

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

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Cars and light trucks in the United States consume about 8 million barrels of gasoline per day, which is more than the total amount of petroleum produced in the United States and accounts for 18 percent of national greenhouse gas (GHG) emissions. Consumption and emissions have been rising at about 1.5 percent per year.²

Plug-in hybrid electric vehicles could alter these trends. On a vehicle technology spectrum that stretches from fossil fuel-powered conventional vehicles (CVs) through hybrid electric vehicles

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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.

2. See U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2002* (Washington: EPA, Office of Policy, Planning, and Evaluation, April 15, 2004), p. 255 (www.epa.gov/climatechange/emissions/downloads06/04CR.pdf); and S. C. Davis and S. W. Diegel, *Transportation Energy Data Book*, 25th ed., ORNL-6974 (Washington: U.S. Department of Energy, Office of Transportation Technologies, September 2006), p. 280 (http://cta.ornl.gov/cta/Publications/Reports/TEDB_Edition25_ORNL_6974.pdf).

(HEVs) to all-electric vehicles (AEVs), PHEVs fall between the latter two types: 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).³ 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 use of petroleum) 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 reductions in petroleum use and GHG emissions 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 emissions of air pollutants and GHGs offset their increased capital costs. However, that study used U.S. fuel prices in its analyses, which are lower than those in many other developed countries, and thus this study is of declining relevance in a changing automotive market.⁴ In any case, few consumers base their decisions about which vehicle to purchase primarily on the cost of fuel, and many are willing to pay a premium for the symbolic and environmental benefits of HEV

3. See Electric Power Research Institute (EPRI), *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles*, Technical Report 1006892 (Palo Alto, Calif.: EPRI, 2002); and EPRI, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, Technical Report 1000349 (Palo Alto, Calif.: EPRI, 2001).

4. L. B. Lave and H. L. MacLean, "An Environmental-Economic Evaluation of Hybrid Electric Vehicles: Toyota's Prius vs. Its Conventional Internal Combustion Engine Corolla," *Transportation Research, Part D—Transport and Environment* 7, no. 2 (2002): 155–62.

ownership.⁵ Like PHEVs, AEVs and fuel cell vehicles promise deeper reductions in emissions, but their higher capital costs make these reductions expensive.⁶ One study, which compared 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; however, the CV emission rates in that study were up to an order of magnitude higher than the current standards in California.⁷ Because capital costs similar to those for AEVs 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; though now at least, one study has examined PHEVs along these lines as well.⁸ In the PHEV study, the authors found that, in the specific case of a compact car PHEV20 (that is, it can travel twenty miles using only grid-supplied electricity) under current market and policy conditions, the expected fuel savings from increased efficiency do not compensate consumers for the increased capital cost. Derek Lemoine reaches a similar conclusion despite using a real options approach to

5. See R. R. Heffner, K. S. Kurani, and T. S. Turrentine, "Symbolism in California's Early Market for Hybrid Electric Vehicles," *Transportation Research, Part D—Transport and Environment* 12, no. 6 (2007): 396–413.

6. See H. L. MacLean and L. B. Lave, "Life Cycle Assessment of Automobile/Fuel Options," *Environmental Science and Technology* 37, no. 2 (2003): and 5445–452; M. Z. Jacobson, W. G. Colella, and D. M. Golden, "Cleaning the Air and Improving Health with Hydrogen Fuel-Cell Vehicles," *Science* 308, no. 5730 (2005): 1901–905.

7. K. Funk and A. Rabl, "Electric versus Conventional Vehicles: Social Costs and Benefits in France," *Transportation Research, Part D—Transport and Environment* 4, no. 6 (1999): 397–411.

8. For cost-effectiveness analysis of HEVs, see Lave and MacLean (2002); for PHEVs, see D. M. Lemoine, D. M. Kammen, and A. E. Farrell, "An Innovation and Policy Agenda for Commercially Competitive Plug-In Hybrid Vehicles," *Environmental Research Letters* 3, no. 1 (2008): 1–10.

better value the fuel flexibility provided by PHEVs' batteries in a world of uncertain fuel prices.⁹ Therefore, PHEVs could be consigned to an insignificant market share, unless their symbolic benefits relative to those of HEVs become sufficiently strong, market conditions become sufficiently favorable, battery technologies become sufficiently cheaper, or policies are implemented that sufficiently support these new vehicles.

