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Economic, Environmental and Security Implications of Plug-in Vehicles

SUMMARY: Plug-in hybrid electric vehicles (PHEVs) will likely play an important role in addressing oil dependency and global warming in the transportation sector. PHEVs use battery packs to store energy from the electricity grid and propel the vehicle partially on electricity instead of gasoline. The attached studies identify two important findings:

1. **ONLY AS GREEN AS THE GRID: Achieving substantial reductions in CO_2 emissions from adoption of PHEVs will depend on investments in low-carbon electricity generation.** The current U.S. electricity average mix can power vehicles with fewer full-supply-chain greenhouse gas (GHG) emissions per mile than gasoline. But PHEVs charged with electricity produced by coal without carbon capture and sequestration can have higher life cycle GHG emissions than gasoline.

2. **SMALL IS BEAUTIFUL: PHEVs with small battery packs will likely be most cost effective for the near future and play an important role in achieving the administration's target of 1 million PHEVs on the road by 2015.** Policy promoting small-capacity PHEVs for urban drivers with short commutes may be an opportunity to jump-start market-driven sustainable adoption of PHEV technology.

   - *Batteries are expensive and heavy*. More batteries allow drivers to travel greater distances on electricity alone and reduce oil consumption. But a heavy battery pack sized for 60 miles of electric-only travel could require 10% more electricity per mile in electric-mode than a pack sized for 7 miles of electric-only travel.

   - *For urban drivers who can charge frequently* – every 20 miles or less – PHEVs with small battery packs have the lowest lifetime vehicle cost, gasoline consumption and greenhouse gas emissions. Nearly 50% of U.S. passenger miles are traveled by vehicles driving less than 20 miles per day, so economic, environmental and oil independence objectives are well-aligned for this subset of drivers.

   - *For drivers who cannot charge frequently*, PHEVs with large battery packs reduce oil consumption and greenhouse gas emissions, and they can help shift air pollution away from population centers. But they are more costly without incentives, even in optimistic scenarios. Increased availability of charging infrastructure could increase the number of drivers who can charge frequently, but policy, pricing and planning should be employed to minimize negative impacts on the electricity grid.

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Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy

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Plug-in hybrid electric vehicles (PHEVs), which use electricity from the grid to power a portion of travel, could play a role in reducing greenhouse gas (GHG) emissions from the transport sector. However, meaningful GHG emissions reductions with PHEVs are conditional on low-carbon electricity sources. We assess life cycle GHG emissions from PHEVs and find that they reduce GHG emissions by 32% compared to conventional vehicles, but have small reductions compared to traditional hybrids. Batteries are an important component of PHEVs, and GHGs associated with lithium-ion battery materials and production account for 2–5% of life cycle emissions from PHEVs. We consider cellulosic ethanol use and various carbon intensities of electricity. The reduced liquid fuel requirements of PHEVs could leverage limited cellulosic ethanol resources. Electricity generation infrastructure is long-lived, and technology decisions within the next decade about electricity supplies in the power sector will affect the potential for large GHG emissions reductions with PHEVs for several decades.

Introduction

Reducing greenhouse gas (GHG) emissions from motor vehicles is a major challenge for climate policy. Modest increases in vehicle efficiency have been offset by increased total travel, and transportation has accounted for about 40% of the growth in carbon dioxide (CO_2) emissions from all energy-using sectors since 1990 (*1*). One approach to reducing GHGs from vehicles is improving fuel economy, e.g., the hybrid electric vehicle (HEV) (*2*). A second approach is a low-carbon fuel, such as cellulosic ethanol (*3–5*). A third approach is a plug-in hybrid (PHEV), which substitutes electricity for a portion of the petroleum used to power the vehicle. We estimate and compare life cycle GHG emissions from PHEVs, an HEV, and a conventional gasoline vehicle (CV). Since emissions from PHEVs largely depend on the sources of electricity used, we consider various electricity generation options with varying carbon intensities as well as the effects of using cellulosic ethanol liquid fuel.

A transition to plug-in hybrids would begin to couple the transportation and electric power generation sectors. Combustion emissions from U.S. (United States) automobiles and light-duty trucks accounted for approximately 60% of GHG emissions from the U.S. transport sector, or 17% of total U.S. GHG emissions (*1*). Powering transport with electricity would shift GHG emissions and criteria pollutants from distributed vehicle tailpipes to largely centralized power plants. Collectively, burning fossil fuels in the transport and power sectors accounted for about 59% of GHG emissions in the United States in 2004 (26.2% and 32.4%, respectively) (*1*). The scale of the U.S. transport sector dictates that the GHG impacts from widespread PHEV adoption will materially affect U.S. GHG emissions.

A plug-in hybrid in a parallel configuration can use an on-board battery to travel on electricity from the grid, and it can operate as a traditional HEV, burning liquid fuel (*6, 7*). PHEVs provide electric-powered travel, but have ranges comparable with conventional vehicles because they can operate as HEVs. The vehicle's battery can be recharged at electrical outlets, hence PHEVs substitute electricity for gasoline to supply a portion of the power needed for travel. Vehicles that travel fewer than 50 km per day are responsible for more than 60% of daily passenger vehicle km traveled in the United States (*8*). Thus, plug-in hybrids may be able to power a substantial portion of daily travel with electricity, and could displace a large fraction of gasoline use. In addition to concerns about climate change, dependence on imported oil supplies is seen as a threat to U.S. national security (*9*) and a passenger transport system partially powered by electricity could reduce oil dependence.

The life cycle GHG emissions benefits of PHEVs depend on the vehicle and battery characteristics, and on the GHG intensity of the electricity and liquid fuel used to power the vehicle. A review of PHEV design considerations and environmental assessments has been completed by Bradley and Frank (*7*). Previous studies investigating GHG impacts from PHEVs focus solely on the impacts of electricity and gasoline for PHEV propulsion. The Electric Power Research Institute (EPRI) has conducted a series of PHEV analyses. Their preliminary reports (*10, 11*) analyzed PHEVs charged with electricity produced from natural gas combined cycle power plants. Other studies have shown larger regional GHG reductions in areas with less GHG-intensive generation portfolios (*12, 13, 50*). Previous estimates have found that 34–73% of the existing light-duty vehicle fleet could be supported as PHEVs from the existing power supply infrastructure (*12, 50*). Kempton et al. estimated potential large GHG reductions using offshore wind to power plug-in vehicles (*14*). A recent EPRI analysis (*15*) modeled the electricity system and PHEV adoption scenarios and found GHG reductions compared to CVs and HEVs. The electricity charging PHEVs in that analysis was 33–84% less carbon intensive than the current U.S. generation portfolio.

This analysis contributes to the PHEV literature by including several aspects omitted by previous work. First, energy use and GHG emissions from battery production are included. Sensitivity analyses are provided to determine how changes in the electricity mix, vehicle efficiencies, battery characteristics, and biofuel use affect the life cycle GHGs from PHEVs. Finally, this analysis highlights how low-carbon electricity decisions and investments are coupled to vehicle and transport sector investments if plug-in hybrids are to reduce life cycle GHGs compared to high-efficiency gasoline-powered vehicles.

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Methods

Life cycle assessment (LCA) quantifies the environmental impacts of a product's manufacture, use, and end-of-life. LCA traditionally utilizes either a process-based methodology or an economic input−output (EIO) methodology (*16–18*). We use data from previous process LCAs, the Economic Input-Output Life Cycle Assessment model (EIO-LCA) (*19*), and the literature to provide a hybrid (*20, 21*) estimation of the life cycle GHG emissions of PHEVs. We compare life cycle energy use and global warming potential (GWP) of PHEVs with those of CVs and HEVs. GWP is measured in grams of CO_2 equivalent (CO_2-eq) with a time horizon of 100 years using the values recommended by the Intergovernmental Panel on Climate Change (*22*). This report includes GHG emissions associated with energy use and fuel production, along with vehicle and storage battery production. Additional detail on the life cycle assessment methods is provided in the Supporting Information.

The systems considered are as follows: a conventional internal-combustion (IC) sedan-type vehicle such as the Toyota Corolla (CV), a hybrid electric sedan-type vehicle (HEV), such as the Toyota Prius, and three PHEVs, powered with liquid fuel and electricity from the grid. The PHEVs considered have electric ranges of 30 km (PHEV30), 60 km (PHEV60), and 90 km (PHEV90). Figure S1 in the Supporting Information displays the study system boundary. The useful life of all vehicles is assumed to be 240,000 km (about 150,000 miles) (*10, 11, 23*). The functional unit of analysis is 1 km of vehicle travel in the United States.

Vehicle Production. Automobile manufacturing for all vehicles considered was assumed to be identical, except for the addition of the storage batteries for HEVs and PHEVs. While HEVs have smaller IC engines than comparable conventional vehicles, we assume HEV electric motors and control equipment account for any differences in impacts. To estimate GHG emissions from vehicle manufacturing (not including the PHEV battery), we use EIO-LCA (*19*) and provide additional detail in the Supporting Information. GHG emissions from vehicle end-of-life have been found to be small as compared to the use phase (*24*) and are therefore omitted.

The PHEVs considered are similar to an existing HEV, with additional battery capacity to enable plug-in capabilities in a parallel configuration. The price premium for HEVs and PHEVs over a conventional vehicle such as a Toyota Corolla will be predominately composed of the additional battery, and to a lesser extent motor controls and electronics (*25*). Also represented in this premium may be intrinsic research, design, and manufacturing costs of a novel automobile as compared to the established complementary assets for a Corolla. Hence, aside from the batteries, the price and impacts of a Corolla were used in the baseline analysis of manufacturing impacts for all vehicles. Table S2 in the Supporting Information summarizes energy and GHG emissions associated with vehicle production.

Battery Production. Successful deployment of a U.S. PHEV fleet will be heavily influenced by battery technology, which has seen recent technological improvements. Most current HEVs and electric vehicles (EVs) utilize nickel−metal hydride (NiMH) batteries. NiMH batteries have displayed good performance characteristics after several years in use in retail EVs and HEVs (*26*). Since NiMH batteries have relatively low energy density (35−55 Wh/kg), they would add considerable mass and volume to the vehicle. An alternative battery chemistry for use in PHEVs is lithium-ion (Li-ion). Li-ion batteries have the advantage of higher energy densities (80−120 Wh/kg), which can facilitate PHEV operation (*26–28*). On the other hand, Li-ion batteries currently face challenges related to aging, cycle life, and relatively high cost. Technological improvements have positioned Li-ion as a likely candidate for use in future plug-in hybrids (*28*) and it is the electricity storage device considered in this analysis for both HEVs and PHEVs.

