A STRATEGY FOR OVERCOMING PLUG-IN-HYBRID BATTERY COST HURDLES IN CALIFORNIA: INTEGRATING POST-VEHICLE SECONDARY USE VALUES

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ABSTRACT

Advances in electric-drive technology, including lithium-ion batteries, as well as the development of strong policy drivers such as California's Global Warming Solutions Act, now contribute to a more promising market environment for the widespread introduction of plug-in vehicles in California. Nevertheless, battery costs remain high. This study explores a strategy for overcoming the significant hurdle to electric transportation fuel use presented by high battery costs. It describes offsetting plug-in-vehicle battery costs with value derived from post-vehicle stationary use, and quantifies the possible effect the net-present-value of several of these benefits might have on battery lease payments. Focusing on blended-mode plug-in hybrids with minimized battery size, even the subset of values explored here (regulation, peak power, arbitrage, and some carbon-reduction credit) promise to lower battery lease payments while simultaneously allowing vehicle upgrades and profitable repurposing of vehicle batteries for stationary use as grid-support, electrical storage/generation devices. Such stationary, post-vehicle "battery-to-grid" or B2G devices could not only provide valuable services needed by existing statewide grid-support markets, but could also provide customer-side benefits, improve utility operation, help defer costly grid upgrades, and potentially support the profitability and penetration of intermittent renewable energy.

Keywords: plug-in hybrid, PHV, PHEV, electric fuel, battery leasing, secondary use, ancillary services, grid storage, electric-drive-vehicle commercialization

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INTRODUCTION

California has been attempting to encourage the commercialization of electric-fuel vehicles since the late 1980s, when the state Zero Emission Vehicle (ZEV) "mandate" was conceived. This effort saw various fits and starts in the 1990s, but did not achieve its original goal to require 2% of vehicles offered for sale by major manufacturers be ZEVs starting in 1998, ramping to up 10% by 2003.

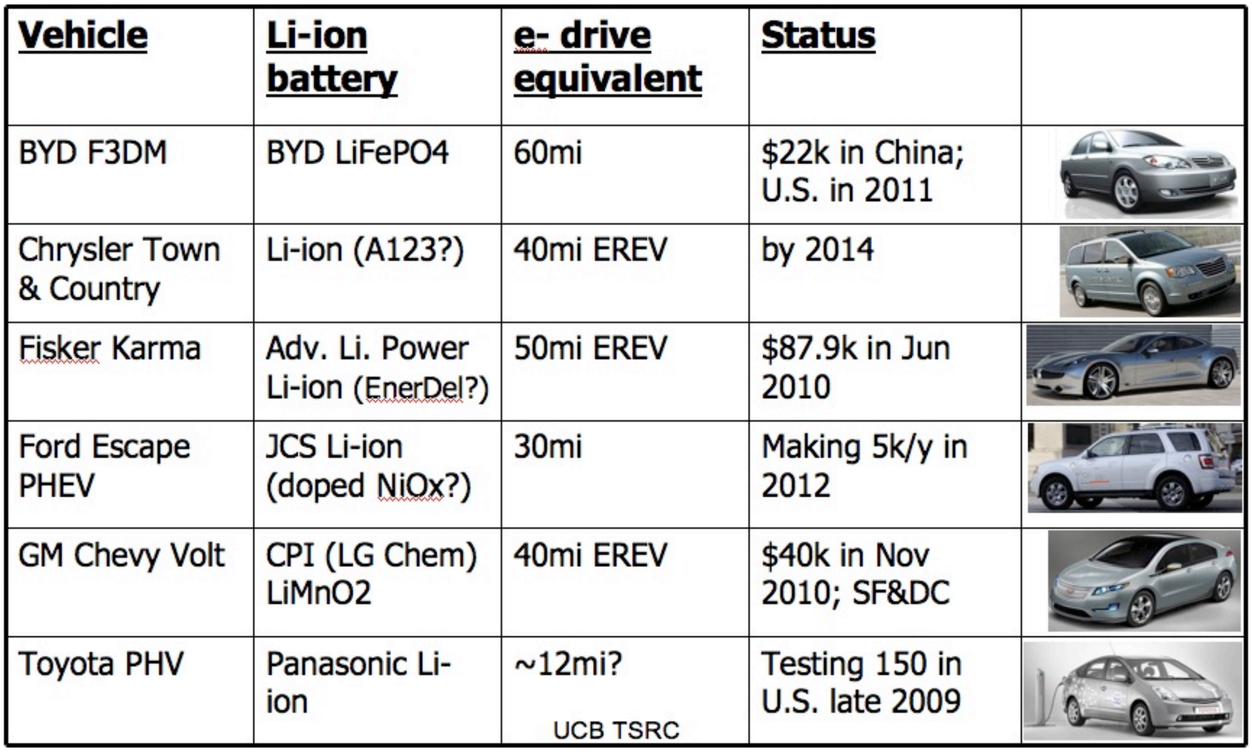
Conditions in 2009 are quite different than they were in the 1990s. As a result, the prospects for widespread introduction of electric-fuel vehicles are much more promising. Important differences include:

- various state and regional efforts to address climate change are dramatically further along than in the 1990s, particularly in California with the passage of AB32, the "Global Warming Solutions Act" that requires California's greenhouse-gas emissions be reduced to 1990 levels by 2020, the Pavley Law focusing on transportation greenhouse-gas emissions, and the Low Carbon Fuel Standard;
- electric-drive technology has advanced in performance and reduced in cost, with much improvement in electric motors and power electronics, and with high-performance lithium-based batteries now on the cusp of volume production;
- the dramatic rise in crude oil and gasoline prices in 2008 has spurred a consumer shift toward more efficient vehicles; and
- the U.S. automobile industry has fallen on hard times, with a faltering business model overly dependent on sales of the largest, heaviest, conventionally-powered passenger vehicles, and is now recognizing that it must innovate and focus on electric-drive technology in order to compete globally.

