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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.

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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 kW_m per vehicle (kW_m is kW mechanical), the US fleet's 176 million light vehicles have a total power capacity of 19,500 GW_m or 19.5 TW_m, which is 24

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] ÷ (602,000 MW × 365 days × 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 × 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 × 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]

[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].

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.