The HEV in our analysis uses a Li-ion battery weighing 16 kg, and the PHEVs use Li-ion batteries weighing 75–250 kg, depending on electric range considered. Data on primary energy use for battery production, resource extraction and processing, and recycling come from Rydh and Sandén's cradle-to-gate analysis (*27*). They report 1200 MJ of primary energy are required during the manufacture of 1 kWh of Li-ion battery storage capacity. In addition to the energy used in manufacturing, between 310 and 670 MJ of primary energy is required to produce the materials for 1 kWh of Li-ion battery energy storage capacity. This range depends on whether the input materials are recycled or virgin. We use a mid value of 500 MJ/kWh of battery capacity for material production, yielding a total of 1700 MJ of primary energy to produce one kWh of Li-ion battery capacity. Impacts from nonrecoverable battery waste disposal are omitted. The GHG intensity of battery production will depend on the fuels used in the primary energy demand, and the fraction of primary energy that is electricity. Additional detail is provided in the Supporting Information, and Tables S2–S4 present energy and GHG emissions associated with Li-ion battery production and the sensitivity of GHG impacts to virgin or recycled material use.

Rydh and Sandén completed their analysis for a Li-ion cell with a metal oxide-based cathode (Co, Mn, Al) (*27*). As cathode and anode materials in Li-ion batteries evolve, energy requirements for battery production may change. Rydh and Sandén report that the energy intensity of NiMH battery production is nearly double that of Li-ion per kWh of capacity, largely due to differences in energy densities. Thus, the adoption of NiMH as the dominant PHEV battery would increase battery impacts to 3–10% of the life cycle impacts from PHEVs, as shown in Table S3. To compare similar products, we assume that the same battery chemistry will be employed in both HEVs and PHEVs.

The lifetime of a Li-ion battery depends on how the battery is used, so the vehicle use phase will influence upstream impacts from battery manufacturing. The lifetime of Li-ion batteries decreases as depth-of-discharge (DOD) of each cycle increases. It is assumed that the batteries in HEVs and PHEVs last the lifetime of the vehicle and will be discharged to a maximum of 80% DOD. If the battery requires a replacement during the life of the vehicle, impacts from battery manufacturing would approximately double. Alternatively, less carbon intensive battery manufacturing or improvements in battery energy density would reduce GHG impacts. Since it is very difficult to predict technological developments of electricity storage devices, our results show impacts due to current battery production in order to indicate the potential to reduce impacts from battery manufacture.

Use Phase. The majority of vehicle life cycle energy use and GHG emissions result from powering the vehicle with liquid fuel or electricity (*4*). In comparing the CV, HEV, and PHEVs, this analysis omits impacts from vehicle service, maintenance, and other fixed costs, assuming these to be similar across vehicle technologies, or that differences have negligible impact in comparison with the use phase (*4*).

When 1 L of gasoline is burned, about 2.3 kg of CO_2 is released (67 g CO_2/MJ of fuel, HHV) (*1*). In addition to combustion, life cycle GHG emissions from gasoline include crude oil extraction and transportation, refining, and fuel distribution. These upstream GHG emissions were estimated to be about 0.67 kg of CO_2-eq per liter of fuel (19 g CO_2-eq/MJ) using the GREET 1.7 model (*29*). For the base case, corn-based ethanol comprises 3% of liquid fuel (volume basis). Other cases consider cellulosic ethanol with reduced life cycle GHG emissions compared to corn ethanol. The life

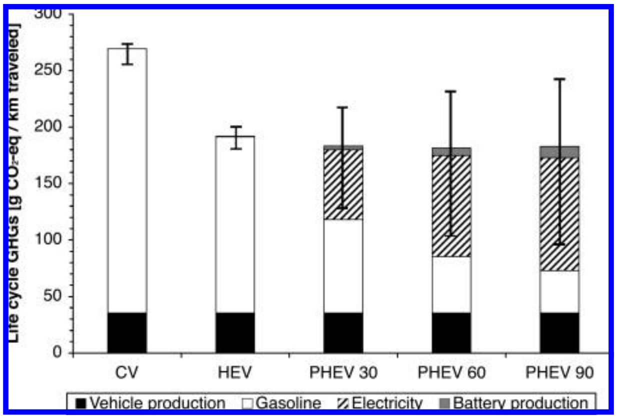

FIGURE 1. Life cycle GHG emissions (g CO_2-eq/km) of conventional vehicles (CVs), hybrid electric vehicles (HEVs), and plug-in hybrids (PHEVs) with all-electric ranges of 30, 60, or 90 km. Life cycle GHG intensity of electricity is 670 g CO_2-eq/kWh (186 g/MJ; U.S. average scenario). Uncertainty bars represent changes in total emissions under the carbon-intensive (950 g CO_2-eq/kWh) or low-carbon (200 g CO_2e/kWh) electricity scenarios.

cycle GHG emissions of corn and cellulosic ethanol used are 73 and 5 g CO_2-eq/MJ (HHV), respectively (*3, 5*).

While electricity consumption does not emit CO_2 at the point of use, the GHG intensity (g CO_2-eq/kWh) of electricity used to charge PHEVs is a key parameter in estimating the life cycle GHG impact. In the electric power sector, there were 3970 billion kWh and 2400 million t of CO_2 produced at power facilities in 2004 (*30*). Thus, the average direct CO_2 intensity of electricity was 171 g CO_2/MJ of electricity (615 g CO_2/kWh). If PHEVs are considered marginal load, the GHG intensity of power plants ramped up, dispatched, and ultimately constructed to meet this additional demand should be used to calculate PHEV impacts. If, on the other hand, PHEVs are considered part of the total load, the GHG intensity of the generation mix serving the load should be used. We adopt three scenarios to represent the GHG intensity of electricity, and show sensitivity of the results to changes in electricity GHG intensity. This method allows straightforward comparisons among the vehicle types, regardless of whether the PHEV load is considered marginal.

Precombustion upstream GHG emissions associated with the extraction, processing, and transportation of fuels for power generation add substantial impacts to direct emissions from combustion: 8–14% for coal and 13–20% for domestic natural gas (*31, 32*). We estimate U.S. average upstream GHG emissions to be 54 g CO_2-eq per kWh of electricity, adding an additional 9% to the direct plant emissions of the U.S. power portfolio (*33*). Direct and upstream impacts are included in the electricity scenarios. Table S1 details power sector GHG emission factors.

For the base-case scenario, electricity used to charge PHEVs has a life cycle GHG intensity similar to the average intensity of the current U.S. power portfolio, or 670 g CO_2-eq per kWh of electricity (*30, 33*). The *carbon-intensive* scenario, at 950 g CO_2-eq/kWh, represents a case where coal (the most carbon-intensive fuel) is the predominant fuel for electricity generation. The *low-carbon* scenario describes an energy system where renewables, nuclear, or coal with carbon capture and sequestration, account for a large share of the generation, thus making the GHG intensity of electricity low, at 200 g CO_2-eq/kWh. Table S6 outlines a representative electricity mix for the *low-carbon* scenario and shows direct and upstream emissions of each generation technology.

Conventional vehicle gasoline consumption is 0.08 L/km (30 mpg, or 2.5 MJ/km), and hybrids (both HEV and PHEV) consume 0.05 L of gasoline/km (45 mpg, or 1.7 MJ/km), for liquid fuel-powered transport (*23, 34, 35*). In addition, 0.20 kWh of electricity (at the power plant) is required for 1 km of electric grid-powered travel (*10*). Electrical transmission and distribution losses, as well as efficiency losses in battery charging are included. Table S5 in the Supporting Information presents parameters for liquid fuel and electricity consumptions during travel. Increased weights of battery packs may affect both liquid fuel and electricity propulsion requirements for PHEVs. To be consistent with previous studies (*15*), effective fuel consumption remains the same as PHEV battery capacity increases in this study. See additional discussion of this issue in the Supporting Information.

Driving behaviors are a key component for assessing the impact of PHEVs. These patterns will determine the fraction of total vehicle travel that is powered by gasoline or by electricity from the grid. Furthermore, driving patterns might also dictate how often a PHEV can be charged. For example, if a car is parked at a workplace regularly, it might be possible to charge the PHEV twice in one day (once at home, once at work). We assume that PHEVs are charged once per day. GHG emissions per km of vehicle travel were calculated for each vehicle using the following relationship:

$$\frac{\mathrm{GHG}}{\mathrm{km}} = (\alpha)\left[\frac{\mathrm{kWh}}{\mathrm{km}} \times \left(\frac{\mathrm{GHG}_{\mathrm{powerplant+upstream}}}{\mathrm{kWH}}\right)\right] + (1-\alpha)\left[\frac{\mathrm{L}_{\mathrm{fuel}}}{\mathrm{km}} \times \left(\frac{\mathrm{GHG}_{\mathrm{fuel+upstream}}}{\mathrm{L}_{\mathrm{fuel}}}\right)\right] \quad (1)$$

where α represents the fraction of travel that is powered by electricity, and $(1-\alpha)$ represents the fraction of travel powered by liquid fuel. The term multiplied by α represents the combustion and upstream impacts of electricity, while the term multiplied by $(1 - \alpha)$ represents the combustion and upstream liquid fuel emissions.

To determine α (the fraction of vehicle travel powered by electricity) a cumulative distribution of daily vehicle kilometers traveled has been constructed (Figure S2 in the Supporting Information) from the U.S. Department of Transportation National Household Travel Survey (*8*). This distribution reports the percentage of total daily vehicle kilometers from vehicles traveling less than a given distance per day. When all daily travel could be powered by electricity, α takes the value of 1 (the PHEV travels fewer km than its electric range); when daily travel is entirely liquid fuel powered (CV and HEV), α is 0. Alpha (α) is a fraction between 0 and 1 when PHEV daily travel is farther than its electric range (the PHEV uses electricity from the grid and liquid fuel). With the PHEV configurations considered in this analysis, electricity from the grid powers between 47% and 76% of vehicle travel (Table S7).

Results

Under the U.S. average GHG intensity of electricity, PHEVs were found to reduce use phase GHG emissions by 38–41% compared to CVs, and by 7–12% compared to HEVs. These use-phase impacts omit battery manufacturing, and can assist in framing impacts if battery manufacturing impacts decrease. The lifetime and performance of the battery is an important parameter for the economic and environmental success of PHEVs. As shown in Figure 1, the additional GHG emissions from Li-ion battery manufacturing (*27*) yield life cycle impacts from PHEVs that are slightly lower than those of HEVs, assuming the original battery lasts the lifetime of the vehicle. Life cycle energy use and GHG emissions are described in Table S8.