Taken together, these developments provide a very different and more promising, though economically challenging, market environment for the widespread introduction of electric-drive vehicles (EDVs) and the "implementation of electric fuel" in California.

There are still considerable remaining challenges, largely related to the high cost of advanced batteries and fluctuating oil and gasoline prices that provide an uncertain economic environment and uncertain consumer response to new vehicle technologies. Even in the absence of vehicle cost, performance, and/or infrastructure limitations, robust private value propositions for electric-fuel vehicles are needed to spark and sustain their widespread commercialization and to displace entrenched gasoline and diesel-powered cars and trucks.

Nevertheless, the confluence of energy, environmental, economic, and other strategic drivers (for example, the concurrent development of advanced batteries for military applications) has led to a groundswell of interest in electric-drive technologies around the world, and to plans by almost all automakers to introduce at least some type of electric-fuel vehicle in significant numbers in the 2010-2013 timeframe—despite lingering concerns about battery development. Figure 1 highlights some of the plug-in-hybrid development efforts of particular relevance to California.



Vehicle	**Li-ion battery**	**e- drive equivalent**	**Status**	
BYD F3DM	BYD LiFePO4	60mi	$22k in China; U.S. in 2011	
Chrysler Town & Country	Li-ion (A123?)	40mi EREV	by 2014	
Fisker Karma	Adv. Li. Power Li-ion (EnerDel?)	50mi EREV	$87.9k in Jun 2010	
Ford Escape PHEV	JCS Li-ion (doped NiOx?)	30mi	Making 5k/y in 2012	
GM Chevy Volt	CPI (LG Chem) LiMnO2	40mi EREV	$40k in Nov 2010; SF&DC	
Toyota PHV	Panasonic Li-ion	~12mi?	Testing 150 in U.S. late 2009	

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FIGURE 1 Light-duty plug-in-hybrid examples.

Focus: Plug-in-hybrid Light-duty Passenger Vehicles

Electric fuel can be used in plug-in vehicles of two basic propulsion architecture types: plug-in hybrids and electric vehicles (EVs). In addition to the electric storage systems (e.g., batteries) and electric motors used by EVs, plug-in hybrids utilize other fueled power systems, ranging from internal-combustion engines burning gasoline to fuel cells electrochemically converting hydrogen fuel and oxygen from air into electricity.

The main contenders for near-term, widespread commercialization of electric-fuel technologies are plug-in gasoline-combustion hybrids and city EVs (battery-electric vehicles providing relatively short-range use, generally using smaller-than-today's-average vehicle platforms). Several factors reinforce the notion that plug-in hybrids face substantially lower barriers to commercialization than do battery-electric vehicles, including vehicle range, battery size and cost, required consumer behavioral change, and refueling/recharging infrastructure.

Though plug-in hybrids offer lesser electric-fuel and gasoline-savings capabilities per charge, they offer greater total vehicle range capabilities, comparable or greater to consumer expectations for conventional vehicle products. It should be noted that all vehicle products needn't have equivalent range or be marketed as conventional vehicles, and different product variations could be offered on the basis of differential valuation of electric range by different market niches/segments [1]. However, because plug-in hybrids do not rely solely on electricity, they offer such electric-fuel range segmentation on an even smaller and cheaper scale with less overall consumer compromise and/or behavioral change. Further, not dependent on recharging, and thus able to utilize a sparser, cheaper, and less coordinated recharging infrastructure without significant compromise, plug-in hybrids face nontrivial but significantly lower infrastructure barriers while simultaneously benefiting from advances in the existing engine and fuel industries.

Thus, despite vehicle complexity and battery challenges created from deep-discharge operation, plug-in hybrids offer lower-cost commercialization and use on most fronts, including the contribution of per-vehicle battery systems to upfront costs. Further, with the struggling global economy and recent oil price declines having caused disproportionate reductions in conventional hybrid vehicle sales, least-cost vehicles are needed for widespread implementation. Even recognizing that gasoline prices will rise again, the incremental costs of plug-in hybrids, let alone EVs, will remain difficult to justify (e.g., [2, 3]), particularly over the next couple of decades as conventional technologies improve.

In light of cost considerations, a focus on small-battery plug-in hybrids seems appropriate. An NREL estimate indicates that using a blended approach may require several fewer kilowatt-hours (kWh) and roughly 50% fewer kilowatts (kW) than using an all-electric-range approach [4]. This contention is supported by the federal government's strategy for plug-in-hybrid research and development (R&D): "Fuel economy, rather than all-electric range (AER) is the key vehicle efficiency metric for the public; all other vehicle aspects must be competitive, including vehicle purchase and operating costs, for a PHEV [plug-in hybrid] to be marketable. A specified AER requirement could drive cost up and decrease the likelihood of production," ([5], p. 3).

