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ADDENDUM

Addendum to 'An innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles'

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Abstract

This addendum adds to the analysis of 'An innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles' (D M Lemoine *et al* 2008 *Environ. Res. Lett.* **3** 014003) to the case of all-electric vehicles (EVs). We pay particular attention to grid impacts, break-even battery costs, and the three ways in which EVs could dramatically change the results we obtained for plug-in hybrid electric vehicles (PHEVs).

Keywords: electric vehicle, plug-in hybrid vehicle, transmission grid

In a recent study (Lemoine *et al* 2008) we modeled the economic and grid impacts of plug-in hybrid electric vehicle (PHEV) usage. We found that based on a cost-benefit framework, California drivers would often use grid-supplied electricity to power their PHEVs, and the California grid should be able to support millions of PHEVs in the near term without requiring additional capacity. We also found, however, that unless battery prices fall or long-term gasoline prices rise, PHEVs' expected fuel savings would not compensate vehicle purchasers for the additional battery cost relative to the current generation of hybrid electric vehicles. Since we completed that project, attention and interest in all-electric vehicles (EVs) have introduced additional vehicle scenarios that are worth exploring. For example, Better Place[4] has partnered with a number of municipalities to encourage significant regional initiatives to introduce and support EVs. Several automobile companies have announced future EV models to complement Better Place. In this note we present a pure EV analysis.

The main differences between the PHEV cases we studied and a new EV case is that the decision to pump gasoline or charge the battery from the grid has been removed[5]. Only PHEV operators have the choice of charging from the grid or purchasing a liquid fuel. It is still important to consider the implications of different charging patterns for the electric grid, but now the driver may have less ability to direct the vehicle's charging to low demand hours because the vehicle requires longer to charge and because the vehicle no longer has the ability to use fuels other than electricity. Table 1 compares PHEVs from the previous analysis (which had a 20 mile all-electric range) with EVs based on prospective Better Place vehicles. Because the charging time for an EV is similar to that for a full-size sport utility vehicle (SUV) PHEV but the charging rate for the EV is likely to be three times greater than what we modeled, the previous worst-case charging pattern results for SUV PHEVs still hold except with the number of vehicles producing a given level of electricity demand being divided by 3 (figure 1).

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[4] http://www.betterplace.com/.

[5] We ignore the possibility of an electric vehicle serving as a second car. In this case, because operating efficiencies are similar for modeled EVs and for PHEVs in all-electric mode, the charging decision analysis should be similar to our earlier work, with the first gasoline-fueled car's fuel efficiency replacing the PHEV's gasoline-mode fuel efficiency in calculations of fuel cost/mile.

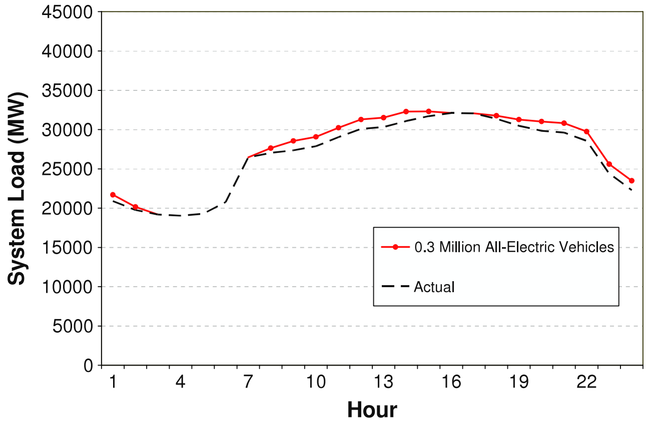

Figure 1. The CAISO system load curve for 3 August, 1999 with a fleet of 0.3 million EVs in the worst-case *Twice-Per-Day-Charging* scenario. EVs charge at a rate of 3 kWh h^{-1} and require 7 h to recharge their batteries. This scenario has the vehicles charging their entire battery capacity in the morning upon arriving at work and in the evening after arriving home. See figure 3 and associated discussion in Lemoine *et al* (2008) for more information.

Table 1. Characteristics of all-electric vehicles (EVs) in this analysis and plug-in hybrid electric vehicles (PHEVs) from the previous analysis.