The potential for PHEVs to achieve large-scale GHG emission reductions is highly dependent on the energy sources of electricity production. We use the U.S. average case to provide baseline comparative impacts and use low-

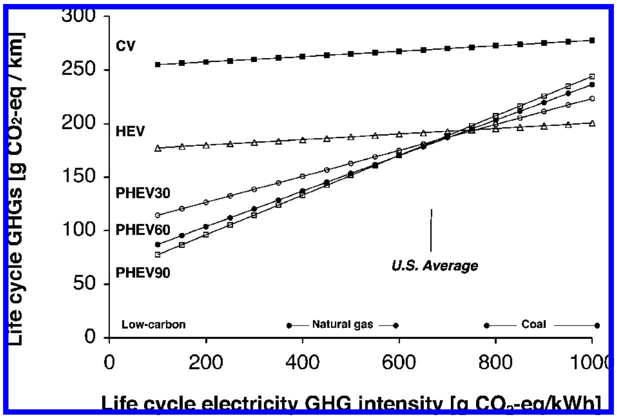

FIGURE 2. Life cycle GHG emissions from vehicles shown as a function of the life cycle GHG intensity of electricity generation. Electricity is used during production of the vehicles, and the slight slope of the CV and HEV lines reflect GHG intensity of electricity used during production. The chart indicates which generation options correspond to various GHG intensities to provide some insight into generation mixes. The low-carbon portfolio could comprise nuclear, wind, coal with carbon capture and sequestration, and other low-carbon electricity generation technologies (see Table S6). The vertical line at 670 g CO2-eq/kWh indicates the U.S. average life cycle GHG intensity.

and high-carbon scenarios to illustrate GHG emissions under varying sources of electricity production. PHEVs reduce life cycle GHG emissions by 32% compared to CVs, but have small reductions compared to HEVs under the current U.S. average electricity GHG intensity. Under the *carbon-intensive* scenario, life cycle PHEV impacts are 9–18% higher than those of HEVs. Without appropriate policies, widespread PHEV adoption could migrate toward this scenario, given the abundance of U.S. coal reserves and planned coal power plant additions (*36*). Under the *low-carbon* scenario, large life cycle GHG reductions (51–63% and 30–47%, compared to CVs and HEVs, respectively) are possible with PHEVs. Thus, if large life cycle GHG reductions are desired from PHEVs, a strategy to match charging with low-carbon electricity is necessary.

PHEV charging is likely to occur in the evening and overnight as commuters return home from work. The GHG intensity of electricity changes with time of day, season, and service territory. It is important to show how changes in GHG intensity of the electricity charging PHEVs affect the comparative life cycle impacts. Figure 2 can be used to evaluate the benefit of PHEVs as compared to CVs and HEVs, based upon the GHG intensity of electricity generation associated with the place and time of interest.

Figure 3 expands on the above scenarios by comparing cellulosic ethanol and gasoline use in each of the vehicles. With an 85% cellulosic ethanol blend (E85) and the current U.S. average electricity, fuel-efficient vehicles that do not use electricity, such as HEVs or other CVs with high fuel economy, will minimize GHGs. In contrast, with a low-carbon electricity portfolio, plug-in hybrids utilizing primarily electricity for propulsion will have lower GHGs in a system where petroleum remains the dominant liquid fuel. Table 1 shows the sensitivity of the life cycle GHG results to changes in GHG intensity of electricity, vehicle efficiencies, and E85 cellulosic ethanol use.

Under widespread PHEV market penetrations, the reduced demand for liquid fuel could have important implications for the feasibility of biofuel use in the transport sector. Cellulosic biofuels offer potential GHG reductions from transport, however the resource base is limited (*37, 38*). Gasoline use in light-duty vehicles is about 17 EJ/year (*30*). To supply 25% of this current demand with ethanol from cellulosic crops, between 50 and 100 million hectares (ha) of land would be required (180 million ha are currently used each year for growing crops (*39*)). This is based on a 40% conversion efficiency from energy in plant matter to energy in ethanol (*40*), and between 6 and 12 Mg of biomass yield per ha (dry basis) annually (*5*). Thus, between 45 and 90 GJ of liquid fuel would be produced per hectare.

Tilman et al. report that biofuels grown on degraded land could provide about 13% of current global petroleum use in transport, and 19% of current global electricity consumption, which would reduce global GHG emissions by 15% (*38*). Furthermore, biomass processing systems that produce both protein for animal feed and carbohydrates for liquid fuel and electricity production could ameliorate the tension between energy and feed crops (*41*). Since it is unlikely that biofuels alone will provide necessary GHG emission reductions, PHEVs could provide a platform to efficiently leverage these low-carbon energy streams. Under the configurations and driving patterns used in this analysis, an all PHEV fleet would reduce current gasoline use from 17 EJ/year to between 4 and 9 EJ/year. Ten million ha of land could supply one EJ of liquid fuel, assuming a yield of 90 GJ of ethanol per hectare. Non-plant-based feedstocks, such as municipal solid waste (MSW), can be used to produce low-carbon liquid fuel, however all of the MSW produced in the U.S. could produce less than 1 EJ of ethanol per year (*42*).

Discussion

For large GHG reductions with plug-in hybrids, public policies that complement PHEV adoption should focus on encouraging charging with low-carbon electricity. Policies could include adjusting renewable portfolio standards to account for potential off-peak charging. If PHEVs supply a sizable portion of passenger travel, charging intelligence will likely be incorporated to maximize utilization of available resources and low-cost electricity, facilitate user billing and replacement of motor fuel taxes for infrastructure funding, as well as potentially enable two-way power flows between vehicles and the grid (*43*). Public policies could utilize charging intelligence to minimize the carbon intensity of electricity used, either by prices or credits.

While it is evident that GHG intensity of the electricity used to charge PHEVs greatly affects their ability to reduce GHG emissions from transport, a policy discussion regarding electricity supply decisions and PHEVs deserves wider attention and dialogue. U.S. power generation facilities, especially aging coal power plants, are generally nearing the end of their useful lives and will have to be replaced or overhauled within the next two decades. Because power plants typically are in service for 30 years or more, technology decisions regarding new generation capacity have profound and long-lasting GHG impacts (*44, 45*). The Department of Energy reports plans to build 50 GW of coal power plants in the next 5 years and a total of 154 GW within the next 24 years (*36*), and the U.S. Energy Information Administration reference case forecasts a 2030 electricity mix with higher carbon intensity than today's mix (*46*). If new coal plants are untenable, increasing demand for natural gas, even in the absence of potential PHEV adoption, will likely require large increases in liquefied natural gas (LNG) imports. The life cycle GHG impacts of LNG for electricity are higher than for domestic natural gas (*31*). Hence large reliance on LNG to power PHEVs could increase emissions relative to using domestic natural gas and introduce additional energy security risks. Large reductions in the GHG intensity of the electricity sector within the next 30 years will only be realized by sustained replacement of retired carbon-intensive capital with low-carbon generation.

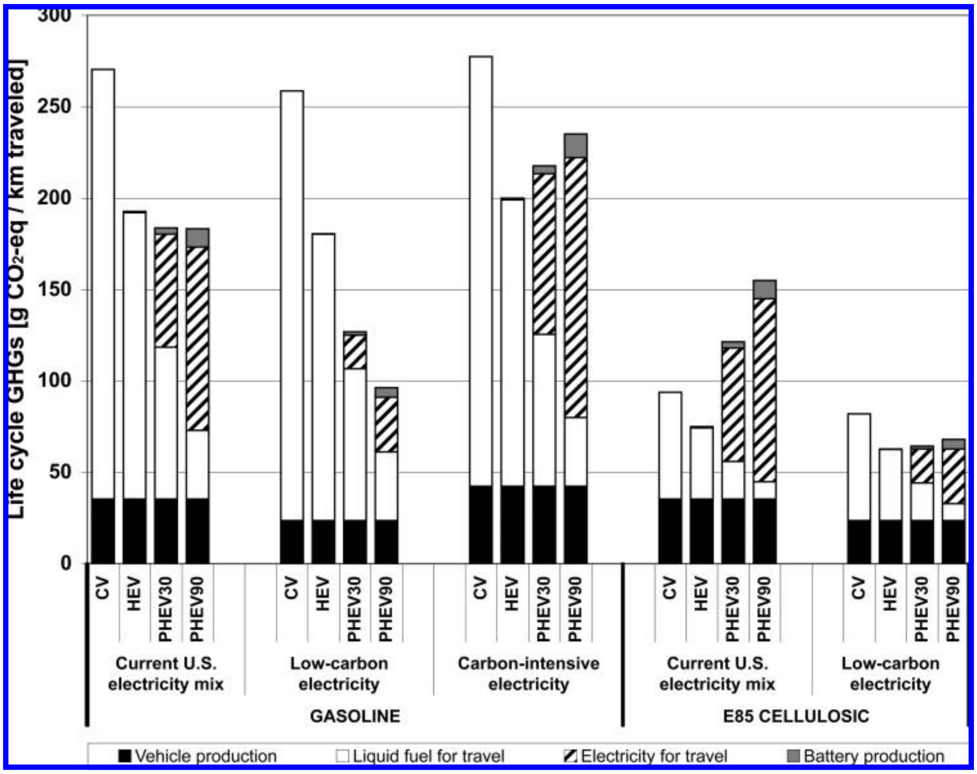

FIGURE 3. Life cycle GHG emissions sensitivity of CVs, HEVs, and PHEVs with 30 and 90 all-electric km ranges under different fuel and electricity carbon intensities. Life cycle carbon intensity of electricity assumed to be 670, 200, and 950 g CO_2-eq/kWh for U.S. average, low-carbon, and carbon-intensive scenarios, respectively. "E85" is a liquid fuel with 85% cellulosic ethanol (volume basis), and the remainder gasoline. Life cycle carbon intensity of gasoline and E85 are 86 and 21 g CO_2-eq/MJ, respectively.