In summary, for a product defined roughly as competition for light-duty-vehicle sales in California, plug-in hybrids can be expected to be cheaper and otherwise easier to adopt than battery EVs, especially in the near term. Further, blended-mode plug-in hybrids can be expected to be easier to adopt than those designed for large AER. For these and other reasons a focus on plug-in hybrids is adopted as the default throughout this analysis—though many of the strategies explored apply to both plug-in types.

A STRATEGY FOR THE ELECTRIC FUEL TRANSITION IN CALIFORNIA

The core problem motivating this analysis is that battery first costs present a major barrier to the commercialization of electric-fuel vehicles. The battery pack for the forthcoming Chevy Volt, for example, is the single largest determining factor for the entire vehicle's ~$40,000 loss-leading price point. Indeed, a recent study estimates the cost of the battery pack alone to be up to

$15,000 [6], equivalent to the retail cost of some conventional vehicles of not dissimilar size. Further, to provide its promised 40-mile all-electric range, the battery must be roughly twice as big (16 kWh), and thus costly, as what is available for propulsion (8 kWh), to allow for both "operational breathing room" (e.g., to maintain battery life by limiting depth-of-discharge) and for capacity degradation over a 15-year, 150,000-mile (241,000-km) lifetime—each accounting for roughly half of the unavailable capacity. Faced with such cost and design challenges, the extent to which such vehicles can be commercialized to the masses remains uncertain.

Working in concert, several strategies could be employed to alter the early commercialization picture for electric-fuel vehicles in California. Like the vehicles they help, these strategies straddle automotive and electrical-energy worlds, embracing their convergence. They include: battery downsizing, standardization, and leasing, with shortened initial vehicle deployment and repurposing/down-cycling into stationary use for building and grid-support services. Third-party or other non-conventional battery ownership arrangements and leasing might not only align incentives for battery improvements and full and responsible use, but may allow the net-present-value of battery services to be accounted for in the initial vehicle transaction, lowering costs, and easing initial design and commercialization expectations.

Indeed, repurposing vehicle batteries for stationary use (including infrastructure) would strengthen the ever-tightening connections between transportation and stationary energy and might help to launch a new era of electric-fuel technologies. The following describes this overall approach and uses a new model to begin the quantification and analysis of its potential benefits.

The Standard Vehicle Battery Pack

Consider a standardized vehicle battery pack with a form factor (or perhaps a few form factors) appropriate for the operation of plug-in hybrids, as well as some relatively minimal balance of plant providing for battery health and standard interfaces (e.g., a voltage monitor, health/throughput meter, some minimal intelligence, and cooling and electrical connections).

If initially (i.e., using today's state of technology) capable of containing 6 kWh—enough to provide a mid-sized blended-mode gasoline plug-in hybrid a roughly 15-mile (24-km) "EV" or "electric" range—such a pack might be expected to cost roughly $9,000 or less in the near term at the retail level (at a conservative $1,250/kWh for the battery modules plus another ~$1,500 for balance of plant).

The Battery Lease

At $9,000 or less per pack during initial introduction, a significant upfront cost hurdle remains. A battery lease could help spread those costs over the operational life of the pack, say 10 years—a reasonable minimum target before use in vehicles might normally be considered, though a challenging technology-development goal for battery suppliers. Indeed, it should be noted here that vehicular applications for batteries are demanding in several ways, including: 1) rigorous operating environment and conditions, 2) load profiles demanding rapid response, deep discharges, and low-state-of-charge operation, and 3) long design life. Nevertheless, if the standardized pack were to be available for 10 years of automotive life for $9,000, a $250 lease setup fee and a 7% real rate of interest would yield a roughly $130/month lease (or the equivalent if structured, e.g., per mile, not including electricity or recharging infrastructure)—still a significant premium to pay for a vehicle with recharge capability. How might this situation be further improved?

Re-defining the Battery-pack Lifecycle

In the plug-in-hybrid commercialization scenario described above, the large-format propulsion battery, a young innovation, is forced to compete in its infancy as a commodity in a competitive automotive supply market. Even with the help of some type of lease, which could align incentives in a such a way as to shift battery design, manufacture, provision, use, and take-back somewhat towards a more lifecycle-oriented electric-fuel-service enabler, the financing picture remains challenging, driven by high initial costs and long and demanding life requirements. Further, because suitability for automotive application is defined so rigorously, including the need to specify for an end-of-design-life capacity, a relatively high-value and capable asset emerges at the end of the financing period. What residual value might remain, and, if brought forward into the initial purchase decision, to what degree might it help ameliorate the battery lease payment?

Several opportunities for creating secondary value from propulsion batteries exist, both during its initial deployment onboard the vehicle—referred to here as supplemental value—as well as afterwards, in subsequent vehicular or stationary applications. Many opportunities would significantly complicate initial commercialization challenges. For example, supplemental use during initial vehicle deployment in applications like vehicle-to-grid, emergency, or mobile power [7]—if used to a significant degree—might further tax immature battery durability and be difficult to anticipate and accommodate into the initial vehicle design requirements and consumer performance expectations. And “cascading” batteries from more demanding vehicular applications to less demanding ones—e.g., from a large, new-model, highly-capable, and possibly pricey OEM plug-in hybrid to a smaller, lower-expectation, possibly cheaper used-hybrid conversion, and then to non-highway vehicle niches, etc.—might increase standardization challenges and/or require complex, customized refurbishing and refitting. Nevertheless, these opportunities should be investigated given the potentially long useful lifetimes of some of the latest battery technologies.

