Strategy for Overcoming Cost Hurdles of Plug-In–Hybrid Battery in California

Integrating Post-Vehicle Secondary Use Values

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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 of hybrid batteries and quantifies the possible effect the net present value that several of these benefits might have on battery lease payments. With a focus on blended-mode plug-in hybrids with minimized battery size, even the subset of values explored (regulation, peak power, arbitrage, and some carbon reduction credit) promises to lower battery lease payments while simultaneously allowing vehicle upgrades and profitable repurposing of vehicle batteries for stationary use as grid support, electrical storage and generation devices. Such stationary, post-vehicle battery-to-grid 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.

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 went through various fits and starts in the 1990s but did not achieve its original goal to require that 2% of vehicles offered for sale by major manufacturers be ZEVs starting in 1998, ramping up to 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 the following:

- 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, which requires that 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 spurred a consumer shift toward more efficient vehicles.
- 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 and the implementation of electric fuel in California.

Considerable remaining challenges remain, 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 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 time frame, despite lingering concerns about battery development. Figure 1 highlights some of the plug-in hybrid vehicle development efforts of particular relevance to California.

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 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 EVs providing relatively short-range use, generally with vehicle platforms smaller than today's average vehicle platforms). Several factors reinforce the notion that plug-in

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

FIGURE 1 Examples of light-duty plug-in hybrids (BYD = BYD Auto; LiFePO4 = lithium iron phosphate; JCS = Johnson Controls-Saft; CPI = Compact Power, Inc.; EREV = extended-range electric vehicle; SF&DC = San Francisco and Washington, D.C.).

hybrids face substantially lower barriers to commercialization than do battery EVs, including vehicle range, battery size and cost, required consumer behavioral change, and refueling and recharging infrastructure.

Though plug-in hybrids offer less electric fuel and gasoline-saving capabilities per charge, they offer greater total vehicle range capabilities, comparable with or greater than consumer expectations for conventional vehicle products. All vehicle products need not 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 and 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 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 if one recognizes that gasoline prices will rise again, the incremental costs of plug-in hybrids, let alone EVs, will remain difficult to justify (*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 estimate by the National Renewable Energy Laboratory indicates that using a blended approach may require several fewer kilowatt-hours (kW-h) and roughly 50% fewer kilowatts (kW) than using an all-electric-range (AER) approach (*4*). This contention is supported by the federal government's strategy for plug-in–hybrid vehicle research and development:

> 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.

STRATEGY FOR 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-mi AER, the battery must be roughly twice as big (16 kW-h), and thus costly, as what is available for propulsion (8 kW-h), to allow for both "operational breathing room" [e.g., to maintain battery life by limiting depth of discharge (DOD)] and capacity degradation over a 15-year, 150,000-mi (241,000-km) lifetime—each accounting for roughly half of the unavailable capacity. 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 or down-cycling into stationary use for building and grid-support services. Third-party or other non-conventional battery ownership arrangements and leasing not only may align incentives for battery improvements and full and responsible use but also 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. This overall approach is described and a new model is used to begin the quantification and analysis of its potential benefits.

Standard Vehicle Battery Pack

A standardized vehicle battery pack is considered 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 and throughput meter, some minimal intelligence, and cooling and electrical connections).

If initially (i.e., with today's state of technology) capable of containing 6 kW-h—enough to provide a midsized blended-mode gasoline plug-in hybrid with a roughly 15-mi (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/kW-h for the battery modules plus another ~$1,500 for the balance of plant).

Battery Lease

With $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, vehicular applications for batteries are demanding in several ways, including (*a*) rigorous operating environment and conditions; (*b*) load profiles demanding rapid response, deep discharges, and low-state-of-charge operation; and (*c*) 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 $131/month lease (or the equivalent if structured, for example, per mile, not including electricity or recharging infrastructure), which is still a significant premium to pay for a vehicle with recharge capability. How might this situation be further improved?

Redefining Battery-Pack Life Cycle

In the commercialization scenario described earlier for the plug-in-hybrid, 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 toward a more life-cycle-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 that value was 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. "Cascading" batteries from more demanding vehicular applications to less demanding ones (e.g., from a large, new-model, highly capable, and possibly pricey original equipment manufacturer plug-in hybrid to a smaller, lower-expectation, possibly cheaper used-hybrid conversion, and then to nonhighway vehicle niches) might increase standardization challenges or require complex, customized refurbishing and refitting, or both. 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 battery packs into stationary electricity appliances. Such devices could be used—distributed in household garages or 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, rerated and repurposed battery packs may effectively provide valuable service years after retirement from the plug-in-hybrid application.