A separate consideration, which the authors of the PHEV study leave open, is PHEVs' cost-effectiveness in reducing GHG emissions, measured in \$/t-CO₂-eq (dollars per metric ton of carbon dioxide equivalent).¹⁰ 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 to achieve these benefits—provided that the \$/t-CO₂-eq cost is not too great. The purpose of this chapter is to address this question, comparing PHEVs with other options for mitigating GHGs (for example, reforestation or improving building insulation) on a cost curve such as that found in the report by Jon Creyts and others.¹¹ Note that while we focus on PHEVs' value as a strategy to abate GHGs, 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 the metric \$/t-CO₂-eq is therefore incomplete. However, 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 the section Break-Even Battery Costs), we find that they could become so under certain

9. D. M. Lemoine, "Valuing Plug-In Hybrid Electric Vehicles' Battery Capacity Using a Real Options Framework," *Energy Journal* (under review).

10. Lemoine, Kammen, and Farrell (2008).

11. Jon Creyts and others, *Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?* (New York: McKinsey & Company and The Conference Board, December 2007), p. xiii (www.mckinsey.com/clientservice/ccsi/pdf/US_ghg_final_report.pdf).

scenarios that we present below (see the section PHEV Cost-Effectiveness in Reducing GHGs, and Sensitivity Analyses). We conclude by discussing the commercial and policy implications of our results.

Methods and Results

We compare a CV, an HEV, and two PHEVs—one that can travel twenty miles using only grid-supplied electricity (called a PHEV20) and one that can travel sixty miles using only grid-supplied electricity (called a PHEV60)—in two models: compact car and full-size SUV, resulting in eight vehicle scenarios, following the assumptions made in prominent prior studies (see table 10-1).¹² 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.

Following the Electric Power Research Institute, we assume that PHEVs operate as AEVs over some number of miles, drawing power only from their batteries until the batteries are depleted, before switching to operation as a hybrid vehicle and drawing power from the gasoline engine. Such PHEVs would need batteries possessing the characteristics of both “energy batteries” (a type of battery that can store and deliver large amounts of energy over longer timescales) and “power batteries” (which can deliver large amounts of energy quickly for the high-power portions of the driving cycle).

12. EPRI (2002); EPRI (2001).

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 Lemoine, Kammen, and Farrell, table 10-1 shows the electricity rates whose cost per mile of PHEV operation is the same as that for various gasoline prices. Lower rates than the ones shown would encourage PHEV owners to drive in electric mode, while higher rates would favor the gasoline-fueled hybrid electric mode. For comparison, average U.S. residential electricity rates are about \$0.083 per kWh, and U.S. gasoline prices averaged about \$2.75 per gallon in 2006.¹³

On the one hand, 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 to incentivize their purchase. But because of utility tariff and tax structures, PHEV owners may pay electricity rates that are higher than the average rates, which would erode the vehicles' cost savings (see Lemoine, Kammen, and Farrell 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 the section GHG Emission Reductions). We therefore 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 the section PHEV Cost-Effectiveness in Reducing GHGs, and Sensitivity Analyses.

Break-Even Battery Costs

13. See U.S. Energy Information Administration, *Annual Energy Review 2006*, DOE/EIA-0384 (2006) (Washington: U.S. Department of Energy, 2007).

Following the methodology of Lemoine, Kammen, and Farrell, we define the *marginal fuel savings* as the net present value (NPV) of a vehicle's fuel-savings cash flow relative to that of a comparison vehicle, 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. The break-even battery cost is the price (in \$/kWh) to which batteries must fall so that consumers can obtain an exact payback from the marginal fuel savings on their more expensive vehicle purchase (compared to having bought the cheaper—and less efficient—comparison vehicle). Rating the different vehicle types along a continuum of efficiency upgrades, we make comparisons between HEVs and CVs, PHEV20s and HEVs, and PHEV60s and PHEV20s. In the base case, we assume that consumers possess a 16 percent discount rate, that batteries represent the entire *marginal vehicle cost*, and that batteries last the entire twelve-year vehicle lifetime.¹⁴ We also assume that the vehicles drive 11,000 miles (17,700 kilometers or km) annually and that PHEV20s drive 39 percent of their miles in all-electric mode while PHEV60s drive 74 percent of their miles in electric mode.¹⁵

Break-even battery costs for the purchase of HEVs and PHEVs at various gasoline prices are presented in table 10-1. For comparison, the U.S. Advanced Battery Coalition (USABC) has adopted a target of \$150/kWh, and our calculated upper bound for battery prices is about \$1,300/kWh (though we have seen an estimate of \$500/kWh)¹⁶ Using our estimated value, we find that consumers' break-

14. Concerning the 16 percent discount rate, see D. L. Greene and J. DeCicco, "Engineering-Economic Analyses of Automotive Fuel Economy Potential in the United States," *Annual Review of Energy and the Environment* 25 (2000): 477–535.

