

Evaluating the Cost-Effectiveness of Greenhouse Gas Emission Reductions from Deploying Plug-in Hybrid Electric Vehicles

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Executive Summary

Plug-in hybrid electric vehicles (PHEVs) have the potential to reduce automotive greenhouse gas (GHG) emissions and petroleum consumption and improve urban air quality. In order for PHEV purchases to become economical to cost-conscious consumers under current market conditions, battery prices must decline from about \$1,300/kWh to below \$500/kWh, or U.S. gasoline prices must remain at roughly \$5/gallon - or policy innovations and incentives need to be instituted that have a roughly equivalent effect. We use the GREET model to estimate that PHEVs can provide cost-effective GHG emission reductions if purchasing the vehicles becomes more economical from a fuel savings perspective, and this is especially true if the vehicles use very low-GHG electricity as the main power source. The latter case could require technologies and regulations to integrate both the vehicles and the generation technologies into the electricity system. Policies to improve battery costs and lifetimes, to decrease the GHG intensity of electricity, and to raise gasoline prices relative to electricity prices can make the significant direct GHG emission reductions from PHEVs cost effective. It is unlikely that in the near-term a carbon price alone would make PHEVs' direct abatement economical because such a price would need to exceed \$100/tonne-CO₂eq. Given current technologies and prices, replacing full-sized conventional sport utility vehicles with hybrid electric sport utility vehicles is a highly cost-effective GHG mitigation strategy. However, a large-scale shift to PHEVs could enable much greater GHG abatement in the future. To facilitate this evolution, a broad and sustained portfolio of PHEV battery research, development, and deployment is justified. Federal policy action supporting both research and deployment could aggressively change the economic landscape in favor of widespread PHEV adoption. An area of particular importance is the inclusion of PHEV opportunities in low-carbon fuel standards, such as those passed in California and under review in several other states as well as in European nations.

1. Introduction

Cars and light trucks in the U.S. consume about eight million barrels of gasoline per day, more than total U.S. petroleum production, and account for 18% of national greenhouse gas (GHG) emissions. Both consumption and emissions have been rising at about 1.5% per year (1, 2).

Plug-in hybrid electric vehicles (PHEVs) could alter these trends. On a vehicle technology spectrum that stretches from fossil fuel-powered conventional vehicles (CVs) through hybrid electric vehicles (HEVs) to all-electric vehicles (AEVs), PHEVs fall between the latter two types (3, 4): they can run either in gasoline-fueled hybrid electric mode (like an HEV) or in all-electric mode with grid-supplied energy (like an AEV). PHEVs are intriguing because they combine the best aspects of CVs (long range and easy refueling) with the best aspects of AEVs (low tailpipe emissions and reduced petroleum use), and hence promise to reduce transportation-related GHG emissions, improve urban air quality, reduce petroleum consumption, and expand competition in the transportation fuels sector. Several companies now offer to convert HEVs to PHEVs, and several automakers, notably General Motors, Daimler-Chrysler, and Toyota, have announced PHEV development projects.

Fueling these announcements is the growing popular consensus that HEVs provide significant petroleum and GHG emission reductions at small costs and the corresponding hope that PHEVs (as well as AEVs and fuel cell vehicles) may offer even more of these benefits. At least one prior study, however, found that neither the fuel savings from HEVs' increased efficiency nor the value to society of their lower air pollutant and GHG emissions offset their increased capital costs (5), though that study used U.S. fuel prices, which are lower than those in many other developed countries, and is of declining relevance in a changing automotive market. In any case, few consumers base their vehicle purchase decisions primarily around fuel costs and many are willing to pay a premium for the symbolic and environmental benefits of HEV ownership (6). Like PHEVs, AEVs and fuel cell vehicles promise deeper emission reductions, but their higher capital costs make these reductions expensive (7, 8). One study comparing the social costs of CVs and AEVs concluded that the value of AEVs' reduced pollution only offsets the high cost of their batteries if the electricity is produced with very low air pollution (9); however, the CV emission rates in that study are up to an order of magnitude higher than current standards in California. Because AEV-level capital costs would be required to obtain the benefits of PHEVs' reduced GHG emissions, these findings suggest that we must be cautious before applying conventional wisdom about HEV cost-effectiveness to PHEVs.

Caution is warranted because PHEV batteries cost more than their HEV counterparts since they must store more energy. Until recently, only HEVs had been analyzed according to the cost-effectiveness criterion (5), though now at least one study has examined PHEVs along these lines as well (10). In the PHEV study, the authors found that, in the specific case of a compact-car PHEV20 under current market and policy conditions (3), the expected fuel savings from increased efficiency do not compensate consumers for the increased capital cost. (11) reaches a similar conclusion despite using a real options approach to better value the fuel flexibility provided by PHEVs' batteries. Therefore, PHEVs could be consigned to a small or non-existent market share unless their symbolic benefits vis-à-vis HEVs become sufficiently strong, market conditions become sufficiently favorable, battery technologies become significantly cheaper, or policies are implemented that sufficiently support these new vehicles.