Repurposing Battery Pack for Stationary Use

The 6-kW-h battery pack described earlier is initially sized on the basis of an expected 20% degradation in capacity over its 10-year automotive design life. After, say, 5 years of high-capacity service in a rigorous vehicle environment, it is repurposed and rerated at 5.4 kW-h with an 80% allowed DOD for 4.3 kW-h of capacity available for stationary use.

Repurposing (to add back the discharge, inverter, cooling, and safety capabilities left behind in the car) and infrastructure installation (e.g., a 240-V, 30+-A plug and wiring with ground-fault interrupt) may cost roughly $7,000. Annualizing over 10 additional years of low average DOD, 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 battery pack and its electrical storage and generation capabilities 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 next.

Grid-Support Services: Regulation and Peak Power

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

At the superutility 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 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 capacity for being on call and available, on the basis of 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 called upon rarely 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 with automotive use. Table 1 summarizes these markets, and the last column shows the assumed time per year that a battery pack might be asked to generate energy (i.e., total call or dispatch time).

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 low in regulation and spinning reserve 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.

From the description of V2G net revenues in the work by Kempton and Tomic (*9*) and from many of their equations, a new model is described constructed to estimate B2G net revenues. Key features of the assessment of regulation services from this battery pack are presented, and after discussion of additional revenue streams, many of the common key inputs are summarized in Table 2.

Cost of Regulation Energy With 4.3 kW-h per pack available after 5 years in automotive application (as described earlier), the repurposed battery pack could fulfill up to an 8.6-kW, half-hour regulation call. By assuming that the stationary battery pack is available 7,060 h per year (20 useful hours per day, with one unavailable day per month), is called upon an average of one-tenth of the time available, and is able to generate at $0.13/kW-h (by buying electricity at an average price of $0.115/kW-h and storing it with 85% roundtrip 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/kW-h) yields approximately $697 per 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 $0.033/kW capacity made available per hour contract ($0.033/kW-h)—an 8.6-kW device could earn an additional $1,971 per year in regulation capacity payments. This computation 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 per year, which is likely to rise, particularly with increased renewable portfolio standards and penetration of variable wind power. For a sense of scale, 85,000 packs making $1,800 per year would earn >$150 million, though revenues are unlikely to remain constant as

TABLE 1 Grid-Support Services

	Response Time	Revenue Payments	Dispatch Call Frequency	Generation Duration per Call	Generation Time (h/year)
Peak power	Medium	For energy generated	~40–60 calls per year (backcalculated from rule of thumb)	3–5 h [4 h]	Industry rule of thumb for central Calif.: [200h/year]
Spinning reserves	10 min	For energy [$0.03/kW-h] and capacity per kilowatt available for contract period [$0.007/kW-h]	[20 calls per year]	10 min to 2 h [1 h]	[20h/year]
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/kW-h] 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 h]	[1/10 of time plugged in]

NOTE: Example values from 2005 modeling done by Kempton and Tomic (*8, 9*) are included in brackets for convenience and subsequent comparison.

TABLE 2 Key Study Inputs

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

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 h, 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 h/year of peak-power energy supplied at $0.13/kW-h would cost $22/year to provide. Receiving $0.50/kW-h 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 h 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 in which 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. Lamont (*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. By interpolating, scaling, and building on his results, a 4.3-kW-h storage device could earn roughly $114/year, arbitraging some 265 kW-h of electricity and assuming an average spark spread of $0.10/kW-h.

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 kW-h 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 kW-h/year of wind energy might be regenerated by the battery-pack storage device. If electricity were displaced at a California average carbon intensity of ~0.3 metric tons of CO_2 equivalent per megawatt-hour (*12*) and $15/metric ton of CO_2 [the low end of the range of California carbon prices predicted by a Deutsche Bank report (*13*)] were received, the value of the carbon reductions would amount to ~$12/year. Though modest, this amount 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.