15. EPRI (2001).

16. Concerning the USABC target of \$150/kWh, see R. A. Sutula, "Progress Report for Electric Vehicle Battery Research and Development Program" (Washington: U.S. Department of Energy, 2001) (www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2001_pr_elec_vehicle_batt.pdf). Concerning the upper bound of \$1,300/kWh, we calculated our estimate from data available on the website of Hymotion, a company that performs conversions of HEVs into PHEVs (<http://www.hymotion.com>). On their website (accessed Spring 2007), they listed the

even costs are lower than actual HEV or PHEV battery prices, implying that, under current battery prices, fuel savings alone would not offset the vehicles' increased capital cost and hence would not justify their purchase (this result is consistent with Lemoine, Kammen, and Farrell and with Lave and MacLean in the case of HEVs).¹⁷

[Table 10-1 about here]

GHG Emission Reductions

To determine the GHG emissions that are avoided by the use of 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.¹⁸ Note that we do not include emissions from vehicle or battery manufacturing.¹⁹ We update GREET with GHG emission data for the full fuel life cycles of a number of different power plant types.²⁰ Then we calculate the life cycle GHG emissions in

price of performing such a conversion for a Toyota Prius, as well as the size (in kWh) of the new battery that they install. By dividing one by the other, we obtained the estimate for \$/kWh. Concerning the estimate of \$500/kWh, we received this estimate from Project Better Place via a personal communication.

17. Lemoine, Kammen, and Farrell (2008); Lave and MacLean (2002).

18. See M. Wang, "Development and Use of GREET 1.6—Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies," ANL/ESD/TM-163 (Argonne, Ill.: Argonne National Laboratory, Center for Transportation Research, August 2001) (www.transportation.anl.gov/pdfs/TA/153.pdf.)

19. See C. Samaras and K. Meisterling, "Life Cycle Assessment of Greenhouse Gas Emissions from Plug-In Hybrid Vehicles: Implications for Policy," *Environmental Science & Technology* 42, no.9 (2008): 3170–176.

20. For more details, see S. Pacca and A. Horvath, "Greenhouse Gas Emissions from Building and Operating Electric Power Plants in the Upper Colorado River Basin," *Environmental Science & Technology* 36, no. 14 (2006): 3194–200; and M. G. Morgan, J. Apt, and L. B. Lave, "The U.S. Electric Power Sector and Climate Change Mitigation," (Arlington, Va.: Pew Center on Global Climate Change, June, 2005) (www.pewclimate.org/docUploads/Electricity_Final.pdf).

units of g-CO₂-eq/mile of each vehicle type when operating in gasoline mode and, when applicable, in electric mode. We present our results in table 10-2.

[set Table 10-2 about here]

The efficiency gains achievable by simply adopting a hybrid drivetrain are significant, as evidenced by the 23 percent lower GHG emissions for compact HEVs and 34 percent lower emissions for SUV HEVs compared with 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 environmental impacts of PHEVs 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 five to ten years.²¹

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

21. See Lemoine, Kammen, and Farrell (2008).

photovoltaic arrays, but not solar thermal; large-scale hydroelectric; or geothermal) must generate using whatever resource level is available and so cannot be dispatched, and they are often given the highest priority in the electricity system's loading order.²² 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—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.²³ 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 PHEVs are operated on coal electricity through integrated gasification combined cycle (IGCC) without carbon capture and sequestration (CCS), compact and SUV PHEVs reduce GHG emissions by 4 percent and 19 percent, respectively, relative to their CV counterparts. But these GHG reductions are actually *less* than those achieved by HEVs running on gasoline (23 percent and 34 percent, respectively). Thus, when the marginal plant is such a coal plant, it is 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 with 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.

22. For more details on displacement of renewable electricity generators, see J. F. DeCarolis and D. W. Keith, "The Costs of Wind's Variability: Is There a Threshold?" *Electricity Journal* (January–February 2005): 69–77.

23. See, by way of comparison, L. Sanna, "Driving the Solution: The Plug-In Hybrid Vehicle," *EPRI Journal* (Fall 2005): 8–17.