A separate consideration, which the authors of the PHEV study (10) leave open, is that of PHEVs' cost-effectiveness in reducing GHG emissions on a dollars-per-metric-tonne-of-carbon-dioxide-equivalent (\$/tonne-CO₂eq) basis. This question is important because PHEVs' reduced emissions of GHGs (as well as other pollutants) have real economic value to society, and hence governments, firms, or individuals might be willing to subsidize PHEV purchases in order to achieve these benefits—provided that the \$/tonne-CO₂eq cost is not too great. The purpose of this paper is to address this question, so that PHEVs may be compared with other GHG-mitigation options (e.g. reforestation, building insulation) on a cost curve like that found in (12) (p. xiii). However, while we focus on PHEVs' value as a GHG abatement strategy, PHEVs also offer social benefits through reduced petroleum consumption and reduced urban air pollution that many other GHG abatement options will not. Any comparison of PHEVs with other abatement technologies on the basis of \$/tonne-CO₂eq is therefore incomplete. We consider only GHGs and leave other air pollutants for future research. Though we conclude that PHEVs are not currently a cost-effective means of mitigating GHGs (see Section 2.3), we find that they could become so under certain scenarios that we present below (see Section 2.5). We conclude by discussing the commercial and policy implications of our results.

2. Methods and Results

We compare a CV, an HEV, and two PHEVs—one that can travel 20 miles using only grid-supplied electricity (called a *PHEV20*) and one that can travel 60 miles using only grid-supplied electricity (called a *PHEV60*)—in both compact car and full-size SUV models (8 vehicle scenarios total), following the assumptions made in prominent prior studies (3, 4) (Table 1). Note from the table that while PHEVs are much more efficient at using gasoline than are CVs, they are only slightly more efficient than HEVs, and thus almost all of the benefits of converting from HEVs to PHEVs lie in PHEVs' ability to switch fuels, allowing a portion of PHEVs' miles to be driven on cheaper and cleaner electricity. Note also that while these prior studies model PHEVs' gasoline-mode fuel economy as higher than that of HEVs, the opposite may turn out to be true because of the extra weight of the PHEVs' batteries.

2.1 Battery sizes and types

We follow (3,4) in considering PHEVs using an AER-focused strategy that requires their batteries to run the vehicle as an AEV over some number of miles. Such PHEVs would need energy batteries (which can store and deliver large amounts of energy over longer timescales) that can also supply the high-power portions of the driving cycle.

2.2 Fuel prices and vehicle purchase incentives

The conditions under which PHEV owners would have an economic incentive to use electricity rather than gasoline are determined by the relative fuel efficiencies of each operational mode and the prices of the two energy sources. Following the methodology of (10), Table 1 shows the electricity rates that provide the same cost per mile of PHEV operation as do various gasoline prices. Lower rates than the ones shown would encourage PHEV owners to drive in electric mode, while higher rates

would favor gasoline-fueled hybrid-electric mode. For comparison, average U.S. residential electricity rates are about \$0.083/kWh, and U.S. gasoline prices averaged about \$2.75/gallon in 2006 (13).

The higher efficiency of PHEVs, and their ability to switch to a generally cheaper fuel, result in cost savings over the lifetime of the vehicles that have the potential to offset PHEVs' higher capital cost and incentivize their purchase. Because of utility tariff and tax structures, however, PHEV owners may pay electricity rates that are higher than the average rates, which would erode the vehicles' cost savings (see (10) for a discussion of tariff and tax considerations). On the other hand, a 'grid optimal' nighttime charging arrangement could enhance PHEV cost savings and take advantage of possibly idle low-GHG generation capacity (though there are several caveats—see Section 2.4). We make the simplifying assumption of a constant \$0.10/kWh electricity price along with a constant \$2/gal gasoline price for our base case scenario, described in Section 2.5.