Summary of Secondary Use Value and Battery Lease

Summing the four revenue streams just described (~$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 DOD, as described earlier, it may be reasonable to assume that the 1 year of car life is worth roughly 2 to 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*). An interesting area for further research would be to better understand the effects of stationary use duty cycles on older vehicle batteries in terms of both lifetime energy throughput (in kilowatt-hours) and calendar time.

At a 7% discount rate, the net present value of 10 additional years of summed revenues, beginning in Year 6 (after 5 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/month lease requiring full depreciation over 10 years is lowered to a $90/month, 5-year lease. This calculation offers both monthly savings and the opportunity to upgrade the vehicle's electric drive performance every 5 years with a newer, presumably cheaper and more capacious and powerful pack.

Sensitivities

Initial modeling reveals several key sensitivities to input assumptions.

Cost of Battery Pack This study of near-term commercialization uses the relatively conservative assumption that a 6-kW-h battery pack, with some minimal balance of plant providing for battery health and standard interfaces (e.g., a voltage monitor, health and throughput meter, some minimal intelligence, and cooling and electrical connections), would 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-kW-h battery pack. The lease payment drops to zero as the battery pack approaches $5,000.

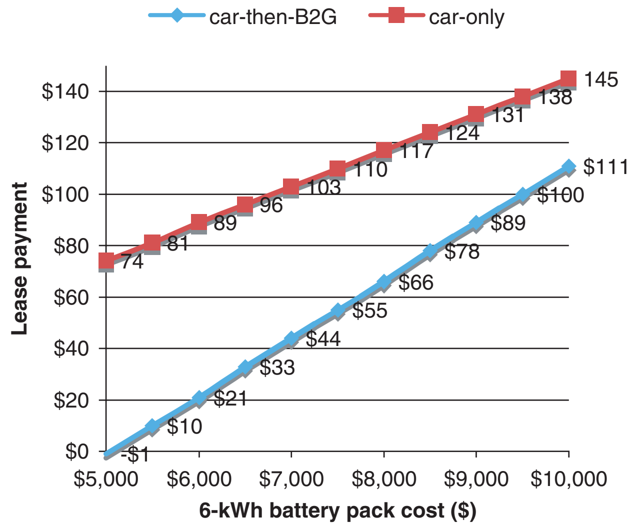

FIGURE 2 Sensitivity of lease payment to battery-pack cost.

Size of Battery Pack Although the benefits calculated earlier 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 (primarily because of 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 (all else remaining the same) over a reasonable range. As discussed earlier, 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, nonlinear change in the lease price because of a step increase in the cost of the electrical facilities necessary to take advantage of the increased B2G battery power capacity.

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 bounding cases: a low case for a 3-kW-h battery pack and unfavorable input assumption values made throughout and a high 9-kW-h case with favorable assumptions.