	EVs[a] (compact cars)	PHEVs[b] (compact cars)	PHEVs[b] (SUVs)
Vehicle efficiency (miles kWh^{-1})	4	4	N/A[c]
Battery pack size (kWh)	28	5	N/A[c]
Charging rate (kWh h^{-1})	3	1	1
Time to fully charge (h)	8	4	7

[a] EVs are based on prospective Better Place vehicles. The battery size includes 25 kWh available for charging as well as extra capacity to account for depth-of-discharge limitations.

[b] PHEVs have a 20 mile all-electric range and are as modeled in Lemoine *et al* (2008), which was based on EPRI (2002). Reported efficiencies are for all-electric mode.

[c] The PHEV analysis did not use efficiencies or total battery pack sizes for SUVs.

We defined grid impacts as occurring if vehicle charging raises the system's peak load. Because transmission and generation resources can at least meet previous peak load, the grid should (with a few caveats) be able to handle charging scenarios that do not increase peak demand. We found that 1 million SUV PHEVs could require an expansion of generation and transmission capacity by stretching morning charging into afternoon hours. While 0.3 million EVs could produce the same potentially problematic result, this result is overly pessimistic because it depends on the EVs needing to charge fully upon arriving at work[6]. This assumption was reasonable for SUV PHEVs under the twice-per-day-charging scenario, but EVs consistently arriving at work with completely depleted battery packs are like conventional vehicles consistently arriving at work with completely empty gasoline tanks, a risky proposition. If EVs have not used all of their battery capacity on their morning commute, then their relatively rapid charging rate means that they may not charge for nearly as long as did the SUVs in our analysis and so may not extend charging into the afternoon hours of high electricity demand. It is therefore unlikely that EVs would have problematic impacts for the general California electric grid unless near-term statewide adoption far exceeds 0.3 million vehicles and their charging patterns are completely unmanaged.

We defined the break-even battery cost as the battery price at which the vehicle's additional battery capacity exactly pays for itself in expected fuel savings. At 4 miles kWh^{-1}, the efficiency of the modeled EV is similar to the all-electric efficiency of the compact car PHEV we modeled previously, but the battery size is now 28 kWh instead of 5.1 kWh. Also, we maintain the assumption that additional battery cost is equal to marginal vehicle cost, but in reality EVs should also have savings from not needing a gasoline engine at all. In the original study, we found that battery costs were too high to make PHEV batteries pay for themselves through expected fuel savings, and this conclusion holds even more firmly for pure EVs (table 2). With gasoline expensive at \$4/gallon and electricity cheap at \$0.05 kWh^{-1}, battery prices would need to fall below \$200 kWh^{-1} for EVs rather than only needing to reach \$700 kWh^{-1} for PHEVs.

Importantly, EVs may differ from PHEVs in three ways that could drastically change both the economic and grid impact analyses. First, Better Place is aiming to sign up vehicle owners to pricing plans that could change the vehicle purchase calculation. If these pricing plans include tiered rates and reduce vehicle purchase costs by keeping battery ownership with the company, then the vehicle purchaser's financial analysis would change radically. Second, several companies are developing software and distributed infrastructure to charge vehicles under centralized direction or, at least, centralized observation, and because they need greater access to charging infrastructure, EV owners may be more likely than PHEV owners to join these plans. If EVs connect to the grid via a centralized interface and, perhaps, centralized command structure, then mitigating grid impacts may focus on changing the charging incentives and coordinating software rather than needing to adjust the behavior of potentially anonymous vehicle loads. While our financial calculations focused on batteries' value in providing transportation services, the combination of a centralized charging interface and new vehicle ownership models could allow companies to obtain additional battery value from end-of-life applications and grid support services. Finally, because EVs are most practical in areas with shorter trip lengths and with distributed charging infrastructure, companies could target particular urban areas for mass introduction of EVs. In this case, EV electricity demand could stretch local transmission and distribution resources even without affecting the grid's peak demand. This targeted adoption scenario could call for careful coordination between EV companies and utilities to ensure the availability of grid resources beyond generation capacity.

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[6] However, as discussed later, EVs could impact local transmission and distribution resources well before they substantially raise peak load and require new generation capacity.

Table 2. Annual and present value of fuel savings and break-even battery costs for an all-electric vehicle (EV) relative to comparable hybrid electric vehicles (HEVs) and to comparable conventional vehicles (CVs). This table adapts table 4 from Lemoine *et al* (2008).