2.3 Break-even battery cost

Following the methodology of (10), we define the *marginal fuel savings* as the net present value (NPV) of a vehicle's fuel savings stream relative to another vehicle under our fuel price assumptions, and we divide these marginal fuel savings by the additional nominal battery capacity required by the first vehicle to obtain the *break-even battery cost* of the first vehicle relative to the second, which is the price (in \$/kWh) to which batteries must fall in order for consumers to obtain an exact payback from marginal fuel savings when deciding to buy the (higher capital cost) first vehicle instead of the second. Conceiving of the different vehicle types as placed along a continuum of efficiency upgrades, we compare HEVs to CVs, PHEV20s to HEVs, and PHEV60s to PHEV20s. In the base case we assume that consumers possess a 16% discount rate (14), that batteries represent the entire *marginal vehicle cost*, and that batteries last the entire 12-year vehicle lifetime. We also assume that the vehicles drive 11,000 miles (17,700 km) annually and that PHEV20s drive 39% of their miles in all-electric mode while PHEV60s drive 74% of their miles in electric mode (4).

Break-even battery costs for the purchase of HEVs and PHEVs at various gasoline prices are presented in Table 1. For comparison, the U.S. Advanced Battery Coalition (USABC) has adopted a target of \$150/kWh (15), and market battery prices are about \$1,300/kWh according to Hymotion, a company that performs PHEV conversions. Thus, we find that consumers' break-even costs are lower than actual HEV or PHEV battery prices, implying that fuel savings alone would not currently offset the vehicles' increased capital cost and thus justify their purchase (this result is consistent with (10), and with (5) in the case of HEVs).

TABLE 1. Efficiency, battery, and cost characteristics of modeled vehicles ^a

	Fuel economy ^b		Grid electricity to travel AER (kWh)	Battery pack size ^b (kWh)	Equivalent electricity price ^c (\$/kWh)			Break-even battery cost ^c (\$/kWh at \$0.10/kWh electricity)		
	(mi/gal)	(mi/kWh)			\$2.00/gal gasoline	\$3.00/gal gasoline	\$4.00/gal gasoline	\$2.00/gal gasoline	\$3.00/gal gasoline	\$4.00/gal gasoline
	Compact car									
CV	37.7									
HEV	49.4			2.2				\$326	\$490	\$653
PHEV20	52.7	4.01	4.99	5.1	\$0.152	\$0.228	\$0.304	\$149	\$320	\$490
PHEV60	55.0	4.04	14.9	15.2	\$0.147	\$0.220	\$0.294	\$29	\$68	\$106
Sport utility vehicle (full-size SUV)										
CV	18.2									
HEV	27.6			5.2				\$412	\$618	\$825
PHEV20	29.5	2.31	8.66	8.9	\$0.157	\$0.235	\$0.313	\$220	\$461	\$702
PHEV60	30.2	2.43	24.7	25.3	\$0.161	\$0.241	\$0.322	\$37	\$79	\$121

^a AER: all-electric range (20 miles for a PHEV20, etc). See Sections 2.1-2.3 for details and assumptions of our calculations. ^b (3, 4). ^c Expanded from the methodology of (10).

2.4 GHG emission reductions

To determine the avoided GHG emissions from HEVs and PHEVs, we use a well-to-wheels assessment of the transportation fuel sector called “The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation” (GREET) model (16). Note that we do not include emissions from vehicle or battery manufacturing (17). We update GREET with GHG emission data for the full fuel lifecycles of a number of different power plant types (18, 19). Then we calculate the life-cycle GHG emissions in gCO₂e/mile of each vehicle type when operating in gasoline mode and, when applicable, in electric mode. We present our results in Table 2.

TABLE 2. Per-mile petroleum consumption and GHG emissions of modeled vehicles ^a

	Petroleum use ^b (BTU/mi)		GHG emissions from gasoline use and from electricity use with different generation mixes ^b (gCO ₂ e/mi)						
	Gasoline	NGCC electricity	Gasoline	US Avg	CA Avg	NGCC	IGCC	IGCC w/CCS	Wind
Compact car									
CV	3,260		294						
HEV	2,490		225						
PHEV20	2,330	10	211	199	116	135	282	38	1.4
PHEV60	2,240	10	203	198	115	134	280	37	1.4
Sport utility vehicle (full-size SUV)									
CV	6,750		605						
HEV	4,450		401						
PHEV20	4,170	18	375	346	202	234	490	65	2.4
PHEV60	4,070	17	367	329	192	222	466	62	2.3

^a **NGCC: natural gas combined-cycle; IGCC: integrated gasification combined-cycle; CCS: carbon capture and sequestration. See Section 2.4 for details of assumptions and calculations.**

^b (16, 18, 19).

The efficiency gains achievable by simply adopting a hybrid drive train are significant, as evidenced by the 23% lower GHG emissions for compact HEVs and 34% lower emissions for SUV HEVs compared to their CV counterparts. PHEVs essentially eliminate petroleum consumption per mile when operating in electric mode, but their GHG emission reductions depend critically on the type of electricity generation used to power the vehicles. We include the U.S. average and California average electricity grid mixes in the table for purposes of comparison, but because PHEVs represent new electricity demand and consume electricity produced by the marginal plant, in the short run it is incorrect to calculate the vehicles' environmental impacts using average electricity emissions. In the long run, if PHEVs become numerous enough to lead to new investment in electricity generation then an analysis using average emissions becomes more reasonable (in the absence of regulatory constraints on the GHG intensity of new power plants), but even under the most aggressive market penetration scenarios this would not occur for 5-10 years (10).