TABLE 1. Sensitivity of Results to Changes in GHG Intensity of Electricity, Vehicle Efficiencies, and E85 Cellulosic Ethanol Use

		life cycle GHG emissions [g CO_2-eq/km]				
scenario	parameter varied	CV	HEV	PHEV 30	PHEV 60	PHEV 90
baseline results (gasoline)		269	192	183	181	183
carbon-intensive scenario	950 g CO_2-eq/kWh	276	199	217	228	235
low-carbon scenario	200 g CO_2-eq/kWh	257	180	126	104	96
high kWh/km required (10% degradation)	0.22 kWh/km	269	192	190	192	195
low kWh/km required (20% improvement)	0.16 kWh/km	269	192	170	162	161
low fuel economy (20% degradation)	10 km/L (CV), 15 km/L (HEV and PHEV)	328	231	204	194	192
high fuel economy (20% improvement)	15 km/L (CV), 23 km/L (HEV and PHEV)	230	166	169	173	177
E85 Cellulosic liquid fuel		94	75	121	144	155
carbon-intensive scenario	950 g CO_2-eq/kWh	101	82	155	191	207
low-carbon scenario	200 g CO_2-eq/kWh	82	63	64	66	68

Long-term planning horizons in the automotive sector are much shorter than those in the power sector, with an automotive fleet cycle of 12–15 years. If PHEVs have high adoption in two or three fleet cycles from now, the electricity supply technology decisions made within the next ten years will affect the GHG intensity of the electricity system encountered by those vehicles. A commitment to developing a low-carbon electricity portfolio becomes even more important if large GHG reductions from PHEVs are desired within the current cycle of electricity capital turnover.

Concerns regarding climate change and national GHG emissions demand that a shift to PHEVs be analyzed, and so GHGs are the focus of this study. However, with a potential transition from a primarily petroleum-based passenger transport sector to one powered with electricity, climate change is one consideration, while the impacts on criteria air pollutants (*47*), reduced oil dependence, and toxic releases are others. A thorough life cycle impact assessment of PHEVs would potentially estimate acidification, eutrophication, photochemical smog, terrestrial and aquatic toxicity, human health impacts, resource depletion, land and water use, and perhaps additional impact categories (*48*). Future research could identify the environmental tradeoffs among these impact categories from a PHEV fleet. While the environmental fate and toxicity of current battery technology materials are not similar to those of lead-acid batteries (*49*), potential toxicity during materials procurement and battery manufacturing, and a strategy to deal with the recovery, recycling, and disposal of vehicle batteries should be part of the dialogue in a transition to large-scale adoption of storage batteries in vehicles.

When charging PHEVs with electricity that has a GHG intensity equal to or greater than our current system, our results indicate that PHEVs would considerably reduce gasoline consumption but only marginally reduce life cycle GHGs, when compared to gasoline–electric hybrids or other fuel-efficient engine technologies. With a low-carbon electricity system, however, plug-in hybrids could substantially reduce GHGs as well as oil dependence.

The effect of PHEVs on GHG emissions from the transportation sector will depend on the rate of consumer adoption. Our focus on low, current, and high GHG-intensive electricity scenarios allows decision makers to think about what an electricity system should look like, over various adoption scenarios, if PHEVs are pursued as a source of large GHG emissions reductions. With the slow rate of capital turnover in the electricity sector, a low-carbon system may require many years to materialize. Considerable reductions in greenhouse gas emissions using plug-in hybrids in the coming decades will likely require decisions within the next ten years to develop a robust low-carbon electricity supply.

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Note Added after ASAP Publication

CHG emissions from cellulosic ethanol was changed from 10 to 5 g in the article and in the Supporting Information published ASAP April 5, 2008; the corrected version was published ASAP April 29, 2008.

Supporting Information Available

Additional detail and discussion life cycle system boundary, cumulative distribution daily passenger vehicle travel, tables (text, 8 tables, 2 figures; 25 pages). This information is available free of charge via the Internet at http://pubs.acs.org.

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Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles

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ABSTRACT

Plug-in hybrid electric vehicle (PHEV) technology is receiving attention as an approach to reducing US dependency on foreign oil and greenhouse gas (GHG) emissions from the transportation sector. PHEVs require large batteries for energy storage, which affect vehicle cost, weight, and performance. We construct PHEV simulation models to account for the effects of additional batteries on fuel consumption, cost, and GHG emissions over a range of charging frequencies (distance traveled between charges). We find that when charged frequently, every 20 miles or less, using average US electricity, small-capacity PHEVs are less expensive and release fewer GHGs than hybrid electric vehicles (HEVs) or conventional vehicles. For moderate charging intervals of 20–100 miles, PHEVs release fewer GHGs, but HEVs have lower lifetime costs. High fuel prices, low-cost batteries, or high carbon taxes combined with low-carbon electricity generation would make small-capacity PHEVs cost competitive for a wide range of drivers. In contrast, increased battery specific energy or carbon taxes without decarbonization of the electricity grid would have limited impact. Large-capacity PHEVs sized for 40 or more miles of electric-only travel do not offer the lowest lifetime cost in any scenario, although they could minimize GHG emissions for some drivers and provide potential to shift air pollutant emissions away from population centers. The tradeoffs identified in this analysis can provide a space for vehicle manufacturers, policymakers, and the public to identify optimal decisions for PHEV design, policy and use. Given the alignment of economic, environmental, and national security objectives, policies aimed at putting PHEVs on the road will likely be most effective if they focus on adoption of small-capacity PHEVs by urban drivers who can charge frequently.

1. Introduction

Increasing concerns regarding high oil prices, oil dependency, and climate change have resulted in policymakers and the automobile industry evaluating alternative strategies for passenger transportation. Plug-in hybrid electric vehicle (PHEV) technology offers a possible approach to reducing life cycle GHG emissions and dependency on oil as a transportation fuel via the use of large rechargeable storage batteries that enable electricity from the grid to provide a portion of the propulsion requirements of a passenger vehicle (Bradley and Frank, 2009; EPRI, 2007; Romm, 2006; Samaras and Meisterling, 2008). Since approximately 60% of United States (US) passenger vehicle miles are traveled by vehicles driving less than 30 miles per day (US DOT, 2003) PHEVs may be able to displace a large portion of gasoline consumption with electricity. While the US transportation sector is overwhelmingly powered by petroleum, oil-fired power plants provide only about 2% of US electricity generation. The balance of the 2006 electricity mix includes coal (49%), nuclear (20%) natural gas (20%), hydroelectric (7%), renewables (3%), and other (1%) (EIA, 2008a). We explore the impact of PHEV battery capacity on fuel consumption, cost, and GHG emissions benefits over a range of charging frequencies. The tradeoffs identified in this analysis can provide a space for policymakers, vehicle manufacturers, and the public to identify optimal decisions to maximize economic, environmental and oil independence objectives with PHEVs.

The price differential between retail electricity and gasoline could make electric-powered travel more cost effective than gasoline, depending on the additional vehicle capital costs (Lemoine et al., 2008; Scott et al., 2007). However, the reduced fuel use, economic costs, and GHG emissions of PHEVs depend on the vehicle and battery characteristics, as well as recharging frequency and the source of electricity used for recharging. For example, the full life cycle GHG emissions associated with

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manufacturing and operating a PHEV could be close to that of traditional hybrids under the current US mix of electricity generation (Samaras and Meisterling, 2008). Trends in electricity generation, battery manufacturing, and vehicle design have critical implications on the relative advantages of PHEVs.

Bradley and Frank (2009) provide a review of the potential PHEV vehicle architectures. All PHEVs have a drivetrain that incorporates an electric motor and an internal combustion engine (ICE), and like conventional hybrid electric vehicles (HEVs) these components can be arranged in series, parallel, or split series/parallel configurations (Frank, 2007). In a series configuration, the engine provides electrical power through a generator to charge the battery and power the motor, and the motor provides torque to the wheels. The primary advantage of the series configuration is the ability to size the engine for average, rather than peak, energy needs and run it at its most efficient operating point. However, relatively large batteries and motors are required to satisfy peak power requirements, and efficiency losses are inherent in converting mechanical energy to electrical energy and back to mechanical energy again. In a parallel configuration, such as the Honda Civic and Accord hybrids, the engine and motor both provide torque to the wheels, and the engine charges the battery only by applying torque to the motor in reverse—there is no separate generator. Because the engine provides torque to the wheels, the battery and motor can be sized smaller, but the engine is not free to operate at its most efficient point. A split series/parallel powertrain, such as the one used in the popular Toyota Prius, uses a planetary gear system power split device and a separate motor and generator to allow the engine to provide torque to the wheels and/or charge the battery through the generator, depending on use conditions. The split drivetrain can take advantage of series and parallel benefits, but it requires more components. We take the split drivetrain configuration of the Prius as the baseline HEV and examine its PHEV versions sized for 7, 20, 40, and 60 miles (11, 32, 64 and 96 km) of all electric range (AER) with comparable performance characteristics.[1]

The storage battery of a PHEV, which can be recharged using conventional electrical outlets, would allow the vehicle to drive for a limited range using energy from the electricity grid. A fully charged PHEV operates in *charge-depleting mode* (CD-mode) until the battery is depleted to a target state of charge (SOC), at which point the vehicle switches to *charge-sustaining mode* (CS-mode), using the engine to maintain the target SOC. A PHEV can be further categorized as (1) *range-extended* or (2) *blended*, depending on its energy management strategy in the charge-depleting state (Bradley and Frank, 2009). A range-extended PHEV functions as a pure electric vehicle (EV) in charge-depleting mode, using only electrical energy from the battery for propulsion and disabling any engine operation. Blended PHEVs invoke a strategy where the motor provides primary power in charge-depleting mode, but the engine is used as needed to provide additional power. In the charge-sustaining state, all PHEVs operate similarly to a standard HEV, using the engine to maintain the target battery SOC. Since the performance of blended configurations can vary widely based on a broad range of control strategy parameters, for simplicity and fair comparisons we restrict attention to the range-extended PHEVs that run entirely on electrical power in the charge-depleting range and switch to operate like an HEV in the charge-sustaining range. Fig. 1 shows a typical pattern for a range-extended PHEV with an initial SOC of 80% and an SOC sustaining target of 35%. The ability to operate entirely on electricity in the charge-depleting range is advantageous for range-extended PHEVs because they are capable of operating for a time entirely on cheaper energy from the electricity grid. Additionally, the electric-only drive mode of PHEVs could facilitate operations in a city center that has limited the use of ICEs for local pollution control (Karden et al., 2007).

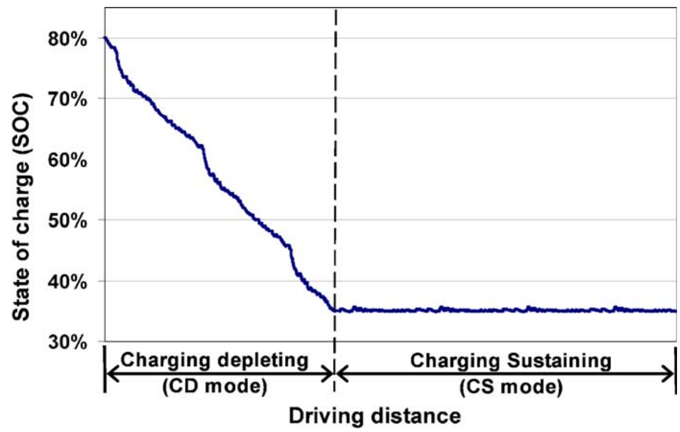

Fig. 1. Typical SOC of a range-extended PHEV.