If PHEVs are operated on electricity generated by less GHG-intensive power plants, GHG reductions are greater. When the electricity is generated from a natural gas combined cycle (NGCC) power plant, compact and SUV PHEVs reduce GHG emissions by 54 percent and 61 percent, respectively, 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 percent relative to CVs under average driving conditions and could reduce GHG emissions by nearly 100 percent when driven only in electric mode.

PHEV Cost-Effectiveness in Reducing GHGs and Sensitivity Analyses

We define the size of the subsidy that is 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 a buyer purchases (CV, HEV, or PHEV) within a broader class of vehicles (compacts or SUVs) (see the section 2.3 Break-Even Battery Cost). If no subsidy is needed, we set the size of the subsidy at \$0, precluding negative values for GHG abatement costs. As mentioned at the beginning of the chapter, consumers do not explicitly follow net present value calculations when they purchase vehicles, 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 the cost-effectiveness of GHG mitigation, we divide the subsidy size for each vehicle option by its GHG reductions to obtain the GHG mitigation cost (\$/t-CO₂-eq). 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, although under lower battery prices, less GHG-intensive electricity, or higher gasoline prices, certain types of PHEV 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 per gallon, a battery price of \$1,000/kWh, a discount rate of 16 percent, no battery replacement over the twelve-year lifetime of the vehicle, and no carbon price.²⁴ The cost-effectiveness of PHEVs' GHG abatement is determined by the size of the subsidy needed to persuade cost-conscious vehicle buyers to purchase the vehicles (the numerator in the \$/t-CO₂-eq cost expression) and by the GHG emission reductions achieved by the PHEV (the denominator in the \$/t-CO₂-eq cost expression). Thus, if we wanted to increase the cost-effectiveness, we could take actions to increase the numerator, decrease the denominator, or both.

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 as compared with \$1,000/kWh in the base case), electricity GHG intensity (with very low-GHG for wind-generated instead of NGCC-generated electricity), and gasoline price (\$4 per gallon compared with \$2 per gallon). We additionally perform a carbon price sensitivity analysis (no price compared with a \$100/t-CO₂-eq price) but find that it is not nearly as important as the other three parameters. We present these select results in table 10-3 and figure 10-1, which show how increasing subsidies encourage “transitions” to more efficient vehicles, which generally follow the CV-HEV-PHEV20-PHEV60 chain of increasingly efficient and increasingly expensive vehicles.

The battery price sensitivity analyses in table 10-3 and figure 10-1 illustrate the critical importance of low battery prices: without affordable batteries, the GHG emission reductions from PHEVs cost well over \$100 per metric ton of carbon dioxide equivalent, which is expensive compared

24. Concerning discount rates, see D. L. Greene and J. DeCicco, “Engineering-Economic Analyses of Automotive Fuel Economy Potential in the United States,” *Annual Review of Energy and the Environment* 25 (2000): 477–535.

with a benchmark price of approximately \$50/t-CO₂-eq.²⁵ 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/t-CO₂-eq carbon price does not change GHG mitigation costs 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/t-CO₂-eq tax would be 1/10 that of the \$100/t-CO₂-eq 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 option for GHG mitigation.

Table 10-3 and figure 10-1 additionally show that vehicle class (CV, HEV) is also an important determinant of the cost-effectiveness of GHG mitigation: 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 (for example, in miles per 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 CV SUVs with *compact* HEVs or PHEVs, but we take consumers' vehicle class preferences as given and thus do not consider cross-class efficiency upgrades. In any case, this result suggests that any automotive strategy for GHG mitigation should focus on reducing emissions from larger vehicles by shifting purchases toward smaller vehicles and by improving the efficiency of larger vehicles.

Additionally, we find that vehicle type (CV, HEV, and PHEV) is an important determinant of cost-effectiveness. Under most market conditions, replacing CVs with HEVs represents the least costly GHG mitigation step, although with cheap enough batteries, replacing HEVs with PHEV20s can be

25. See Jon Creyts and others (2007).

cost-effective in its own right, setting aside the GHG abatement benefits. For example, the cost-effectiveness of replacing SUV HEVs with PHEV20s does not depend on GHG valuation if batteries cost \$200/kWh. On the other hand, replacing PHEV20s with PHEV60s represents a costly GHG abatement strategy, under base case conditions—where it can cost more than \$2,000/t-CO₂-eq—and the same is true under other scenarios we consider. These findings suggest that automotive GHG reduction strategies should focus initially 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 (that is, increase our calculated \$/t-CO₂-eq 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 10-1 are already rather ambitious in comparison with the current battery price of \$1,300/kWh. That is, whether battery prices need to decline to \$500/kWh (as our results suggest) 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 10-3]