The marginal power plant varies with time and location, but under the standard U.S. power system arrangement it is often a thermal plant burning natural gas because the output of such plants can be controlled, making them "dispatchable." In contrast, nuclear power plants (as well as many coal plants) attempt to operate at maximum capacity at all times, though they may end up operating below capacity at night when demand is low. Many renewable electricity generators (such as wind or photovoltaic arrays, but not solar thermal, large-scale hydroelectric, or geothermal) must generate using whatever resource level is available and so cannot be dispatched (20), and they are often given the highest priority in the electricity system's loading order. Therefore unless these renewable electricity generators would have needed to scale back their production in the absence of PHEVs by, for instance, shedding wind during low-demand nighttime hours (cf. 21), they cannot be considered the marginal plants for PHEV charging and it would be inappropriate to consider new PHEV demand as being supplied by them. Under other theoretical power system arrangements involving more actively managed charging, it might be possible for wind turbines to charge PHEVs, but such arrangements would have many complexities and require further study.

If operated on integrated gasification combined cycle (IGCC) coal electricity without carbon capture and sequestration (CCS), compact and SUV PHEVs reduce GHG emissions by 4% and 19% relative to their CV counterparts. But these GHG reductions are actually *less* than those achieved by HEVs running on gasoline (23% and 34%, respectively). Thus, when the marginal plant is such a coal plant, it is *always* better from a GHG perspective to drive either an HEV or, almost equivalently, a PHEV in gasoline-fueled hybrid electric mode rather than a PHEV in grid-supplied all-electric mode. In comparison to CVs running on gasoline, however, PHEVs charging from coal are the better option (though more so in the case of SUVs than compacts). These findings may have severe implications if electric utilities want to push PHEV charging into off-peak hours when coal-fired units may be the marginal plants in some U.S. regions. When operated on natural gas combined cycle (NGCC) electricity, compact and SUV PHEVs reduce GHG emissions by 54% and 61% relative to their CV counterparts. For very low-GHG plants, such as IGCC plants with CCS, wind turbines, or nuclear plants, PHEVs can reduce GHG emissions by as much as 85% relative to CVs under average driving conditions and could reduce GHG emissions by nearly 100% when driven only in electric mode.

2.5 PHEV cost-effectiveness in reducing GHGs, and sensitivity analyses

We define the size of the subsidy necessary to incentivize PHEV purchases as the marginal vehicle cost minus the marginal fuel savings, assuming that expected fuel costs determine which type of vehicle (CV, HEV, or PHEV) a buyer purchases within a broader class of vehicles (such as compacts or SUVs) (see Section 2.3). If no subsidy is needed, we set the size of the subsidy at \$0, precluding negative values for GHG abatement costs. As mentioned in Section 1, vehicle purchasers do not explicitly follow net present value calculations, but the comparison between expected fuel savings and additional capital cost is an interesting one and may serve as a passable proxy for the general attractiveness of PHEVs. To measure GHG mitigation cost-effectiveness, we divide the subsidy size for each vehicle option by its GHG reductions to obtain the GHG mitigation cost (\$/tonne-CO₂eq). Note that while we discount future fuel savings, we do not similarly discount future GHG emission reductions. As we describe below, we conclude that neither HEVs nor PHEVs currently represent a cost-effective means of reducing GHG emissions, though under lower battery prices, less GHG-intensive electricity, or higher gasoline prices, certain PHEV types could become cost-effective.

In the base case, we perform these cost-effectiveness calculations using the GREET model for PHEVs charging from an NGCC plant at an electricity price of \$0.10/kWh and with a gasoline price of \$2/gal, a battery price of \$1,000/kWh, a discount rate of 16% (14), no battery replacement over the 12-year lifetime of the vehicle, and no carbon price. Parameters can affect the cost of PHEVs' GHG abatement by changing the size of the subsidy needed to persuade cost-conscious vehicle buyers to purchase the vehicles (the numerator in the \$/tCO₂-eq cost expression) or by changing the GHG emission reductions achieved by PHEV use (the denominator in the \$/tCO₂-eq cost expression). We also perform a number of sensitivity analyses and find that the parameters whose variation produces the greatest change in cost-effectiveness are battery price (\$200/kWh in the sensitivity analysis vs. \$1,000/kWh in the base case), electricity GHG intensity (with very low-GHG wind instead of NGCC), and gasoline price (\$4/gal vs. \$2/gal). We additionally perform a carbon price sensitivity analysis (no price vs. a \$100/tonne-CO₂eq price) but find that it is not nearly as important as the other three parameters. We present these select results in Table 3 and Figure 1, which show how increasing subsidies encourage “transitions” to more efficient vehicles. Generally, transitions follow the CV-HEV-PHEV20-PHEV60 chain of increasingly efficient and increasingly expensive vehicles.