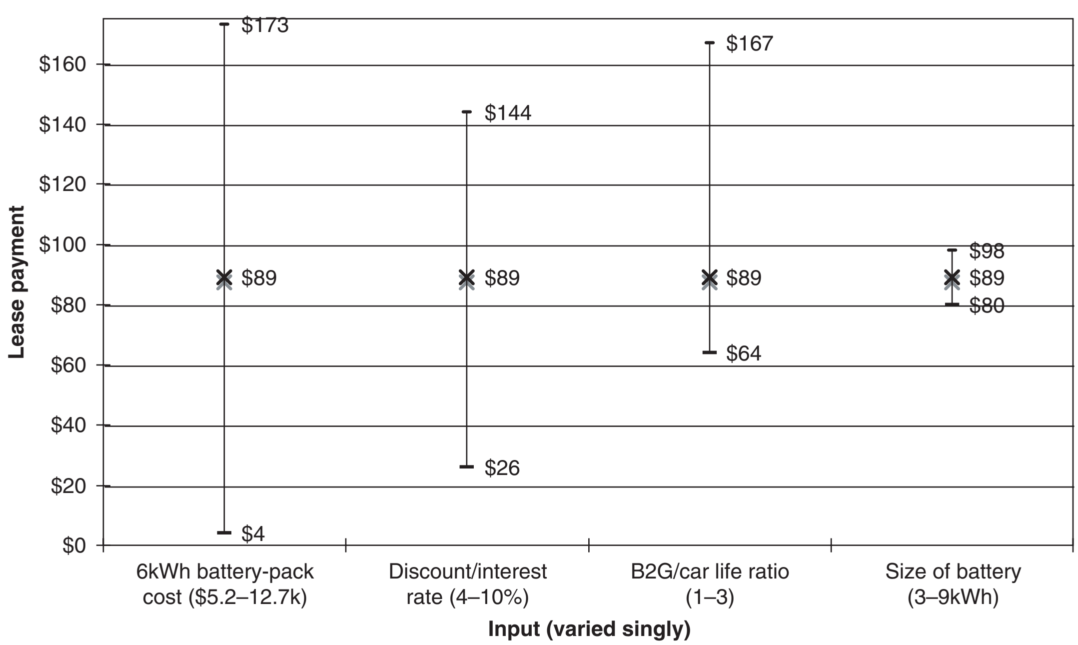

FIGURE 3 Comparison of sensitivity of lease payment to key inputs, varied singly.

TABLE 3 Estimates of Battery-Pack Grid Support Value per Year with Illustrative Uncertainty Range

Battery-to-Grid (B2G) Value, per year	Low (3 kW-h with unfavorable inputs)	Best-Guess Estimate (6 kWh)	High (9 kW-h, 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 infrastructure capital costs ($)	−629	−977	−1,660
Net revenue, covering infrastructure capital ($)	−373	1,059	6,207

Other Unquantified Values

Many other potential values have not 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, the following:

- Transmission, distribution, and generation support and upgrade deferral;
- Other ancillary and grid services;
- Other aspects of renewables firming and carbon reduction;
- Power reliability;
- Residential and commercial load following;
- Uninterruptible or high-quality power requirements or both, for example, for data centers or telecommunication facilities; and
- Demand–response capacity and deployment.

The Sandia National Laboratories 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 telecommunications backup. Residential load following and telecommunications backup were considered favorable because the life-cycle costs were estimated to be below the low end of the calculated value spread. In addition, recycling and end-of-life disposal—whether initially an additional form of residual value or a necessary cost (e.g., because of the cost of shipping heavy batteries to recycling and 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. Since 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 hybrids present lower barriers to commercialization than do all-battery EVs. This finding 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 difficult 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 hybrids 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 (5 versus 10 years in the vehicle) and repurposing or downcycling into stationary use as electrical storage and generation devices for building and grid-support services. Even the subset of other post-vehicle values explored here—regulation, peak power, arbitrage, and some carbon reduction credit—promises to lower battery lease payments while simultaneously allowing vehicle battery upgrades and profitable repurposing of vehicle batteries for stationary use. For example, if such residual value could be brought into the lease calculation for the battery of a midsized plug-in hybrid, a $131-per-month, car-only lease requiring full depreciation over 10 years is lowered to a $90/month, 5-year lease in the repurposing scenario. Conservatively high, prevolume battery costs were assumed, and lower costs would improve this picture dramatically (e.g., the required lease payment goes to zero as the 6-kW-h pack cost approaches $5,000 rather than $9,000, and in a bounding scenario combining several reasonable but optimistic assumptions, the value more than covers the lease payment by several hundred dollars). This scenario offers both monthly savings and the opportunity to upgrade the vehicle's electric drive performance every 5 years with a newer, cheaper, and more capacious and powerful battery pack.

Of course, the realization of these benefits is predicated on several assumptions and preconditions, requiring coordination, standardization, code, and safety-procedure development and granting such 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 not only may align incentives for battery improvements and full and responsible use but also 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.

In the future, energy services companies, utilities, and other grid entities would appear to be prime candidates to play a major role in implementing these strategies. Not only do they have a unique understanding of the grid and will necessarily be central to plug-in hybrid recharging, but they also 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 Public Utilities Commission code and possibly encouraged by national Public Utility Regulatory Policies Act "smart grid" regulations, so long as competitiveness and the interests of the rate payer 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 not only could provide valuable services needed by existing statewide grid-support markets but also could provide additional value not analyzed here. Benefits to the customer side of the meter, 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, the authors intend to analyze more of these values, with a comprehensive sensitivity analysis, to address the open questions of whether these markets are cumulatively adequate to attract interest and how they might evolve beyond simple saturation, transforming the electrical landscape as large numbers of vehicles and batteries become available.

In addition, further analysis should weigh the benefits of implementing household and building B2G units (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 and 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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