[Figure 10-1]

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, bringing down prices below \$500/kWh (which is approximately the upper bound of the break-even battery costs presented in table 10-1), or both—as opposed to the ambitious \$150/kWh target of the U.S. Advanced Battery Coalition (USABC).²⁶ 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 (whether stand-alone or as part of a feebate program), tax incentives, or nonmonetary incentives (such as preferred parking spaces or access to carpool lanes) to consumers who purchase PHEVs. Additionally, they could include making the price of gasoline disproportionately higher than the price of electricity, as might occur if energy security concerns become paramount. The second goal policymakers might pursue is to increase the cost-effectiveness of PHEVs in mitigating GHGs. 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. It is important to note, however, that 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 the adoption of PHEVs before costs become sufficiently low or battery lives become sufficiently long could negatively affect the public's perception of the vehicles

26. For more details on battery research, see R. A. Sutula, "Progress Report for Electric Vehicle Battery Research and Development Program" (Washington: U.S. Department of Energy, Energy Efficiency and Renewable Energy, 2001) (www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2001_pr_elec_vehicle_batt.pdf).

and thus impede widespread adoption. As attractive as PHEV technology is today, policymakers must remain cognizant of such trade-offs 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 that is 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 that too may be considered double counting. Similarly, PHEVs might be used to meet the recently adopted Low Carbon Fuel Standard for California, though again, how to do so without double counting or interfering with the operation of other policies is not yet clear.²⁷

Actual and proposed plans to control GHG emissions from the electric power sector in general also complicate this analysis. For example, if GHG emissions from the electricity sector are capped, PHEV use brings a fraction of transportation emissions under a hard cap—and if that cap is binding, then use of electricity by PHEVs generates no new GHG emissions. In this case, we can say that

27. (22) For more details on this standard in California, see A. Schwarzenegger, Executive Order S-01-07, “Low Carbon Fuel Standard (LCFS)” (Sacramento, Calif., January 18, 2007); (23) A. R. Brandt and others, *A Low-Carbon Fuel Standard for California Part 2: Policy Analysis* (Sacramento, Calif.: Office of the Governor, Air Resources Board, 2007); (24) S. M. Arons and others, *A Low-Carbon Fuel Standard for California Part 1: Technical Analysis* (Sacramento, Calif.: Office of the Governor, Air Resources Board, 2007).

PHEVs that replace CVs or HEVs avoid 100 percent 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 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 charging became important when PHEV adoption rates were very high, between 5 and 10 million PHEVs out of a fleet of some 17 million cars and light-duty trucks.²⁸ PHEVs could also have implications for the sector if their batteries were used to provide ancillary services to the grid because of the challenge of setting up and running such a service. Thus, managing the economic and environmental implications of PHEVs will be a major challenge that will require new technical, commercial, and regulatory interfaces. However, governments may be justified in undertaking a broad and sustained program of research, development, and demonstration of appropriate technologies, regulations, and policies because PHEVs have the potential to achieve such significant GHG reductions (even though they may prove rather costly without steep declines in battery prices and increases in low-GHG electricity generation). Advances in these areas could encourage the adoption of PHEVs in conjunction with the decarbonization of the electricity supply.

Promoting PHEVs by amending the federal Renewable Fuels Standard

Though several policies suggested above could reward PHEVs for greenhouse gas emission abatement, the prospect of double counting avoided emissions challenges some of the most sweeping

28. Lemoine, Kammen, and Farrell (2008).

measures, diminishing the basis of support for PHEVs. Meanwhile, the U.S. has already enacted a Renewable Fuel Standard (RFS) policy that deserves reconsideration in light of unintended consequences arising from competition for resources common to the production of food, fuel, forests, and feedstocks. These environmental and economic impacts are expected to intensify as refiners deliver an increasing volume of biofuels to meet the RFS mandate, and credit for the use of fuel electricity in PHEVs may be able to offer a compelling solution.

If the volumetric RFS were converted to a qualitative Low Carbon Fuel Standard (LCFS), the new policy could be structured to reward forms of transit with the very lowest GHG-per-mile, which generally include mass transit, reductions in vehicle-miles traveled, and the use of PHEV vehicles. Despite the fact that several key lawmakers support a LCFS, leaders of the 110th Congress that authorized the RFS through the Energy Independence and Security Act in 2007 have indicated little interest in revisiting that policy debate, which limits the extent of modifications that may be accomplished in the near-term.