One secondary application that might present somewhat lower and simpler initial performance, design, standardization, and other challenges might be the one-time repurposing of plug-in-hybrid vehicular battery packs into stationary electricity appliances. Such devices could be used—distributed in household garages/basements or aggregated into power centers—as power and energy storage devices providing various services to the grid, the utility, and the neighborhood electrical distribution system, as well as the building in which they were located, with benefits on both sides of the electrical meter. No longer facing portability and environmental survivability requirements, re-rated and repurposed battery packs may effectively provide valuable services years after “retirement” from plug-in-hybrid application.

“Repurposing” the Pack for Stationary Use

Consider the 6-kWh battery pack described above, initially sized based on an expected 20% degradation in capacity over its ten-year automotive design life. After, say, five years of high-capacity service in a rigorous vehicle environment, it is “repurposed” and re-rated at 5.4 kWh with an 80% allowed depth of discharge for 4.3 kWh of capacity available for stationary use.

Repurposing (to re-add the dis/charge, inverter, cooling, and safety capability left behind in the car) and infrastructure installation (e.g., a 240V, 30+A plug and wiring with ground-fault interrupt) may cost roughly $7,000. Annualized over 10 additional years of low-average-depth-of-discharge, mild-temperature, and otherwise less-demanding remaining stationary life, leads to nearly $1,000 in annual capital costs. Can this electric storage appliance provide a net benefit that could be brought forward to help with the original battery-lease financing?

Revenue Streams

Once repurposed and situated for stationary use, the pack and its electrical storage/generation capability could provide several services, including regional grid support; avoided generation, transmission, and distribution upgrades for utilities; avoided energy and demand charges for buildings; and emergency power. A subset of these values is analyzed below.

Grid-support Services: Regulation and Peak Power

Adapting and building upon previous research [7-9], that explored the case of vehicle-to-grid (V2G) service provision for supplemental value, this subsection explores stationary battery-pack electrical storage/power provision, or battery-to-grid (B2G) services for secondary value.

At the super-utility level, a regional grid operator—in California, the Independent System Operator (CAISO)—is charged with the nearly statewide, larger-scale balance of electricity supply and demand, in order to maintain the availability and quality (e.g., frequency) of the electricity being bought by consumers [10]. To meet these demands, markets for peak power, spinning-reserves, and regulation services have been created, requiring increasingly rapid response. They are relatively costly to serve with large power plants and might be better served by relatively small, agile generators and/or storage devices scattered about the electrical landscape. Peak-power markets only pay participants for the energy actually supplied. In contrast, ancillary-service (spinning-reserve and regulation) markets also pay generation for being on-call and available, based on the power capacity promised over a given contract period. Thus an important determinant of revenues for a device selling services in ancillary-service markets is the number of hours it is assumed to be grid-connected, available, and on-call each day.

Actual generation is typically rarely called upon each year in these three markets, and even when it is, it is generally required for very short periods of time. Thus the demands on a B2G device selling such services would be relatively modest, particularly when compared to automotive use. Table 1 summarizes these markets, and the last column shows the assumed time per year a battery pack might be asked to generate energy (i.e., total call or dispatch time).

TABLE 1 Grid-support Services

	Response time	Revenue payments	Dispatch call frequency	Generation duration per call	Generation time (h/y)
Peak power	Medium	For *energy* generated	~40–60 calls per year (back calculated from rule of thumb)	3–5 hours [4 hours]	Industry rule of thumb for central CA: [200h/y]
Spinning reserves	10 min	For *energy* [$0.03/kWh] and *capacity* per kilowatt available for contract period [$0.007/kW-h]	[20 calls per year]	10 min to 2 hours [1 hour]	[20h/y]
Regulation **reg. up** = supply electricity to grid; **reg. down** = draw from grid	<1 min; direct control of independent system operator (ISO)	For *energy* [$0.10/kWh] and *capacity* [reg. up and down: $0.04/kW-h; reg. up only: $0.02/kW-h]	Many short calls per day	A few minutes [reg. up and down: 20 min; reg. up only: 1.4 hours]	[1/10th of time plugged in]

*Example values from 2005 modeling done by Kempton and Tomic [8, 9] are included in brackets for convenience and subsequent comparison.

Peak power revenues are sensitive to the usual variety of electricity-generation factors, such as “fuel” (input electricity) prices. However, because actual energy-production levels tend to be particularly small in regulation and spinning-reserves markets, their revenues tend not to be very sensitive to the cost of fuel inputs or energy-converter degradation. Their profits are sensitive, however, to the prices offered to generation capacity for being on call and to the capital costs of the “generation” technology. A device can contract for either regulation or spinning reserves, but probably not both. Previous studies and preliminary modeling indicate that regulation is likely to be the most profitable service for battery packs to provide.

Starting from the description of V2G net revenues in [9] and utilizing many of the equations described therein, this subsection describes a new model constructed to estimate B2G net revenues. Key features of the assessment of regulation services from this battery pack are presented below, and, after discussion of addition revenue streams, Table 2 summarizes many of the common key inputs.