The battery price sensitivity analyses in Table 3 and Figure 1 illustrate the critical importance of low battery prices: without affordable batteries, the GHG emission reductions from PHEVs cost well over \$100 per tonne of CO₂-equivalent, which is expensive compared to a ~\$50/tonne-CO₂eq benchmark price (12). The sensitivity analyses for low-GHG electricity and for the gasoline price illustrate the importance of these parameters as well.

According to the carbon price sensitivity analysis, a \$100/tonne-CO₂eq carbon price does not change GHG mitigation cost as significantly as do the other parameters. Additionally, because the effect of the carbon tax scales linearly with the size of the tax, the effect of a \$10/tonne-CO₂eq tax would be 1/10 that of the \$100/tonne-CO₂eq tax presented here. Thus, we conclude that a carbon tax or economy-wide GHG cap-and-trade system would not be particularly helpful in making PHEVs a cost-effective GHG mitigation option.

Table 3 and Figure 1 additionally show that vehicle class (CV, HEV) is also an important determinant of GHG mitigation cost-effectiveness: we find that because of the very low fuel efficiency of conventional (CV) SUVs, it is more cost-effective to replace them with HEV or PHEV varieties than to replace CV compact cars with more efficient versions. This is because the same percentage increase in fuel efficiency (e.g., in miles/gallon) saves more fuel when the initial fuel efficiency is lower. An even better and more cost-effective way to reduce GHGs, of course, would be to replace SUV CVs with *compact* HEVs or PHEVs, but we take consumers' vehicle class preferences as given and thus do not consider cross-class efficiency upgrades. This result suggests that any automotive GHG-mitigation strategy should focus on reducing emissions from larger vehicles by shifting purchases towards smaller vehicles and by improving the efficiency of larger vehicles.

Additionally, we find that vehicle type (CV, HEV, PHEV) is an important determinant of cost-effectiveness. Under most market conditions, replacing CVs with HEVs represents the least costly GHG mitigation step, though with cheap enough batteries, replacing HEVs with PHEV20s can be cost-effective in its own right aside from GHG abatement benefits (e.g., the SUV transitions with battery prices of \$200/kWh). Replacing PHEV20s with PHEV60s, however, represents a costly GHG control strategy, under base case conditions—where it can cost more than \$2,000/tonne-CO₂eq—and under the other scenarios we consider. These findings suggest that automotive GHG reduction strategies should initially focus on vehicles with smaller and cheaper batteries, such as HEVs and PHEV20s, as opposed to vehicles with larger batteries, such as PHEV60s and AEVs. Nonetheless, vehicles with larger batteries may have more value in longer-term abatement strategies that look beyond the directly achievable GHG emission reductions.

Finally, we acknowledge that several of the assumptions outlined above probably make our direct abatement cost results a lower bound. Taking these considerations into account, then, would reduce PHEVs' cost-effectiveness further (i.e. increase our calculated \$/tonne-CO₂eq values). However, the fact that PHEVs might turn out to be even less cost-effective than we have calculated here would not qualitatively change our conclusions because the break-even battery costs in Table 1 are already rather ambitious in comparison to the current \$1,300/kWh battery price. That is, whether battery prices need to decline to \$500/kWh (as we found) or to a still lower level, the best strategy in either situation would be to undertake a broad and sustained portfolio of battery research and development (R&D).

Table 3. Cost of GHG emission reductions (in \$/tCO₂-eq) implied by subsidizing purchases of hybrid electric and plug-in hybrid electric vehicles

	Compact Cars			SUVs		
	CV → HEV	→ PHEV20	→ PHEV60	CV → HEV	→ PHEV20	→ PHEV60
Base case*	\$163	\$429	\$2,498	\$113	\$270	\$1,994
Wind-generated electricity	\$163	\$196	\$982	\$113	\$128	\$904
\$200/kWh batteries	\$0	\$26	\$440	\$0	\$0	\$338
Wind and \$200/kWh batteries	\$0	\$12	\$173	\$0	\$0	\$153
\$4/gal gasoline	\$84	\$258	\$2,298	\$34	\$103	\$1,820
\$100/tCO₂-eq carbon tax	\$120	\$373	\$2,441	\$70	\$215	\$1,940

*The base case uses natural gas combined cycle (NGCC) generation for PHEVs' electricity, \$1000/kWh batteries, \$2/gal gasoline, no carbon tax, \$0.10/kWh retail electricity prices, a discount rate of 16% for fuel savings, a 12-year vehicle lifetime, and no anticipated battery replacement. The other five scenarios are deviations from the base case. Vehicles are valued only on the basis of their fuel consumption (by consumers) and their GHG emissions (by the government). Vehicle characteristics and emission rates are as in Tables 1 and 2.