The federal RFS obligates refiners to deliver a certain quantity of biofuels to market each year as an alternative to gasoline. The policy distinguishes between four categories of renewable fuels that are differentiated based on environmental attributes – and avoided greenhouse gas emissions in particular. Among them, the RFS reserves largest market quota for a category called “renewable biofuel,” which is defined as a fuel with greenhouse gas emissions profile that is 20 to 50 percent less than gasoline. Refiners are required to increase purchases of renewable biofuels each year, reaching 15 billion gallons in 2022. However, the law also waives the basic environmental performance criteria of a 20 percent reduction in greenhouse gas emission relative to gasoline for 13.5 billion gallons of corn ethanol production capacity that was pre-existing or under construction at the time of passage. 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, and new studies indicate that the GHG impact of corn ethanol may be high enough to invalidate it as a renewable fuel under the RFS.

In an EPA study completed before the passage of the RFS, the only other transportation fuel source in the 20 to 50 percent GHG reduction range was electricity, which delivered a 46 percent reduction based on the national average carbon content of electricity. By allowing 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 through reduced gasoline use) while improving its carbon footprint and also mitigating the detrimental impact that the RFS for corn ethanol is having on other markets as well as on the environment.

The key to this policy modification is the structure of compensation for major actors. Today the United States pays fuel blenders \$0.51 for each gallon of ethanol they buy to displace gasoline, and the 2007 Farm Bill will reduce that figure to \$0.45 per gallon beginning in 2009. In the congressional budgeting process, those funds have already been committed and “paid for” through 2022. As a result, the federal government is committed to paying \$2,100 in subsidies for corn ethanol to displace 4,600 gallons of gasoline, approximately the same amount avoided by a 100-mpg PHEV over its life compared with a 30-mpg passenger car.²⁹

If electricity used by PHEVs qualified as an RFS offset (namely a substitute) for the corn ethanol mandate, the blenders could claim a calculated credit of 4,600 gallons simply by reallocating money they would have spent on ethanol and instead paying automakers a fee. For example, the refiner could pay approximately \$6,000 for every 100-mpg PHEV, avoiding \$7,000 in ethanol purchases it

29. Although the fleet average today is roughly 23 mpg, we use a 30 mpg comparison as a target figure, assuming increases in Corporate Average Fuel Economy (CAFE) standards and because the “first adopters” may be purchasers of hybrid vehicles, who are already selecting from a higher mpg subset of available vehicles.

would otherwise be mandated to make.³⁰ Furthermore, the federal government would be relieved from paying the equivalent of \$2,100 for the avoided 4,600 gallons 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 \$8,100 a vehicle, which would accomplish the policy imperative to cover the (diminishing) cost premium for the production of next-generation battery technologies. To accomplish this goal, the RFS would be modified to require or encourage fuel producers to pay this fee on the basis of 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 because of a 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 per PHEV, which could be warranted as they drive the market for their core product out of the transportation sector altogether. Automobile manufacturers would receive a source of cash to drive down their costs, and even if none of the \$7,000 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, this addition of electricity as an alternative to ethanol in the RFS would be rewarding improvements in energy security, food security, and GHG emissions—all with one simple modification to an existing policy framework.

Concluding Summary

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

Plug-in hybrid electric vehicles (PHEVs) could significantly reduce automotive greenhouse gas (GHG) emissions and petroleum consumption, while improving energy security and urban air quality. However, their widespread adoption depends upon technological and economic advances in batteries because fuel savings do not fully or rapidly compensate consumers for the capital costs of batteries today. In order for PHEV purchases to become economical to consumers, battery prices must decline from \$1,300 per kilowatt-hour (kWh) to below \$500/kWh, or U.S. gasoline prices must remain at roughly \$5 per gallon—or the federal government must institute policy innovations with equivalent effects, such as policies to lower battery cost and increase battery lifetimes (e.g. a broad and sustained program of battery RD&D), or those to widen the difference between gasoline and electricity prices (e.g. changes in energy taxes).

