kW lines in a parking structure would require an 80 A circuit (equivalent to the capacity of a hot tub with electric heating). A 20 kW line would require a 100 A circuit.

For a residential V2G line connection, in many or most single-family houses, a 40 A or 9.6 kW connection would be accommodated for the costs of wiring a socket. At 15 or 20 kW, a service upgrade is increasingly likely to be required.

Costs are highly site-specific. For wiring a new 50–70 A outside plug to a circuit box already having sufficient capacity, 40 ft. away, we estimate total cost of US$ 655.[11] If a service upgrade (say, from 100 to 200 A) is required, the cost could increase by US$ 1000 up to as much as US$ 5000, mostly for labor, including permitting, shutoff, etc. For selling exclusively to the spinning reserves market, say a fuel cell vehicle that produces but cannot buy power, technically even a modest 100 A home service could accommodate over 20 kW and a 150 A over 30 kW, because unlike regulation, the current for spinning reserves would always flow vehicle-to-grid; thus, the V2G flow would always subtract from, not add to, the house loads (assuming building code and NEC approval). In our earlier work [11], we analyzed the V2G station cost, as if it were a NEC 625-compliant EV "charging station," but we no longer consider this appropriate or necessary—battery and fueled vehicles are different, and V2G implies a need to rethink the best ways to achieve the connection's functions and failure modes.

These considerations make clear that no single definitive cost can be given. Based on the above, we assume US$ 1500 capital cost for a 15 kW residential connection for regulation or spinning reserves, installed as a retrofit. This is in the range of the estimated cost of a plug (US$ 700–800) and off-board charger (US$ 300) estimated by DeLucchi et al. [54], who also acknowledge a large range about the mean. For a commercial location, the cost would be substantially less.

A.3. Communication and computing needs

We consider V2G communications to both a fleet and to dispersed vehicles. For a fleet parked in one location, managed as a collective, communications needs are simplified. Each parking space could have its telecommunications connection through a short-range, inexpensive, wireless protocol, such as Bluetooth. Only one precision certified meter is needed, at the grid connection to the whole parking lot, rather than certifying the V2G contribution of each individual vehicle.

For dispersed V2G sources, assuming an aggregator, a more general and long-distance communications link would be needed. This will be facilitated by a parallel but unrelated development—the automobile industry is making 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. With telematics capability come 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.

To allow for aggregators of dispersed V2G, and for several business models, we suggest five additions to electronic communication from the vehicle—a serial number for the vehicle, an electronic identification of which fixed (stationary) electric utility meter the vehicle is plugged into, an on-board certified meter, electronic verification that the vehicle is plugged in to a connection of known kW capacity, and an electronic "offer" and "acceptance" of a spot power contract.

A unique vehicle identifier is essential for an aggregator of V2G to bill or credit to the correct vehicle. The vehicle must also tell the utility which fixed meter it is plugged into, information it could obtain either via an electronic meter number or query of the fixed-meter. For meters without electronic identification, the fixed meter could be identified by positioning (using a global positioning system (GPS) or using the directionality of the cell phone network).

A precision certified energy meter on-board enables a shift in the notion of what entity can be a utility account. The vehicle meter becomes a "metered account" whose power may be flowing through a fixed-location traditional meter (a "fixed-meter"). The billing system must take account of which fixed-meter the vehicle is plugged into, so that the mobile-meter energy can be added or subtracted to the amount registered on the fixed-meter to reconcile the fixed-meter's billing.

It is important to electronically verify the plug capacity and that the vehicle is plugged in. These are needed, because the high-value power markets we analyze achieve most of their revenue by being available and ready to provide power (capacity payments), rather than by energy payments.

As power enters the grid from dispersed individual residences, and especially if it becomes a large enough fraction that power flow through substations would be reversed, some limited upgrades (e.g., within substations) would be required and some additional communications

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[11] For example, the following retail prices were noted in 2004 in several hardware stores; for a 125 A Jacusi panel with 60 A GFI, US$ 80, 14–50 R outlet $US 25, 40′ of 4 AWG gage copper wire US$ 100, and estimates by two electricians averaged installation requiring 5 h @ US$ 90 per hour, total US$ 655.

and control would be desirable. The electric utility industry is already planning for this eventuality due to a number of factors including distributed generation, and renewable energy, as well as V2G. We do not cover this but note progress both at the strategic level and with specific standards; the EPRI "Roadmap for the 21st Century" identifies as its first of three priorities "smart power", which "will evolve to support dynamic two-way communication with advanced end-use devices, ..., [including] two-way energy/information consumer access portals." ([4], pp. 1–4). At the standards level, IEEE SCC211547 is setting standards for interconnecting distributed resources with electric power systems [55], while IEC 6185 is established object models for communication between substations and devices, a base usable for bi-directional power flow from V2G [5].

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