Cost of Regulation Energy With 4.3 kWh per pack available after 5 years in automotive application (as described above), the repurposed battery pack could fulfill up to an 8.6-kW, half-hour regulation call. Assuming the stationary battery pack is: 1) available 7,060 hours per year (20 useful hours per day, with one unavailable day per month); 2) called upon an average of one-tenth of the time available; and 3) able to “generate” at $0.13/kWh (by buying electricity at an average price of $0.115/kWh and storing it with 85% round-trip efficiency); providing regulation energy costs roughly $816 per year.

Regulation Revenues Regulation revenues include energy and capacity payments. Selling regulation energy at the same average price ($0.115/kWh) yields approximately $697/year. On the capacity front, batteries could sell both regulation-up (capacity to produce power) and regulation-down (capacity to consume power, which can be used to charge the battery). Using the CAISO's 2006–2008 regulation capacity price (regulation up plus regulation down)—which averages to $0.033 per kilowatt capacity made available per hour contract ($0.033/kW-h)—an 8.6-kW device could earn and additional $1,971 per year in regulation capacity payments. This brings regulation revenue to a total of $2,668 per year, or $1,852 per year net of energy costs.

It would take about 85,000 battery packs to amount to the 2006–2008 average CAISO regulation requirement of 732 MW/y—which is likely to rise, particularly with increased renewable portfolio standards and penetration of variable wind power. For a sense of scale, 85,000 each packs making $1,800 per year would earn >$150 million, though revenues are unlikely to remain constant as markets begin to saturate and the value of regulation services starts to fall.

Peak Power In order to meet a peak-power call of up to 4 hours, the full 4.3-kW battery pack could be rated at only 1.1 kW, significantly limiting the battery pack's ability to earn peak-power revenue. At 1.1 kW, 150 hours/year of peak power energy supplied at $0.13/kWh would cost $22/year to provide. Whereas receiving $0.50/kWh for peak power energy would earn the battery pack $81/year, for revenue net of energy of $59/year. These values are modest but at only 150 hours per year could easily be complementary with some of the other values discussed here. Further, in some markets the peak power opportunity could be significantly greater.

Electricity Arbitrage

Peak power markets represent an extreme case where the grid will pay unusually high prices for energy during a relatively small number of hours per year. There also exists an opportunity to arbitrage, or "buy low" (generally at night) and "sell high" (generally during daily peaks), on a more modest scale throughout the year, based on time-variable pricing. Reference [11] used bins of real California electricity price (equals system marginal cost) data to explore how much opportunity for arbitrage existed for a theoretical 1-kW storage device of various storage capacities. Interpolating, scaling, and building upon their results, a 4.3-kWh storage device could earn roughly $114/year, arbitraging some 265 kWh of electricity, and assuming an average spark spread of $0.10/kWh.

TABLE 2 Key Study Inputs

	Estimate
Capital Costs – Battery Pack	
Initial cost	
cost of battery (per kWh)	$1,250
size of battery (kWh)	6.0
cost of balance of battery pack	$1,500
Total battery pack cost	*$9,000*
In car	
design life in car (y)	10
depth of discharge allowed in car	0.80
Initial available capacity in car (kWh)	*4.8*
In house	
time in car (y)	5
capacity degradation in car (per y)	0.978
capacity remaining after car (kWh)	5.37
depth of discharge allowed in house	0.80
Available capacity in house (kWh)	*4.29*
Annualized costs	
discount rate	0.07
life factor (B2G cycle-life/car cycle-life)	2
Energy	
cost of "fuel" (per kWh)	$0.115
kWh in / kWh out	0.85
Cost of electricity out (per kWh)	*$0.13*
Regulation	
dispatch/contract ratio	0.1
capacity price for reg. up+down (per kW-h)	$0.033
regulation energy price (per kWh) = fuel cost from above	$0.1150
total CA regulation required, up+down (MW/y)	732
Peak Power	
peak-power demand (h/y)	150
price of peak power (per kWh)	$0.50
Arbitrage	
"spark spread" including transmission & losses (per kWh)	$0.10

Carbon reduction

Electrical storage could increase the rated capacity of intermittent wind power and store otherwise wasted (e.g., nighttime) wind energy [11] for strategic displacement of high-carbon generation, thereby conceivably earning some carbon-reduction credit.

To begin the undoubtedly complex process of identifying, estimating, and assigning some carbon-reduction value to a standardized battery pack, the following rough calculation is made. Given 4.3 kWh of storage, 353 days of availability, and 85% roundtrip efficiency, and assuming roughly two fills per day on otherwise "wasted" wind energy, approximately 2,600 kWh/y of wind energy might be re-generated by the battery-pack storage device. If displacing electricity at a California *average* carbon intensity of ~0.3 metric tons of CO_2 equivalent per megawatt-hour [12], and receiving \$15/TCO_2 (the low end of the range of California carbon prices predicted by a Deutsche Bank report, [13]), the value of the carbon reductions would amount to ~\$12/year. Though modest, this indicates that the B2G strategy can begin to benefit from even low carbon prices, much lower than what might be needed to help plug-ins overcome their price premium through fuel savings. Further, detailed analyses of opportunities for renewable energy-enablement and carbon reductions are needed.

Secondary-Use-Value Summary and the Battery Lease

Summing the four revenue streams described above (~\$1,850/year for regulation + ~\$60/year for peak power provision + ~\$110/year from arbitrage + ~\$10/year for carbon reduction) and subtracting the ~\$7,000 annualized cost of repurposing the battery pack and supplying sufficiently high-power infrastructure (-~\$1,000/year) yields secondary-use net revenues of over \$1,000 per year for the stationary battery pack.