Annual fuel savings from EVs relative to both HEVs and CVs[a]							
Gasoline price ($/gal)		$2		$3		$4	
		HEV	CV	HEV	CV	HEV	CV
Electricity price ($ kWh^{-1})	$0.05	$308	$446	$531	$738	$753	$1030
	$0.10	$170	$309	$393	$600	$616	$892
	$0.15	$33	$171	$256	$463	$478	$755
	$0.20	−$105	$34	$118	$325	$341	$617
	$0.25	−$242	−$104	−$19	$188	$203	$480
	$0.30	−$380	−$241	−$157	$50	$66	$342
Present value of fuel savings from EVs				16% discount rate over 12 years[b]			
Gasoline price ($/gal)		$2		$3		$4	
		HEV	CV	HEV	CV	HEV	CV
Electricity price ($ kWh^{-1})	$0.05	$1600	$2318	$2757	$3834	$3914	$5351
	$0.10	$885	$1603	$2042	$3120	$3200	$4636
	$0.15	$171	$889	$1328	$2405	$2485	$3922
	$0.20	−$544	$174	$613	$1691	$1770	$3207
	$0.25	−$1259	−$540	−$101	$976	$1056	$2492
	$0.30	−$1973	−$1255	−$816	$261	$341	$1778
Break-even EV battery cost ($/kWh)[c]				16% discount rate over 12 years[b]			
Gasoline price ($/gal)		$2		$3		$4	
		HEV	CV	HEV	CV	HEV	CV
Electricity price ($ kWh^{-1})	$0.05	$62	$83	$107	$137	$152	$191
	$0.10	$34	$57	$79	$111	$124	$166
	$0.15	$7	$32	$51	$86	$96	$140
	$0.20	−$21	$6	$24	$60	$69	$115
	$0.25	−$49	−$19	−$4	$35	$41	$89
	$0.30	−$76	−$45	−$32	$9	$13	$63

[a] EV efficiency is 4 miles kWh^{-1}, HEV efficiency is 49.4 miles/gallon, and CV efficiency is 37.7 miles/gallon (EPRI 2002). Each vehicle travels 11 000 miles year^{-1} (US Department of Transportation 2001).

[b] The 16% discount rate corrects for vehicle depreciation and declining vehicle usage over a 12 year vehicle lifetime and is based on an interest rate of 6% (Greene and DeCicco 2000).

[c] Accounting for an 80% depth-of-discharge limitation, the HEV battery pack size is 2.2 kWh (EPRI 2002). The total EV battery pack size is 28 kWh. We take the additional battery cost to represent the entire marginal vehicle cost (which is less defensible for EVs), we do not include battery replacement or new business models, we treat future fuel prices as constant and certain, and we assume that the purchase of an EV does not change the cost of other household electricity consumption.

Electrified transportation may be crucial to the transition to a low-carbon future because it becomes cleaner as the grid becomes cleaner. PHEVs promise to connect a portion of vehicle miles to potentially low-carbon electricity sources, and EVs promise to completely merge transportation into the electricity system. If electricity sector emissions are capped and if this cap is not either set in anticipation of EVs or adjusted upon their adoption, then switching to EVs could displace all of the greenhouse gas (GHG) emissions of gasoline-fueled vehicles. In reality, electricity sector GHG targets may be adjusted if there is no economy-wide carbon price and if EVs and PHEVs lead the electricity sector to provide transportation sector GHG abatement. Nonetheless, EVs and PHEVs provide the ability to clean up transportation sector emissions even after the vehicles have been purchased. Whereas each generation of more efficient gasoline-fueled vehicles requires the fleet to turn over in order to obtain all of the potential GHG emission reductions, EVs only require the fleet to adopt their technology once in order to obtain maximum emission gains. Introducing EVs soon can begin the slow process of adopting the vehicles that could enable achievement of long-term GHG targets.

References

EPRI 2002 Comparing the benefits and impacts of hybrid electric vehicle options for compact sedan and sport utility vehicles (1006892) http://www.epriweb.com/public/000000000001006892.pdf

Greene D L and DeCicco J 2000 Engineering-economic analyses of automotive fuel economy potential in the United States *Annu. Rev. Energy Environ.* **25** 477–536

Lemoine D M, Kammen D M and Farrell A E 2008 An innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles *Environ. Res. Lett.* **3** 014003

US Department of Transportation 2001 National household travel survey http://nhts.ornl.gov/index.shtml