GHG abatement cost implied by subsidizing purchases of HEVs and PHEVs

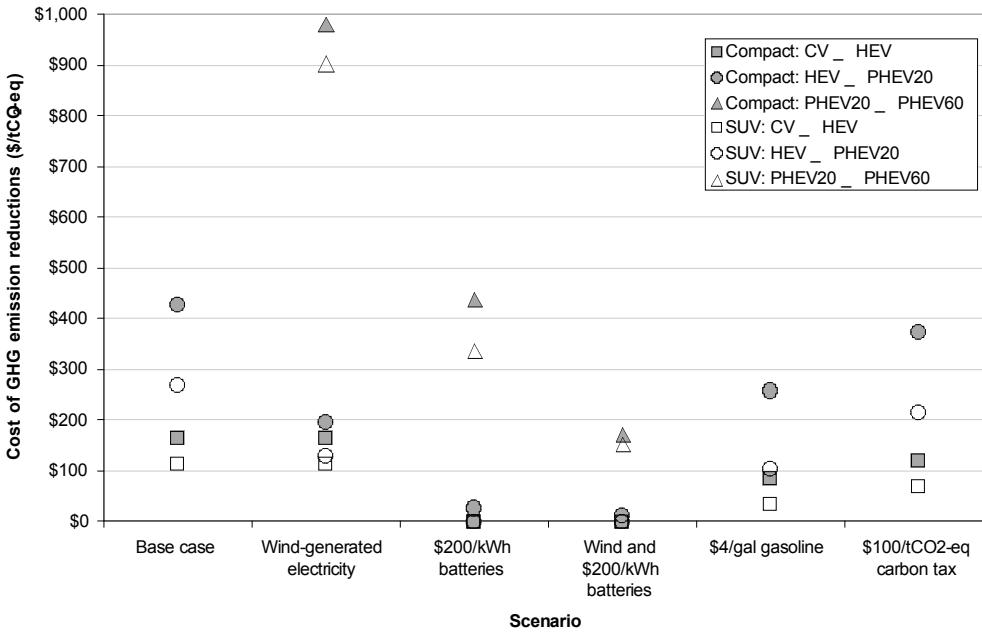


Figure 1. The GHG abatement cost implied by the subsidy needed to persuade cost-conscious compact car and sport utility vehicle (SUV) buyers to forgo conventional vehicles (CVs) for hybrid electric vehicles (HEVs), HEVs for plug-in hybrid electric vehicles with a 20 mile all-electric range (PHEV20s), and PHEV20s for plug-in hybrid electric vehicles with a 60 mile all-electric range (PHEV60s). The base case uses natural gas combined cycle (NGCC) generation for PHEVs' electricity, \$1000/kWh batteries, \$2/gal gasoline, no carbon tax, \$0.10/kWh retail electricity prices, a discount rate of 16% for fuel savings, a 12-year vehicle lifetime, and no anticipated battery replacement. The other five scenarios are deviations from the base case. Vehicles are valued only on the basis of their fuel consumption (by consumers) and their GHG emissions (by the government). Vehicle characteristics and emission rates are as in Tables 1 and 2. Some values (see Table 3) are greater than \$1,000/tCO₂-eq.

3. Discussion

Policymakers might pursue two separate goals with respect to PHEVs. The first is to make the vehicles more cost-effective from the consumer's point of view. To do so, legislators might enact policies encouraging or supporting a broad program of battery R&D, with the goal of increasing battery lifetimes and/or bringing down prices below \$500/kWh (which is approximately the upper end of the break-even battery costs we present in Table 1) as opposed to the admirable and ambitious \$150/kWh target of the US Advanced Battery Coalition (USABC) (15). Battery companies should aim for this target as well. Policymakers might also encourage PHEV adoption by reducing vehicle costs or increasing vehicle benefits. Such policies could include providing loans, rebates, feebates, tax incentives, or non-monetary incentives (such as preferred parking spaces or access to carpool lanes) to consumers who purchase PHEVs, and they could include raising the price of gasoline disproportionately more than the price of electricity. The second goal policymakers might pursue is to increase PHEVs' GHG mitigation cost-effectiveness. The above policies for consumer cost-effectiveness would help here as well, as would policies (such as a renewable portfolio standard) that lower the GHG intensity of the electricity grid and especially of marginal generators. Importantly, enacting a carbon tax or an economy-wide cap-and-trade system would not be directly useful for making PHEVs cost-effective in terms of fuel savings or direct GHG abatement.