However, even if PHEVs do *not* become economical for consumers, their purchase might still be valuable to society if their significant GHG reductions can be achieved cost-effectively (using a benchmark price of about \$50/t-CO₂-eq).³¹ Using the GREET model, we determine that in order for PHEVs' reductions to become cost-effective, either their purchase must approach near-economical levels—requiring the same policy innovations described above—or very low-GHG electricity must be used to power them, which would require policies to decrease the GHG intensity of electricity, such as renewable portfolio standards (as well as technologies and regulations to integrate PHEVs into an electricity grid with a greater proportion of intermittent renewables). Importantly, we determine that any carbon price would have to greatly exceed \$100/t-CO₂-eq in order to render PHEVs' reductions cost-effective, and hence a carbon price represents an impractical means of achieving this goal.

We additionally determine that given current technologies and prices, replacing full-sized conventional SUVs with hybrid (HEV) SUVs is actually a *more* cost-effective GHG abatement strategy than is subsidizing the adoption of compact car PHEVs. This is because conventional SUVs

³¹ See Jon Creyts and others (2007).

have such comparatively low fuel efficiency that the same percentage efficiency increase saves more fuel for SUVs than it does for compact cars. In the near term, then, policymakers could reduce the most GHG emissions by pursuing policies to encourage SUV hybridization (or efficiency increases in general). In the longer term, however, PHEVs could enable much greater GHG abatement, and hence the policy innovations described above—to lower battery cost and increase battery lifetimes, to widen the difference between gasoline and electricity prices, and to decrease the GHG intensity of electricity—appear justified.

Further, to immediately accelerate financial support for PHEV development and deployment, Congress could make a modest change to the new Renewable Fuel Standard, offering flexibility to refiners that are obligated to buy billions of gallons of ethanol to displace gasoline. Because the national average carbon content of electricity has a much smaller carbon footprint than corn ethanol, refiners could make a payment to PHEV manufacturers instead of ethanol producers, receiving RFS credits equal to the gallons of gasoline the PHEV would displace with electricity.

Table 10-1. 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
<i>Compact car</i>										
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
<i>Sport utility vehicle (full-size SUV)</i>										
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

AER = all-electric range (twenty miles for a plug-in hybrid electric vehicle or PHEV20, sixty miles for a PHEV60).

-- Not applicable.

a. See the sections on battery types and sizes, fuel prices and vehicle purchase incentives, and break-even battery costs for details and assumptions of our calculations.

b. EPRI (2001, 2002).

c. Expanded from the methodology of Lemoine, Kammen, and Farrell (2008).

Table 10-2. 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 (g-CO ₂ -eq/mi)						
	Gasoline	NGCC electricity	Gasoline	U.S. avg	Calif. avg	NGCC	IGCC w/o CCS	IGCC with CCS	Wind
<i>Compact car</i>									
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
<i>Sport utility vehicle (full-size SUV)</i>									
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

BTU = British thermal units; CCS = carbon capture and sequestration; IGCC = integrated gasification combined cycle; GHG = greenhouse gas; NGCC = natural gas combined cycle; PHEV20 = plug-in hybrid electric vehicle that can travel twenty miles using only grid-supplied electricity; PHEV60 = can travel sixty miles on grid-supplied electricity.

-- Not applicable.

a. See the section on reductions in GHG emissions for details of assumptions and calculations.

b. Wang (2001); Pacca and Horvath (2006); Morgan, Apt, and Lave (2005).

Table 10-3. Cost of GHG Emission Reductions Implied by Subsidizing Purchases of HEVs and PHEVs^a

	<i>Compact cars</i>			<i>SUVs</i>				
	<i>CV</i>	<i>HEV</i>	<i>PHEV20</i>	<i>PHEV60</i>	<i>CV</i>	<i>HEV</i>	<i>PHEV20</i>	<i>PHEV60</i>
Base case ^b	\$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-a-gal. gasoline	\$84	\$258	\$2,298		\$34	\$103	\$1,820	
\$100/t-CO ₂ -eq carbon tax	\$120	\$373	\$2,441		\$70	\$215	\$1,940	

GHG = greenhouse gas; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle.

a. Cost of GHG emission reductions are in the valuation of dollars per metric ton of carbon dioxide equivalent (\$/t-CO₂-eq).

b. The base case uses natural gas combined cycle (NGCC) generation for PHEVs' electricity, \$1000/kWh batteries, \$2-a-gal gasoline, no carbon tax, \$0.10/kWh retail electricity prices, a discount rate of 16 percent for fuel savings, a twelve-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 10-1 and 10-2.