Because stationary use can be made significantly less demanding with lower average depth of discharge, as described above, it may be reasonable to assume that the 1 year of car life is worth roughly 2–3 years of stationary life. For example, if consistently cycling at 30% DOD, a battery pack might get ~30,000 cycles, the equivalent energy throughput of 9,000 80% DOD cycles (= 3 times the 3,000-cycle life at 80% DOD) [14]. This is an interesting area for further research: to better understand the effects of stationary-use duty-cycles on older vehicle batteries in terms of both lifetime energy throughput (kWh) and calendar time.

At a 7% discount rate, the net present value of 10 additional years of summed revenues, beginning in year six (after five years' service in a plug-in hybrid), is over \$5,000 or nearly 60% of the initial capital cost of the battery pack. If such "residual" value could be brought into the lease calculation, the \$131 per month lease requiring full depreciation over ten years is lowered to a \$90/month, five-year lease. This offers both monthly savings in addition to the opportunity to upgrade the vehicle's electric-drive performance every five years with a newer, presumably cheaper and more capacious and powerful pack.

Sensitivities

Initial modeling reveals several key sensitivities to input assumptions, including the following.

Cost of Battery Pack This study of near-term commercialization uses the relatively conservative assumption that a 6-kWh battery pack, with some minimal balance of plant providing for battery health and standard interfaces (e.g., a voltage monitor, health/throughput meter, some minimal intelligence, and cooling and electrical connections) will cost \$9,000. Battery costs are expected by some to drop rapidly as manufacturing facilities are built for a variety of automaker electric-drive-vehicle programs. Figure 2 shows how the monthly lease payment (incorporating secondary value) varies with the assumed initial cost of the 6-kWh battery pack. Note that the lease payment drops to zero as the battery pack approaches \$5,000.

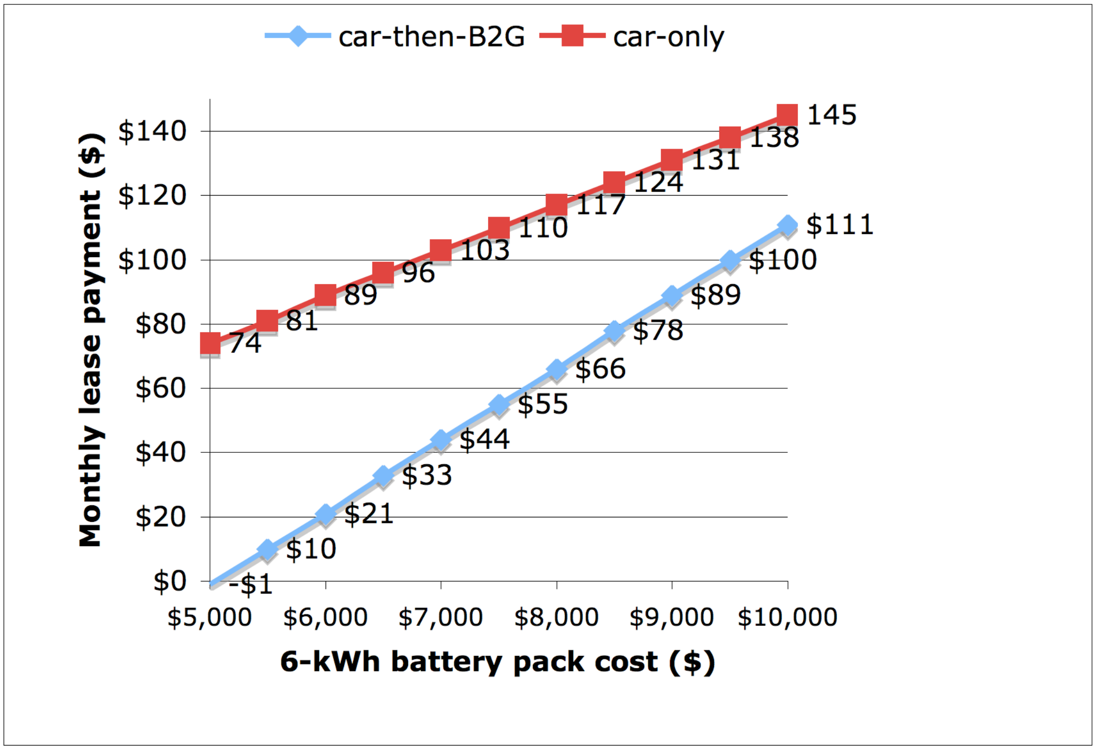

FIGURE 2 Sensitivity of the lease payment to the battery pack cost.

Size of Battery Pack Although the benefits calculated above do generally increase with available storage capacity (even when not accompanied by favorable input assumptions), bigger is not always better: infrastructure capital costs are lumpy and uncertain but high at high power levels (due primarily to electrical service upgrades which include significant labor costs), dampening the benefits in high-power B2G scenarios as they pass thresholds for greater required infrastructure investment.

Availability Regulation revenues, and thus the overall results, are sensitive to variation in the number of hours per day the devices are available, on-call, and being paid for regulation.