Since PHEVs rely on large storage batteries for any economic or environmental benefits relative to traditional hybrids and ICE vehicles, the characteristics and design issues associated with PHEV batteries play an important role in the potential adoption of PHEVs. Consumer acceptance and adoption will mainly depend on battery cost, operating cost, power and performance, battery cycle and calendar life, and safety, among other characteristics. Overviews of the current state of battery technology for PHEV applications as well as future goals are provided in Axsen et al. (2008), Burke (2007), Kalhammer et al. (2007) and Karden et al. (2007). The two current dominant battery technologies considered likely candidates for PHEV applications are nickel-metal hydride (NiMH) and lithium-ion (Li-ion) batteries. NiMH batteries have performed well and have proven reliable in existing hybrids vehicles (Kalhammer et al., 2007). However, their relatively low energy density (Wh/L) and specific energy (Wh/kg) implies large, heavy batteries for extended electric travel. Li-ion batteries have higher energy density and specific energy and are benefiting from increased technological advancement, but concerns remain regarding calendar life, and safety (internal corrosion and high environment temperatures could cause Li-ion batteries to combust) (Karden et al., 2007). Another issue is that both batteries self-discharge more rapidly at high temperature, which reduces charge capacity and battery life (Axsen et al., 2008). In spite of the technical difficulties to be overcome, Li-ion batteries have been widely evaluated for their great potential as PHEV energy storage devices (Axsen et al., 2008; Burke, 2007; Kalhammer et al., 2007; Karden et al., 2007), thus we focus on Li-ion batteries in this study.

The energy required to produce the raw materials and manufacture the Li-ion battery has been estimated to account for approximately 2–5% of the life cycle GHG emissions from a PHEV, which is relatively small if the original battery can last the life of the vehicle (Samaras and Meisterling, 2008). During vehicle operation, the battery mass in PHEVs is large enough to affect fuel economy and acceleration. Due to data constraints, previous studies evaluating the GHG benefits of PHEVs assumed that the additional weight of potentially large storage batteries did not affect the gasoline fuel economy or the electrical requirements for propulsion. Zervas and Lazarou (2008) presented relationships between ICE vehicle weight and CO_2 emissions and argued that exploring weight thresholds for passenger cars in the European

[1] The AER settings in this study cover a wide range of PHEV capacities. Two planned mass-production PHEVs, the Prius plug-in (AER 7 miles) (Maynard, 2008) and the Chevrolet Volt (AER 40 miles) (Bunkley, 2008), are within our evaluation range.

Union could help reduce GHGs from passenger transportation. Furthermore, a preliminary regression estimation of the impact of weight and power on traditional hybrids found that weight decreases hybrid fuel economy (Reynolds and Kandlikar, 2007). Hence, technical sensitivity analysis is warranted to explore the impact of additional battery and potential structural weight on fuel consumption, greenhouse gas emissions, and operating costs of PHEVs.

2. Method

2.1. Effects of battery weight on PHEV performance

Conventional vehicles (CVs) that hold more fuel can travel farther without refueling. Similarly, PHEVs with larger battery capacity can travel farther on electricity before drawing on liquid fuel. However, batteries have a considerably lower specific energy than liquid fuel: when a vehicle is filled with 10 gal (38 L) of gasoline, it contains approximately 360 kWh of energy embodied in the fuel. The vehicle weighs an additional 28 kg, and it gradually loses that weight as the fuel is combusted in the engine. In contrast, a PHEV battery pack may contain 3–30 kWh and weigh 30–300 kg plus the additional vehicle structural weight required to carry these batteries, and the vehicle must carry this weight even after the battery is depleted. Additional battery weight decreases the attainable efficiency in miles per kWh in CD-mode as well as miles per gallon in CS-mode (once the battery is depleted to its lower target SOC). Thus, while increased battery capacity extends AER, it decreases efficiency in both CD- and CS-modes.

Because extra battery weight may require additional structural support in the vehicle body and chassis, we investigate the effects of additional weight needed to support each additional kg of battery and impose a parameter called the *structural weight multiplier*. Via informal discussions with several automakers, we estimate that this multiplier is typically around +1 × (1 kg of additional structural weight required per kg of battery) with a range of +0 × (no additional weight required) to +2 × (2 kg of additional structural weight required per kg of battery). The requirement for the additional structural weight is dependent on the vehicle type and its design. For example, if a vehicle base structure is optimized for light weight, then adding batteries may require additional structural elements to support the weight of batteries and the additional weight of the structure itself will call for more structural support. On the other hand, if a vehicle is weight-constrained by other considerations, such as crash-test performance or hauling capacity, the vehicle may require only limited structural weight to support the added batteries. We assume that 1 kg of additional structural weight is required for each kg added to the vehicle (+1 × case) as our base case, and we investigate the +0 × and +2 × cases for the purpose of sensitivity analysis. We also account for the weight of larger electric motors required to maintain target performance characteristics in heavier vehicles. Particularly, we size the motor of each vehicle such that it can accelerate from 0–60 miles per hour (mph) (0–100 km/h) in a time comparable to the Prius (10 s) when the vehicle is in CS-mode.

2.2. Plug-in hybrid vehicle simulation

We use the US Department of Energy Powertrain System Analysis Toolkit (PSAT) vehicle physics simulator (Argonne National Laboratory, 2008) to model and examine design tradeoffs between battery capacity and PHEV benefits. PSAT is a forward-looking vehicle simulator, meaning it models the driver as a control system that attempts to follow a target driving cycle of defined vehicle speed at every time step by actuating the accelerator and brake pedals. For the PHEV simulations in our study, we used the model year 2004 Toyota Prius as a baseline for engine, body and powertrain configurations.[2] Additional battery capacity was added to the base configuration in order to attain a set of AER requirements, and the electric motor was scaled to maintain acceleration characteristics at low SOC. The PSAT split hybrid control strategy for maximum engine efficiency was modified so that the vehicle operates in electric only CD-mode without engaging the engine until the battery reaches 35% SOC, after which time the vehicle switches to CS-mode and operates like a Toyota Prius, using the split control strategy with a target SOC of 35% and SOC operating range 30–40%.

The design variables controlled in this study are the number of battery modules and the size (power scaling factor) of the electric motor. The engine model is a 1.4 L four-cylinder engine with a 57 kW maximum power. The base motor is a permanent magnet type with a maximum peak power of 52 kW and a weight of 40 kg including a 5 kg controller. Performance map and weight characteristics of larger motors needed for the PHEV cases are predicted using a motor scaling parameter.[3] The battery model is based on a Saft Li-ion battery package, where each module is comprised of three cells in series with a specific energy adjusted to 100 Wh/kg (Kalhammer et al., 2007). The weight of each cell is 0.173 kg, and its capacity is 6 Ah with a nominal output voltage of 3.6 V. Accounting for the weight of packaging using a factor of 1.25, the weight of one 3-cell module is 0.65 kg. The total battery size and capacity was scaled by specifying an integer number of battery modules.[4] Additional structural weight in the body and chassis required to support the weight of the battery and motor are controlled by the structural weight multiplier. In order to compare the performance of HEVs to PHEVs using comparable technology and prices, we use the current Prius model as our HEV base case but replace its original NiMH battery and control strategy with the Saft Li-ion battery module and a simplified split control strategy.[5] The CV in our study is simulated by using a Honda Civic configuration in the PSAT package with an altered car body and tires to match Prius specifications. The engine, motor and battery configurations of the base HEV and CV are shown in the last two columns of Table 1.

Simulations were performed to test PHEVs with 7-, 20-, 40-, and 60-mile AERs under three cases of structural weight multipliers +0 ×, +1 ×, and +2 ×. We used the Environmental Protection Agency (EPA) Urban Dynamometer Driving Schedule (UDDS) (EPA, 1996) driving cycle to measure fuel efficiency in CS-mode and electricity efficiency in CD-mode in the vehicle simulations. In each test, the number of battery modules needed to reach the target AER was first determined. To compare equivalent-performance vehicles, motor size (power) was then adjusted to achieve a 0–60 mph acceleration time specification of 10.0s+0.5/−0.0, which is approximately the acceleration performance of a Toyota Prius. This procedure was repeated iteratively until convergence to a vehicle profile that satisfies both required AER and acceleration specifications for each case.

[2] We use the default MY04 Prius configurations in the PSAT software package. The vehicle body weight is 824 kg, drag coefficient is 0.26, frontal area is 2.25 m^2, tire specification is P175/65 R14, and front/rear weight ratio is 0.6/0.4.

[3] The performance map and motor and controller weight are scaled linearly with peak power.

[4] Results of PHEV simulation may vary depending on battery configuration. In this study we assume that battery modules are arranged in series for simplicity.

[5] We assume a target SOC at 55% (Kelly et al., 2002) for the base HEV, and the number of Li-ion battery modules is adjusted to match the original NiMH battery capacity of 1.3 kWh.

Table 1
PHEV configurations and performance results.