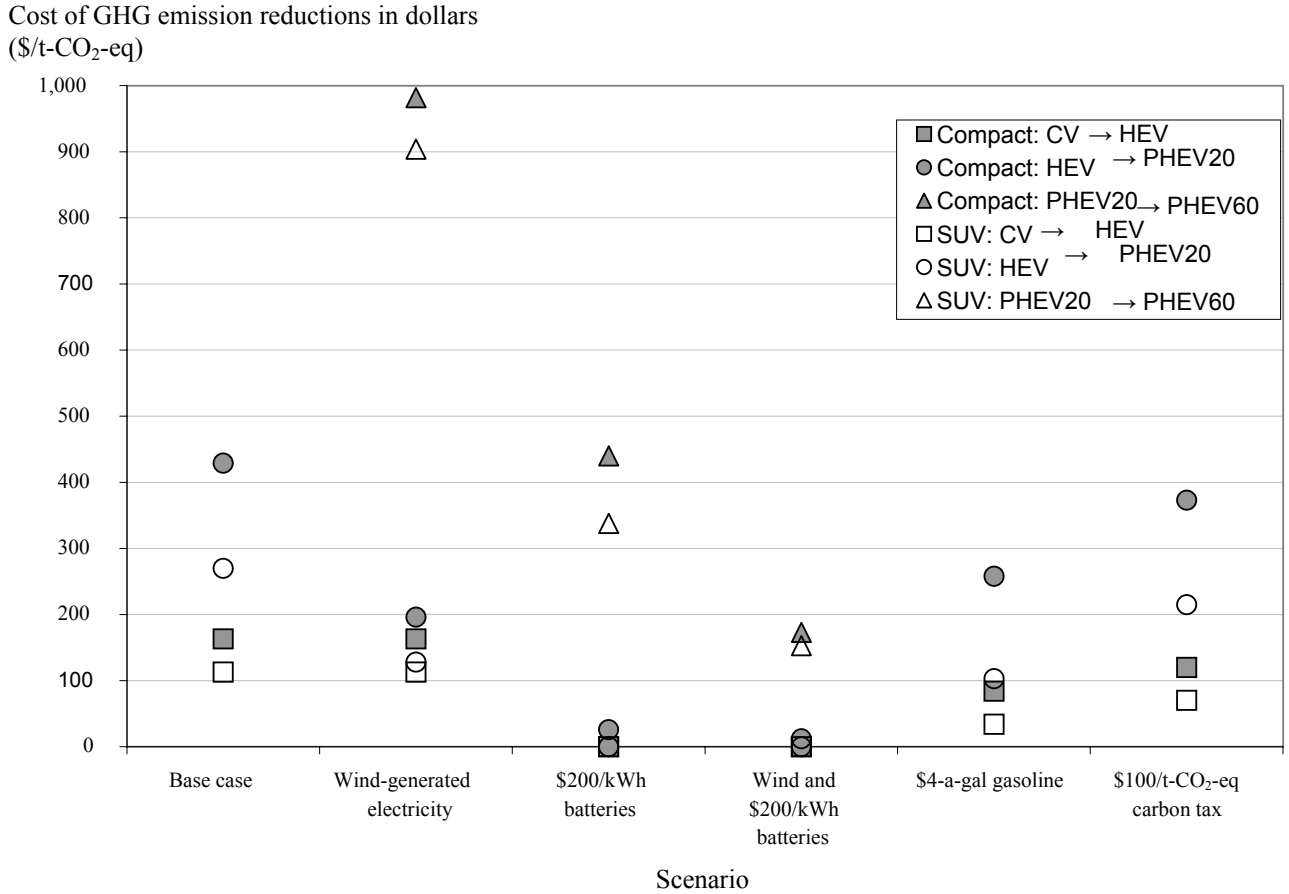


Figure 10-1. GHG Abatement Cost Implied by Subsidizing Purchases of HEVs and PHEVs^a

GHG = greenhouse gas; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle.

a. The GHG abatement cost implied by the subsidy needed to persuade cost-conscious buyers of compact cars and sport utility vehicles (SUVs) to forgo conventional vehicles (CVs) for hybrid electric vehicles (HEVs), HEVs for plug-in hybrid electric vehicles with a twenty-mile all-electric range (PHEV20s), and PHEV20s for plug-in hybrid electric vehicles with a sixty-mile all-electric range (PHEV60s). The base case uses natural gas combined cycle (NGCC) generation for PHEVs' electricity, \$1,000/kWh batteries, \$2-a-gal gasoline, no carbon tax, \$0.10/kWh retail electricity prices, a discount rate of 16 percent for fuel savings, a twelve-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 10-1 and 10-2. Some values (see table 10-3) are greater than \$1,000/t-CO₂-eq.