Illustrative Sensitivity Comparison Figure 3 compares the overall effect of varying four key inputs one at a time (ceteris paribus) over a reasonable range. As discussed above, battery-pack cost is an important determinant of the monthly lease amount. The exact size of the battery (keeping the pack cost constant) is less important. However, it should be noted that increasing the battery size much above the range considered here would likely result in a dramatic, non-linear change in the lease price due to a step increase in the cost of the electrical facilities necessary to take advantage of the increased B2G battery power capacity.

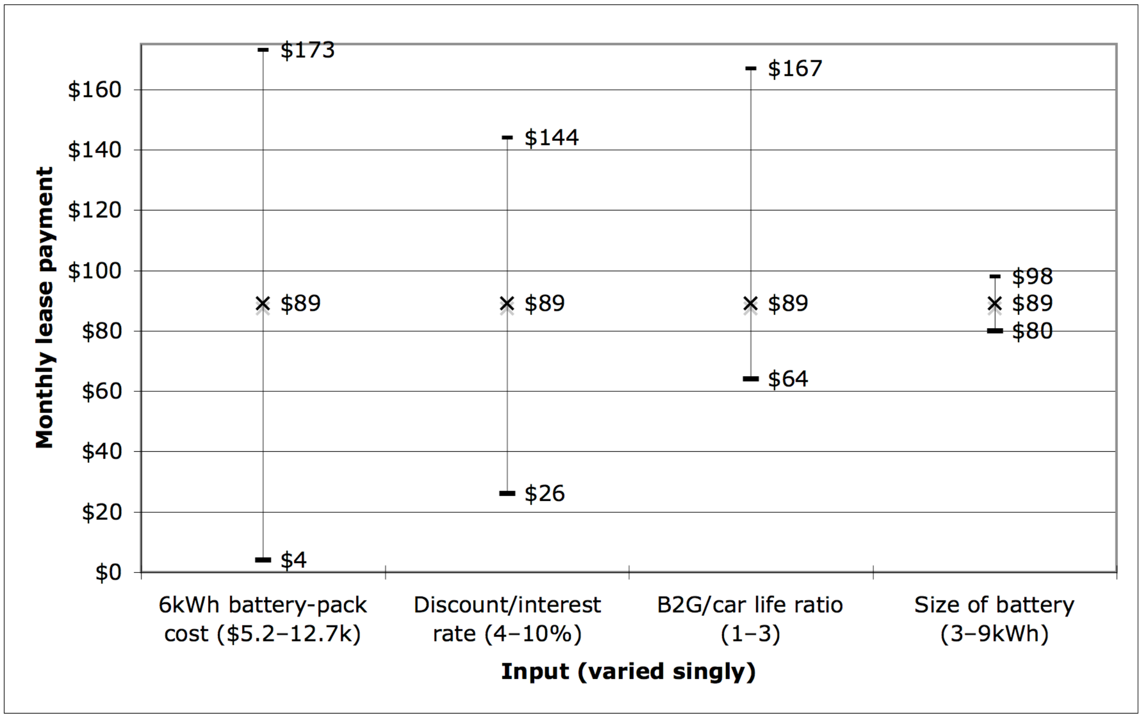

FIGURE 3 Comparison of the sensitivity of the lease payment to key inputs, varied singly.

Bounding Cases and Uncertainty Range

The strategy presented thus far has focused on a best-guess "estimate" case. Table 3 summarizes this case, as well as presenting bounding cases: a "low" case for a 3-kWh battery pack and unfavorable input assumption values made throughout, and a "high" 9-kWh case with favorable assumptions.

TABLE 3 Battery-pack Grid-support-value Estimates (Per Year) with Illustrative Uncertainty Range

Battery-to-grid (B2G) value, per y	"Low" (3 kWh with unfavorable inputs)	"Estimate" (6 kWh)	"High" (9 kWh, favorable inputs)
Regulation revenue covering energy costs	$227	$1,852	$7,172
Peak-power revenue covering energy	$6	$59	$174
Arbitrage revenue covering energy	$24	$114	$323
Carbon avoided by wind storage	$0	$12	$198
Annualized infra. capital costs	-$629	-$977	-$1,660
Net revenue, covering infra. capital	-$373	$1,059	$6,207

Other Unquantified Values

Many other potential values have not yet been quantified here. Previous studies [15, 16], both published in 2002, lay foundations for evaluating dozens of these potential values, and some of the analysis remains pertinent today. Potential sources of additional value include, but are not limited to:

- transmission, distribution, and generation support and upgrade deferral;
- other ancillary/grid services;
- other aspects of renewables firming and carbon reduction;
- power reliability;
- residential and commercial load following;
- uninterruptible and/or high-quality power requirements, for example for data centers or telecommunication facilities; and
- demand-response capacity and deployment.

The national lab study [15] focused on nickel-metal-hydride (NiMH) batteries, but suggested that the results are likely to be broadly applicable to other chemistries. Of the applications studied, the report identified no "show stoppers" and four "possible" applications for used EV batteries: transmission support, light commercial load following, residential load following, and distributed node telecommunication backup. Residential load following and telecomm backup were considered "favorable" because the lifecycle costs were estimated to be below the low end of the calculated value spread. Additionally, recycling and end-of-life disposal—whether initially an additional form of residual value or a necessary cost (e.g., due to the cost of shipping heavy batteries to recycling/disposal centers)—should be examined and compared across strategies.