Note, however, that incentivizing adoption of PHEVs before costs become sufficiently low or battery lives become sufficiently long could negatively affect the public's perception of the vehicles and thus impede widespread adoption. As attractive as PHEV technology is today, policymakers must remain cognizant of such tradeoffs when considering the adoption of these types of policies.

At least one of the policies outlined above, the renewable portfolio standard (RPS), has been enacted in a number of jurisdictions, and other regulations, such as green electricity marketing, have been enacted or are being considered as well. The existence of such policies could affect our analysis because concerns over double counting make it unclear whether PHEVs would achieve the GHG abatement we have estimated. This is because renewable electricity production currently creates power as well as renewable energy credits (RECs), which are purchased by the utility to satisfy RPS requirements or by a particular customer to validate his or her purchase of renewable energy. If renewable or low-GHG power used to charge a PHEV creates a REC that is sold to some other party (such as the utility), then it may be deemed inappropriate to also assign the GHG emission reductions to the PHEV. Another possible solution is to create a third commodity for the PHEV, an emission reduction credit (ERC), but it may also be considered double counting to do so. In addition, PHEVs might be used to meet the recently adopted Low Carbon Fuel Standard for California (22-24), though

again, how to do so without double counting, or interfering with the operation of other policies, is not yet clear.

Actual and proposed plans to control GHG emissions from the electric power sector in general also complicate this analysis. Most interestingly, if electricity-sector GHG emissions are capped, PHEV use brings a fraction of transportation emissions under a hard cap. If that cap is binding, then PHEV electricity use generates no new GHG emissions, and we can say that PHEVs that replace CVs or HEVs avoid 100% of gasoline GHG emissions for miles driven in electric mode, irrespective of the marginal plant or vehicle efficiency. However, expanding the electricity sector's allowed GHG emissions to account for demand growth due to PHEV adoption would erode this effect.

In the long term, if pro-PHEV policies and/or technological advances prove successful and PHEVs become widely adopted, their increased electricity demand could have implications for the electric power sector, potentially changing the shape of the daily load curve and raising electricity prices. In our study of the impact of PHEV charging in northern California, we found that this became important at very high rates of PHEV adoption, between 5 and 10 million PHEB vehicles out of a fleet of some 17 million cars and light-duty trucks (10). Managing the economic and environmental implications of PHEVs will therefore be a major challenge that will require new technical, commercial, and regulatory interfaces. Interest in using PHEVs' batteries to provide services to the grid could lead private companies and utilities to take the lead on this front. On the other hand, there is uncertainty about whether PHEVs will ever achieve widespread adoption. In any case, because PHEVs can achieve significant GHG reductions that may prove rather costly without steep declines in battery prices and increases in low-GHG electricity generation, governments may be justified in undertaking a broad and sustained program of research, development, and demonstration of appropriate technologies, regulations, and policies that could encourage the adoption of PHEVs in conjunction with the decarbonization of electricity supply.

Promoting PHEVs by amending the federal Renewable Fuels Standard

The benefits of incumbent status often slow rate of adoption of attractive new technologies, particularly when some of the benefits – such as greenhouse gas reduction – are not monetized in the economy at large. To accelerate the adoption, innovative support mechanisms are often necessary.

There is a novel and technically compelling argument for qualifying "fuel electricity" as an offset and/or substitute in the "renewable biofuel" category of the Renewable Fuel Standard (RFS). One change would be to simply convert the RFS to a Low-Carbon Fuel Standard. This would have the advantage of opening the opportunity for PHEV deployment in areas where the grid is relatively clean, and could even be structured to reward the very lowest greenhouse gas per mile forms of transit, that generally include mass-transit, reductions in vehicle-miles traveled, and the use of PHEV vehicles.

In the Energy Independence and Security Act of 2007, the RFS definition of "Renewable Biofuel" specifies a 20-50% GHG reduction over gasoline, and the law requires refiners to purchase increasing volumes of fuels that would meet this standard, reaching 15 billion gallons in 2022. However, the law also grandfathered 13.5 billion gallons of corn ethanol production capacity, exempting it from that performance requirement. New studies indicate that the GHG impact of corn ethanol may be high enough to invalidate it as a Renewable fuel. The RFS is then, in effect, a government mandate

requiring refiners to buy all the corn ethanol production available from plants that were under construction in 2007, no matter how large the greenhouse gas footprint of the fuel cycle may be.