	PHEV	Structural weight factor	+0 ×				+1 ×				+2 ×				HEV	CV
		Target AER (mile)	7	20	40	60	7	20	40	60	7	20	40	60		
Vehicle design	Engine	Engine power (kW)	57	57	57	57	57	57	57	57	57	57	57	57	57	113
		Weight (kg)	114	114	114	114	114	114	114	114	114	114	114	114	114	251
	Motor	Motor power (kW)	55	57	60	65	56	61	68	77	57	65	77	93	55	
		Motor weight (kg)	37	38	40	43	37	41	45	51	38	43	51	62	37	
		Controller weight (kg)	5	5	6	6	5	6	6	7	5	6	7	9	5	
		Structural weight (kg)	0	0	0	0	3	7	12	19	7	19	38	62	0	
		Total weight (kg)	42	44	46	50	46	53	64	78	51	69	97	133	42	
	Battery	Number of modules	46	123	248	376	46	127	260	408	46	130	276	444	20	
		Number of cells	138	369	744	1128	138	381	780	1224	138	390	828	1332	60	
		Battery volume (m^3)	0.13	0.35	0.70	1.06	0.13	0.36	0.74	1.15	0.13	0.37	0.78	1.26	0.06	
		Battery capacity (kWh)	3.0	8.0	16.1	24.4	3.0	8.2	16.8	26.4	3.0	8.4	17.9	28.8	1.3	
		Battery weight (kg)	30	80	161	244	30	82	168	264	30	84	179	288	13	
		Structural weight (kg)	0	0	0	0	17	69	156	251	34	143	332	550	0	
		Total weight (kg)	30	80	161	244	47	152	324	516	64	227	511	837	13	
	Vehicle	Vehicle weight (kg)	1516	1567	1651	1737	1536	1649	1832	2037	1558	1740	2051	2414	1499	1475
Simulation results	CD mode	Efficiency[a] (Wh/mile)	178	178	179	182	179	183	188	197	181	188	200	215	–	–
		Simulation AER (mile)	7.5	20.2	40.4	60.2	7.5	20.2	40.3	60.2	7.4	20.2	40.3	60.3	–	–
	CS mode	Efficiency (gal/100 mile)	1.96	1.98	1.99	2.01	1.94	2.00	2.04	2.09	1.95	2.03	2.09	2.20	1.93	3.53
		0–60 mph time (s)	10.2	10.2	10.3	10.1	10.2	10.1	10.2	10.2	10.1	10.1	10.3	10.2	10.1	10.3
Operation cost and GHG emissions	Oper. cost	CD mode ($/mile)	0.022	0.022	0.022	0.023	0.022	0.023	0.024	0.025	0.023	0.023	0.025	0.027	–	–
		CS mode ($/mile)	0.059	0.059	0.060	0.060	0.058	0.060	0.061	0.063	0.058	0.061	0.063	0.066	0.058	0.106
	Oper. GHGs	CD mode (kg/mile)	0.148	0.148	0.149	0.151	0.148	0.152	0.156	0.164	0.150	0.156	0.166	0.178	–	–
		CS mode (kg/mile)	0.222	0.225	0.226	0.228	0.220	0.227	0.232	0.237	0.221	0.230	0.237	0.249	0.219	0.400

[a] Battery to wheels electrical efficiency is reported here. An 88% charging efficiency is used to estimate plug to wheels efficiency.

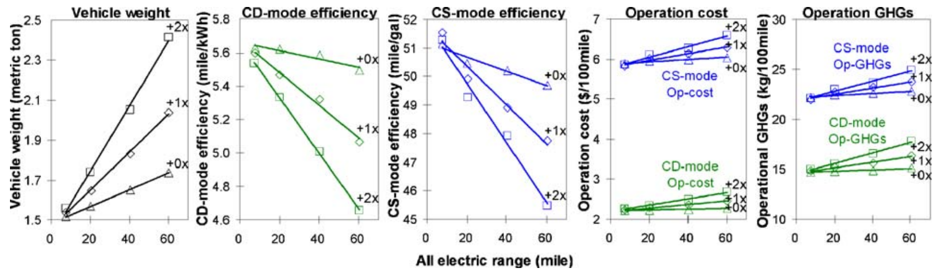

Fig. 2. Effect of increasing target AER (adding batteries) on PHEV weight, efficiency, and operation-associated cost and GHG emissions.

2.3. Economic and GHG parameters

The PHEV operation costs in this study are evaluated based on an electricity charging cost of \$0.11/kWh and retail gasoline price \$3.00/gal (\$0.80/L), which were similar to US prices in 2007 (EIA, 2008b). Sensitivity to changes in energy prices is evaluated in Section 3.2. The total operating cost to travel a particular distance is the sum of the cost of the electricity needed to charge the battery[6] and the cost of the gasoline used. For distances less than the AER, the battery was only charged as much as needed for the trip. For distances greater than the AER, the battery was charged to the maximum SOC. Moreover, in order to calculate the vehicle cost, we estimated the vehicle base cost, excluding the Li-ion battery, using the Prius MSRP less its NiMH battery cost of \$3900 (Naughton, 2008), resulting in a vehicle base cost of \$17,600. The base total battery capacity cost[7] is assumed to be \$1000/kWh (Lemoine et al., 2008), and future low cost cases are examined in a sensitivity analysis. The same base vehicle cost is used in our cost estimation for the CV, HEV and PHEV.

Life cycle GHGs are expressed in kg CO_2-equivalent (CO_2-eq) with a 100-year timescale (IPCC, 2001). The GHG emissions calculations in this study assume a US average grid mix of 0.730 kg of CO_2-eq emitted per kWh of electricity charged to the PHEV battery,[8] and 11.34 kg of CO_2-eq per gallon of gasoline (3.0 kg CO_2-eq per liter).[9] We further assume 8500 kg CO_2-eq per vehicle for vehicle manufacturing (excluding emissions from battery production) plus 120 kg CO_2-eq for each kWh of Li-ion battery capacity produced (Samaras and Meisterling, 2008). These values represent the US average life cycle emissions, including combustion and the upstream fuel cycle impacts.

3. Results and discussion

The final PHEV configurations and simulation results are shown in Table 1, which reveals that additional weight affects required battery capacity, CD-mode electrical efficiency, CS-mode gasoline fuel efficiency, operation cost per mile, and GHG emissions per mile. Greater motor power is needed to achieve baseline acceleration performance as the vehicle weight increases, although the weight of the larger motor itself is small compared to the additional battery weight. Increased weight also requires more batteries to achieve a target AER, creating a compounding effect. Further, the additional battery volume of large-capacity PHEVs may cause design feasibility issues and require significantly reduced cargo area and/or elimination of the spare tire.

Based on the simulation results of CD-mode and CS-mode efficiency under fixed 0–60 mph acceleration specifications, Fig. 2 shows the net effects of increasing AER on vehicle weight, efficiency, operation cost and operation-associated GHG emissions. We found that relationships are fairly linear in this range; increasing the target AER of a given PHEV by 10 miles results in an additional ~95 kg of vehicle weight. This additional weight reduces CD-mode and CS-mode efficiencies by 0.10 mile/kWh and 0.68 mile/gal, respectively. These efficiency reductions cause an increase in vehicle operating costs of \$0.40–\$0.80 per 1000 miles in CD-mode and CS-mode, respectively, and an increase in operation-associated GHG emissions of 3.0–3.2 kg CO_2-eq per 1000 miles in CD-mode and CS-mode, respectively. The linear regression functions for the +1 × structural weight case are

$$\begin{aligned}
\eta_{CD} &= -0.010 d_{AER} + 5.67 \\
\eta_{CS} &= -0.068 d_{AER} + 51.7 \\
c_{OP-CD} &= 0.004 d_{AER} + 2.20 \\
c_{OP-CS} &= 0.008 d_{AER} + 5.79 \\
v_{OP-CD} &= 0.029 d_{AER} + 14.6 \\
v_{OP-CS} &= 0.032 d_{AER} + 21.9
\end{aligned} \tag{1}$$

where d_{AER} is AER in miles, η_{CD} and η_{CS} are the CD-mode and CS-mode efficiencies in units of miles per kWh and miles per gallon, respectively, c_{OP-CD} and c_{OP-CS} are the operation costs per 100 miles under CD- and CS-mode, respectively, and v_{OP-CD} and v_{OP-CS} are operation GHG emissions in kg CO_2-eq per 100 miles in CD- and CS-mode, respectively. It should be noted that while costs and GHG emissions both increase with AER in CD- and CS-modes, this does not imply that total cost and emissions will increase, since PHEVs with larger AERs can travel more miles on low cost, potentially low GHG electricity. These costs and emissions associated with efficiency losses are small relative to overall PHEV operation costs and emissions. In the following sections, we examine the effect of AER and charging frequency on fuel economy, operating cost, and GHG emissions.

3.1. Operational performance

To compare the operational performances of different vehicle configurations, we examine three PHEV characteristics: fuel consumption (i.e. fuel economy), operational costs and operational GHG emissions. Because these three performance criteria depend on the distance traveled between charges, two key quantities are needed. For a distance d traveled between charges

[6] We assume an 88% charging efficiency between outlet and PHEV battery (EPRI, 2007).

[7] We intend total battery capacity cost to account for the full cost implications of adding battery capacity to the vehicle, including cell, packaging, wiring, controls, assembly, and increased structural and motor requirements.

[8] We use life cycle electricity emissions at the power plant of 0.67 kg CO_2-eq per kWh (Samaras and Meisterling, 2008), and we assume a 9% power transmission and distribution loss (EIA, 2008a).

[9] For gasoline, 8.81 kg CO_2-eq per gallon (2.33 kg CO_2-eq per liter) is generated in combustion and 2.54 kg CO_2-eq per gallon (0.67 kg CO_2-eq per liter) is emitted in the supply chain (EPA, 2006; Wang et al., 2007).

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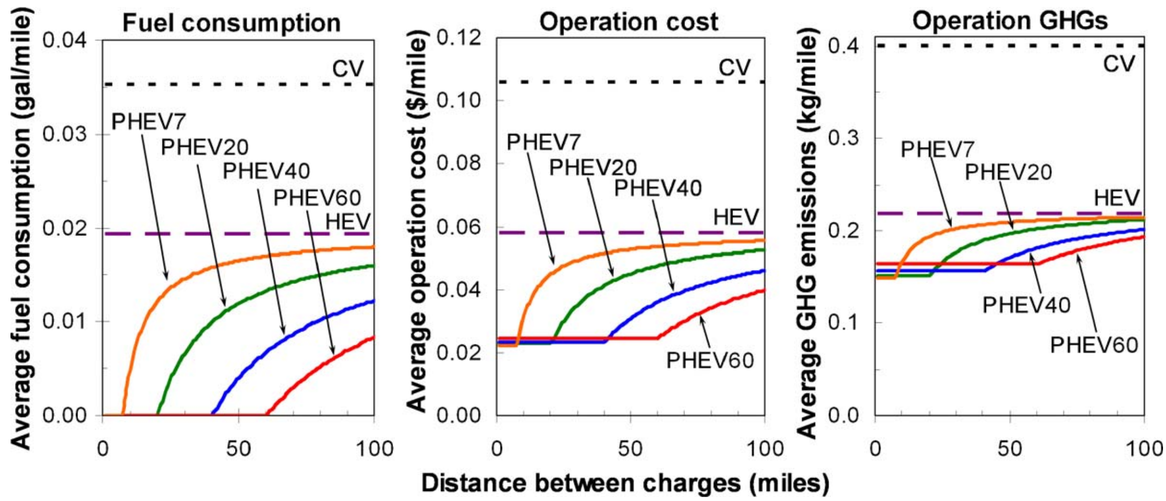

Fig. 3. Operation-associated fuel consumption, cost, and GHG emissions for CVs, HEVs, and PHEVs with 7, 20, 40, and 60 mile AERs as a function of the distance driven between charges.

in a vehicle with an all electric range of d_{AER}, the distance traveled in CD-mode d_{CD} and the distance traveled in CS-mode d_{CS} are calculated as:

$$d_{CD} = \begin{cases} d & \text{if } d \leqslant d_{AER} \\ d_{AER} & \text{if } d > d_{AER} \end{cases}$$
$$d_{CS} = \begin{cases} 0 & \text{if } d \leqslant d_{AER} \\ d - d_{AER} & \text{if } d > d_{AER} \end{cases} \quad (2)$$

The results of fuel economy (CS-mode efficiency) in Table 1 indicate that as the target AER increases from 7 to 60 miles, the modeled urban driving fuel economy decreases 7.4% from 51.5 miles per gallon (mpg) to 47.7 mpg in the +1 × base case due to increased weight. This effect is reduced under lower structural weight assumptions and amplified for larger structural weight. The average fuel consumption per mile g is calculated by

$$g = \frac{1}{d}\left(\frac{d_{CS}}{\eta_{CS}}\right) \quad (3)$$

where η_{CS} is the fuel efficiency in CS-mode. Fig. 3 shows the average fuel consumption for PHEVs compared to the HEV and CV. PHEVs consume no gasoline within the AER. Beyond the AER, fuel is consumed at a greater rate for heavier vehicles. The graph shows that PHEVs consume less gasoline than HEVs and CVs over the entire range of charging frequencies examined.