SUMMARY AND RECOMMENDATIONS

This study discusses overcoming the significant hurdle to electric transportation fuel use presented by high battery costs. As battery costs are expected to fall over time, efforts should focus on reducing barriers to adoption in the near term in order to establish markets, supply chains, and infrastructure, and build production volumes. Less costly, less compromised in performance, requiring a sparser and cheaper infrastructure, less disruptive to consumer behavior, and able to benefit from existing fuel and engine systems as they improve over time, plug-in-hybrid vehicles present lower barriers to commercialization than do all-battery electric vehicles. This is despite increased challenges presented by deep-discharge battery operation and the complicated marriage of combustion-mechanical and electric drivetrains, and despite the greater emissions and energy-dependence reductions provided by large-battery designs.

Policies aimed at supporting the initial transition to electric-fuel technologies should equally focus on minimized-battery plug-in hybrids, while maintaining frameworks open enough to allow niche and subsequent development of large-battery and battery-EV markets and technologies. Particularly in these economic times, measures with significant costs aimed at overcoming challenges specific to battery EVs may not be in the broadest interest of efficiently supporting wide, rapid, cost-effective initial electric-fuel implementation in California.

Working in concert, several strategies could be employed to alter the early commercialization picture for electric-fuel vehicles in California. Like the plug-in-hybrid vehicles they are designed to help, these strategies straddle automotive and electrical-energy worlds, embracing their convergence. The combination of strategies examined here includes:

battery downsizing, standardization, and leasing, with intentionally shortened initial vehicle deployment (five, versus 10 years in the vehicle) and repurposing/down-cycling into stationary use as electrical storage/generation devices for building and grid-support services. Even the subset of post-vehicle values explored here—regulation, peak power, arbitrage, and some carbon reduction credit—promise to lower battery lease payments while simultaneously allowing vehicle battery upgrades and profitable repurposing of vehicle batteries for stationary use. For example, if such post-vehicle “residual value” could be brought into the lease calculation for a mid-sized-plug-in-hybrid-vehicle battery, a $131-per-month, car-only lease requiring full depreciation over ten years is lowered to a $90/month, five-year lease in the repurposing scenario. Conservatively high, pre-volume battery costs were assumed, and lower costs would improve this picture dramatically (e.g., the required lease payment goes to zero as the 6-kWh pack cost approaches $5k rather than $9k, and in a bounding scenario combining several reasonable but optimistic assumptions the value more than covers the lease payment by several hundred dollars). This offers both monthly savings in addition to the opportunity to upgrade the vehicle’s electric-drive performance every five years with a newer, cheaper and more capacious/powerful pack.

Of course, the realization of these benefits is predicated upon several assumptions and pre-conditions, requiring coordination, standardization, code and safety-procedure development, and granting such “battery-to-grid” (B2G) units access to several existing and future markets. Initial policy steps already identified that would allow or improve the strategies like those described here include: modifying certificating procedures to include battery storage devices as CAISO generating units, further rewarding fast-response units in proportion to their operational and other benefits, and providing investment incentives [17].

Battery lease models offer one potentially powerful mechanism for helping to establish a framework for capturing battery values throughout their life cycle. Third-party ownership arrangements and battery leasing might not only align incentives for battery improvements and full and responsible use, but may allow the net-present-value of these and other battery services to be accounted for in the initial vehicle transaction, lowering costs, and easing initial design and commercialization expectations.

Looking forward, energy services companies, utilities, and other grid entities would appear to be prime candidates to play a major role implementing these strategies. Not only do they have a unique understanding of the grid and will necessarily be central to plug-in vehicle recharging, they have billing access and existing relationships with consumers throughout California, where most electric-fuel transactions will likely take place. Given the many potential benefits to the grid, and the unique position utilities occupy, rate-based utility investment in vehicle/B2G batteries may be justified. Action appears to be at least arguably allowed by the California PUC code, and possibly encouraged by national PURPA “smart grid” regulations, so long as competitiveness and the interests of the ratepayer can be maintained. Clarification of these policies, and directing the in-depth investigation of specific manifestations of the strategies such as those discussed here, would strengthen the ever-tightening connections between transportation and stationary energy and spur a new era of electric-fuel technologies.

Directions for future work

B2G devices could not only provide valuable services needed by existing statewide grid-support markets, but could provide additional value not analyzed here. Customer-side-of-the-meter benefits, demand-response capability, improved utility operation, deferred grid upgrades, and further support of the profitability and penetration of wind power and other carbon-reduction measures, for example, could greatly improve these already intriguing prospects. End-of-life recycling and disposal must also be considered. In subsequent projects, we intend to analyze more of these values, with a comprehensive sensitivity analysis, to address the open questions of 1) are these markets cumulatively adequate to attract interest and 2) how might they evolve, beyond simple saturation, transforming the electrical landscape as large numbers of vehicles and batteries become available?

Additionally, further analysis should weigh the benefits of implementing household/building B2G (in both the current context and the context of the coming “smart grid” wherein household device control may be implemented for other reasons anyway) versus spatially aggregating B2G units into “battery-pack power plants” or demand-response units. These larger systems should have economies of capital, operational, and transactional scale, avoid concerns about safety in home-use devices, and possibly simplify other challenges. However, they may not offer some of the more localized benefits to “feeder level” power distribution systems.

Finally, other overall strategies of importance to the commercialization of electric-fuel and plug-in technologies not examined here include: low-load/efficient vehicle platform development, various approaches to increase battery production volume, identification of motivated target consumers, and the development of other forms of creative financing and policy incentives for vehicle adoption.

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