In an EPA study prior to the passage of the RFS, the only other transportation fuel source in the 20-50% GHG reduction range was fuel electricity (which shows a 46% reduction, using the national average carbon content of electricity). By allowing fuel electricity to serve as a substitute to satisfy the Renewable Biofuel mandate in the RFS, the U.S. could accomplish the same energy security goals (reduced oil imports via reduced gasoline use) while also mitigating the detrimental impact that the RFS for corn ethanol is having on other markets as well as on the environment.

The U.S. today pays blenders \$0.54/gal to buy ethanol to displace gasoline, and those funds have already been committed and “paid for” through 2022 in the Congressional budgeting process. While a 100 mpg PHEV avoids 4,667 gallons of gasoline over its life compared to a 30mpg passenger car, the federal government has committed to paying \$2100 in subsidies for corn ethanol to accomplish the same objective¹.

If Fuel-Electricity were to qualify as an RFS offset (namely a substitute) for the corn ethanol mandate, the blenders could simply pay auto-makers a fee, for example \$6,000² for every 100mpg PHEV, avoiding \$7,000 in ethanol purchase costs. Furthermore, the federal government would be relieved from paying the equivalent of \$2,100 per vehicle under the corn ethanol mandate, which could also be redirected to manufacturers of plug-in cars using fuel electricity. The total benefit to manufacturers of PHEVs could be \$8100 per vehicle, which could cover the (diminishing) cost premium for the production of next generation battery technologies. To accomplish this goal, the RFS would be modified to either require or encourage fuel producers to pay this fee based on PHEV sales through individual blender-automotive company deals, or – more simply – an industry-wide payment scheme could be instituted to reflect PHEV sales to private individuals or fleets. The blenders would save through reduced need to purchase fuels, which are currently running at or above the cost of gasoline.

The policy would fit entirely within the budgetary framework of the existing RFS, with no net cost to the federal government. The net benefit to the blenders would be \$1,000/PHEV, which could be warranted as they drive the market for their core product out of the transportation sector altogether. The automobile manufacturers would receive a source of cash to drive down their costs, and even if none of the \$7000 payment from the blenders were passed onto consumers, the cost of conserved gasoline for PHEV drivers would still be less than half the present cost of gasoline. Finally, from a social benefit perspective, we would be rewarding improvements in energy security, food security, and GHG emissions – all with one simple modification to an existing policy framework.

Acknowledgments

Research for this paper began as a course project at UC Berkeley undertaken by author S. M. A. and James Wilcox, with the help of Richard J. Plevin. Timothy E. Lipman and Zack Subin (UC Berkeley),

¹ While the fleet average today is roughly 23 mpg, we use a 30 mpg comparison as both a target figure assuming CAFÉ increases and because the ‘first adopters’ may be hybrid vehicle purchasers, who are already selecting from a higher mpg subset of available vehicles.

² We suggest a value close to the total ethanol purchase total, hence \$6,000 out of a total fuel cost of \$7,000, but both higher and lower costs could be reasonably proposed and justified.

Administrator 8/30/08 11:15 AM

Comment: Average passenger vehicle is roughly 23mpg. Wouldn't this be better figure to us here? Would generate roughly 25% more gallons and federal subsidy payments

Administrator 8/30/08 11:28 AM

Comment:
Very interesting idea. Several questions:

1. Where did \$6k figure come from?

2. What are the mechanics here? Blenders could, at their discretion, pay auto-makers \$6k for every PHEV sold to a third party? Doing so would relieve the blender of the obligation to purchase a certain amount of ethanol? I see the direction you're going but not how it would work. Need to spell out a bit more.

Derek Lemoine 9/6/08 1:37 PM

Comment: We don't use mpg for PHEVs elsewhere in the paper, and I doubt it's a good measure of their efficiency since it can mean many things. Can we rephrase this in terms of PHEV20, etc? If not, we can let it go.

Administrator 8/30/08 11:19 AM

Comment: Not if the cars were flex-fuel PHEVs.

Derek Lemoine 9/6/08 1:38 PM

Comment: As long as we cap the # of PHEVs with the cap tied to the achievement of the existing RFS goals.

as well as John German (American Honda Motor Company), provided helpful comments on draft versions. We thank T. J. Glauthier and Daid Sandalow for highly insightful comments on this paper. This research was made possible by support from: the Class of 1935 of the University of California, the Energy Foundation, and the Karsten Family Foundation (to D.M.K.); and NSF's Graduate Research Fellowship Program (GRFP) (to D.M.L.).

We dedicate this paper to Dr. Alex Farrell, collaborator, colleague, and friend who passed away in April, 2008, during work on an earlier version of this project.

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