The second performance characteristic is average operation cost, which represents the average consumer expense per mile associated with recharging cost and fuel expense. Capital costs associated with batteries are discussed in Section 3.2. The average operation cost c_{OP} is calculated by:

$$c_{OP} = \frac{1}{d}\left(\frac{d_{CD}}{\eta_{CD}}\frac{c_{ELEC}}{\eta_C} + \frac{d_{CS}}{\eta_{CS}}c_{GAS}\right) \quad (4)$$

where η_{CD} is CD-mode vehicle electrical efficiency, η_C is the charging efficiency, c_{ELEC} is the cost of electricity, and c_{GAS} is gasoline cost. Table 1 shows the average operation cost per mile for CD-mode and CS-mode under the three structural weight multiplier cases assuming $c_{ELEC} = \$0.11/\text{kWh}$, $\eta_C = 88\%$ and $c_{GAS} = \$3.00/\text{gal}$ (described in Section 2.3). Larger capacity PHEVs are heavier, thus increasing the operation cost in both CD- and CS-mode; however, they also extend the distance that the vehicle operates in the less expensive CD-mode. Fig. 3 shows the average operation cost per mile as a function of distance between charges.

Table 2
Parameter levels for sensitivity analyses.

Sensitivity analysis parameter	Unit	Low level	Base level	High level
Structural weight	–	+0 ×	+1 ×	+2 ×
Discount rate	%	0	5	10
Gas price	$/gal	1.5	3	6
Battery SOC swing	%	–	50	80
Battery specific energy	Wh/kg	–	100	140
Battery replacement frequency over life	–	–	0	1
Electricity price	$/kWh	0.06	0.11	0.30
Total battery capacity cost	$/kWh	{250,500}	1000	–
CO_2 lifecycle emissions in electricity	kg/kWh	0.218	0.730	–
Carbon tax	$/ton	–	0	100

For frequent charges, a PHEV with an AER approximately equal to the distance between charges minimizes the operation cost. Each PHEV has clear operation cost advantages when the driving distance between charges is less than or equal to its AER. Once the driving distance extents beyond the AER, the operational costs of PHEVs increase rapidly. For urban driving distances less than 100 miles, all PHEVs have lower operation cost than the HEV and CV.

The third consideration is greenhouse gas emissions, which were calculated by including combustion and supply chain emissions associated with electricity $\nu_{ELEC} = 0.730$ kg CO_2-eq per kWh, battery charging efficiency $\eta_C = 88\%$, and gasoline $\nu_{GAS} = 11.34$ kg CO_2-eq per gal, as described in Section 2.3. The average operation-associated GHG emissions per mile ν_{OP} is calculated using the following equation:

$$\nu_{OP} = \frac{1}{d}\left(\frac{d_{CD}}{\eta_{CD}}\frac{\nu_{ELEC}}{\eta_C} + \frac{d_{CS}}{\eta_{CS}}\nu_{GAS}\right) \quad (5)$$

Table 1 lists the GHG emissions per mile for each case in both CD-mode and CS-mode. The data show that the average life cycle GHG emissions associated with driving in CS-mode are roughly 1.5 times those associated with CD-mode. Fig. 3 shows the average use phase GHG emissions per mile as a function of distance traveled between charges. For frequent charging, a smaller capacity PHEV minimizes operation-associated emissions. Larger capacity PHEVs are able to reduce more operational emissions for

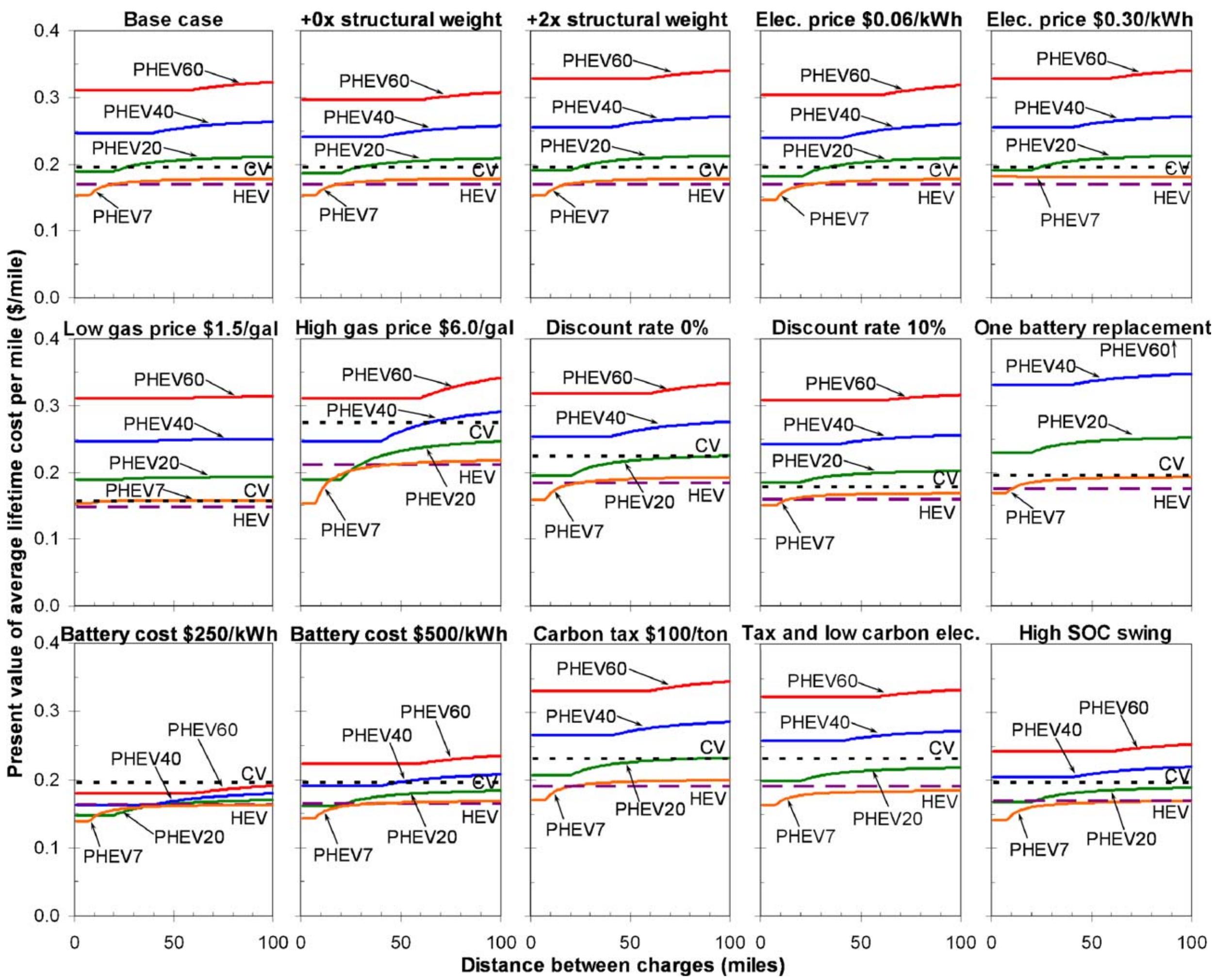

Fig. 4. Net present value of vehicle lifetime costs per lifetime miles driven as a function of the distance driven between charges. Base case assumes 12 year 150,000 mile lifetime, +1 × structural weight, no battery replacement over the vehicle life, $3 gasoline, $0.11/kWh electricity, 5% discount rate, $1000/kWh total battery capacity cost, 50% SOC swing, no carbon tax, and an average US electricity mix.

longer driving distance up to 100 miles. Generally the results show that PHEVs have significantly lower operational GHG emissions than the HEV and CV for urban driving.

3.2. Lifetime economic and environmental implications and sensitivity analyses

For further evaluating the net cost implications over the vehicle lifetime, we calculate the total cost by taking into account the vehicle base cost, battery purchase price, and net present value of operation costs, battery replacement cost, and costs imposed by a potential tax on CO_2. The equation for the net present value of lifetime cost per mile is given by:

$$c_{\mathrm{TOT}} = \frac{1}{d_{\mathrm{LIFE}}}\left((c_{\mathrm{VEH}} + c_{\mathrm{BAT}}\kappa) + \sum_{n=1}^{N}\frac{(c_{\mathrm{OP}} + \rho v_{\mathrm{OP}})d_{\mathrm{ANUL}}}{(1+r)^n} + \rho(v_{\mathrm{VEH}} + v_{\mathrm{BAT}}\kappa) + \gamma\frac{c_{\mathrm{BAT}}\kappa(1+\rho)}{(1+r)^{N/2}}\right) \tag{6}$$

We assume that the annual vehicle miles traveled $d_{\mathrm{ANUL}} = 12{,}500$ miles (20,000 km) (EPA, 2005), the vehicle lifetime $N = 12$ years, and thus vehicle lifetime mileage $d_{\mathrm{LIFE}} = 150{,}000$ miles (240,000 km)[10]. Vehicle purchase cost includes the vehicle base cost (excluding the battery) $c_{\mathrm{VEH}} = \$17{,}600$ plus total battery capacity cost $c_{\mathrm{BAT}} = \$1000$/kWh multiplied by battery capacity κ, in kWh. The second term in Eq. (6) is net present value of operation costs c_{OP} (Eq. (4)) plus the carbon tax paid for operation over vehicle's lifetime. The carbon tax is estimated by tax rate ρ per kg of CO_2-eq and operational GHG emission per mile υ_{OP} (Eq. (5)), conservatively assuming a consumer would bear the full cost of a carbon tax imposed on producers. The net present value of annual operational costs and carbon taxes are calculated using a discount rate r. The third term is carbon tax cost for the GHG emissions of vehicle and battery manufacturing, v_{VEH} and v_{BAT}, respectively. The last term is the present value of battery replacement cost with carbon tax on the battery if a replacement occurs, where $\gamma = 0$ for no battery replacement and $\gamma = 1$ for one time replacement at half vehicle life (the 6th year). The parameters for the base case study are listed in the center column of Table 2, including +1 × structural weight, 5% discount rate, $3.00/gal gasoline price, 50% battery SOC swing (80–30%), battery

[10] Our fundamental conclusions are unchanged if $d_{\mathrm{LIFE}} = 100{,}000$ miles or $N = 15$ years are assumed instead.

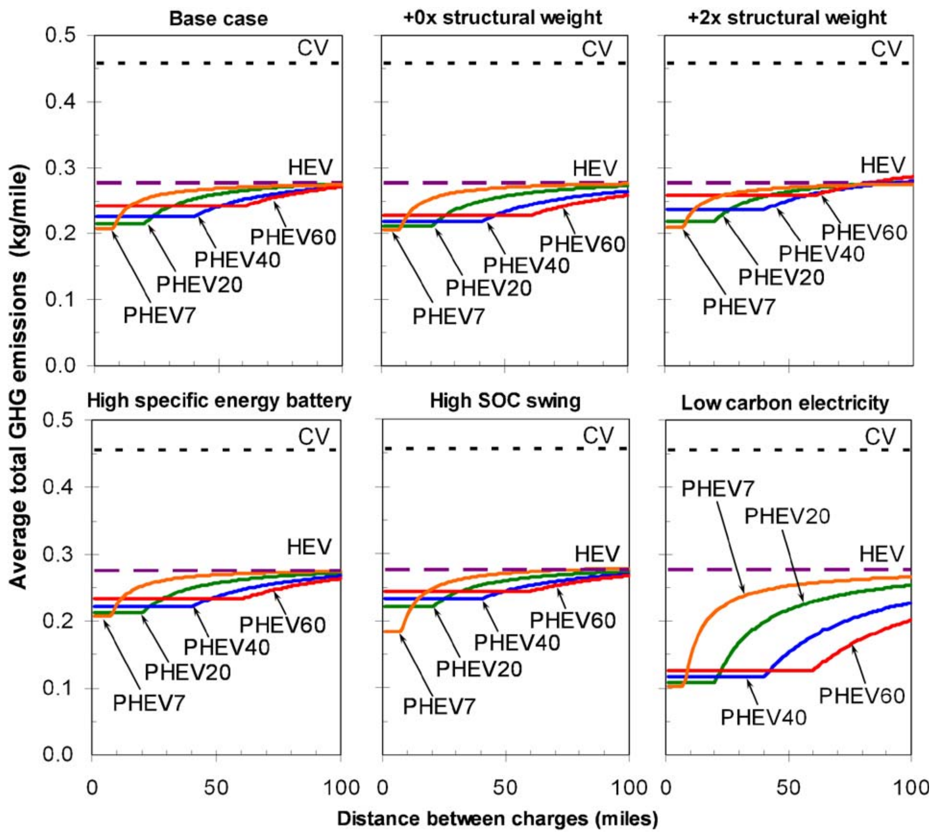

Fig. 5. Lifetime greenhouse gas emissions per lifetime miles driven as a function of the distance driven between charges. Base case assumes 12 year 150,000 mile lifetime, +1 × structural weight, 100 Wh/kg battery specific energy, 50% SOC swing, and an average US electricity mix.

specific energy 100 Wh/kg, no battery replacement over vehicle life, total battery capacity cost \$1000/kWh, average US electricity mix, and no carbon tax ($\rho = 0$). The cost analysis results of the base case are shown in Fig. 4. It can be seen that the small PHEV7 has the best economic performance for frequent charges within ~20 miles. When the driving distance between charges becomes longer, the HEV is less expensive. We also found that the PHEV20 and the CV are have similar costs, which are slightly higher than the HEV, while large-capacity PHEVs have significantly higher average costs over their lifetime. The relative benefit of the HEV over the CV is based on a total battery capacity cost \$1000/kWh assumption, which is less expensive than past NiMH battery costs reported for the Prius (Naughton, 2008).

We conducted several sensitivity analyses listed in Table 2, and the results are shown in Fig. 4. We found that increase or decrease of structural weight does not alter the rank of vehicle cost competitiveness; however, the cost of large PHEVs is more sensitive to structural weight increases. If the battery must be replaced at half of the vehicle's life, the cost of PHEV7 and HEV are somewhat affected, but the average costs of medium and large PHEVs surge due to their high battery costs. Low gasoline prices of \$1.50/gal make PHEVs less competitive, although the small-capacity PHEV7 is comparable with the HEV and CV. High prices of \$6.00/gal increase the cost competitiveness of PHEVs and make the small-capacity PHEV7 competitive for all driving distances. However, larger PHEVs are still more costly than the HEV. Low off-peak electricity prices of \$0.06/kWh make PHEVs only slightly more cost competitive, and high peak electricity prices of \$0.30/kWh make the HEV the low-cost option, although the small capacity PHEV7 remains close in cost (Cherry, 2009). Low consumer discount rates (0%) improve PHEV competitiveness and high discount rates (10%) make PHEVs less competitive, but in all cases the PHEV7 is competitive for drivers who charge frequently, and it is similar to HEV costs when charged infrequently. Total battery capacity costs of \$500/kWh further improve cost competitiveness of the PHEV7, and cheap costs of \$250/kWh would significantly increase competitiveness of PHEVs, making them similar to or less expensive than HEVs and CVs across all distances driven between charges. A battery technology with an increased SOC swing, which would allow more of the battery's physical capacity to be used in operation, would also improve PHEV competitiveness, making moderate ranged PHEVs cost competitive with the HEV and CV. A \$100 tax per metric ton (\$0.10/kg) of GHG emissions associated with production and use would not improve PHEV competitiveness significantly under the current electricity grid mix. This result is consistent with the high carbon abatement costs for PHEVs estimated by Kammen et al. (2008) and Lemoine (2008). However, a carbon tax combined with low-carbon electricity at current prices would improve competitiveness of PHEVs and make the PHEV7 most cost effective for all drivers.

To account for net GHG emissions over the vehicle life, we include the operation GHG emissions (Eq. (5)) plus the emissions associated with vehicle and battery manufacturing. The equation is given by

$$v_{TOT} = v_{OP} + \frac{1}{d_{LIFE}}(v_{VEH} + v_{BAT}\kappa) \tag{7}$$

where $v_{VEH} = 8500$ kg CO_2-eq is the assumed life cycle GHG emissions of vehicle manufacturing excluding its battery and $v_{BAT} = 120$ kg CO_2-eq per kWh is the life cycle GHG emissions of batteries (Samaras and Meisterling, 2008). The resulting total

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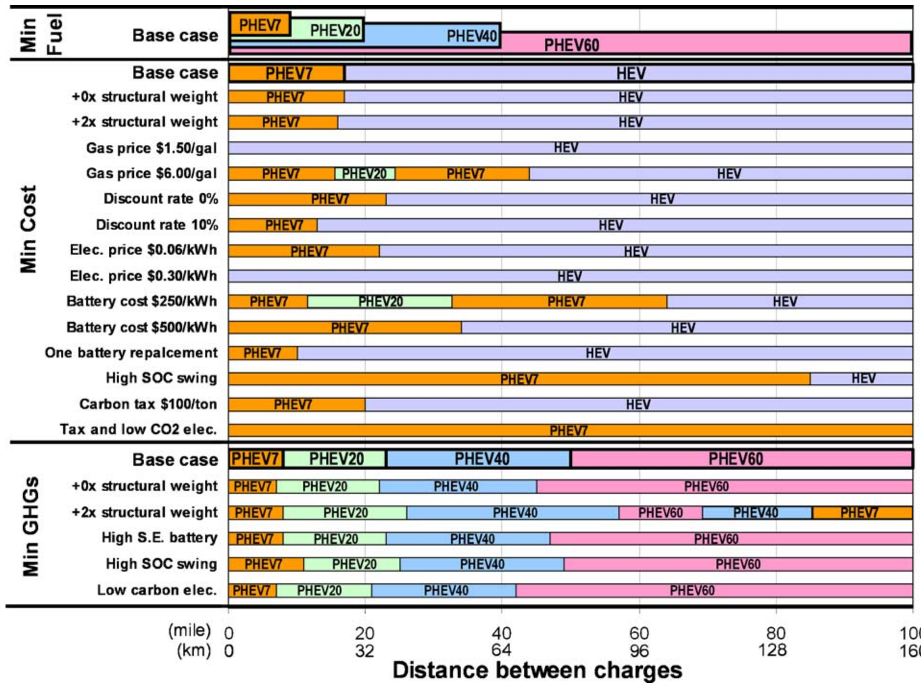

Fig. 6. Best vehicle choice for minimum fuel consumption, cost, or greenhouse gas emissions as a function of distance driven between charges across sensitivity scenarios.

GHG emissions for the base case and the other five scenarios are shown in Fig. 5. It can be seen that all of the PHEVs reduce GHG emissions compared to the HEV and CV, and the PHEV7 has the lowest average GHG emissions for small trips under the average US grid mix. New battery technology with a high specific energy of 140 Wh/kg (USABC, 2008) or a high SOC operating range (swing of 80%) implies reduced battery requirements, which lowers emissions associated with all PHEVs; however, general trends remain unchanged. Low-carbon electricity with average battery charging emissions of 0.218 kg CO_2-eq per kWh[11] would significantly lower GHG emissions from PHEVs.

3.3. Vehicle selection decisions

Fig. 6 summarizes the best vehicle choice for minimizing fuel consumption, lifetime cost, or lifetime greenhouse gas emissions as a function of the distance the vehicle will be driven between charges. For short distances of less than 10 miles between charges, the PHEV7 is the robust choice for minimizing gasoline consumption, cost, and emissions. For distances of ~10–20 miles, the PHEV7 has the lowest lifetime cost, and the PHEV20 has lower fuel consumption and greenhouse gas emissions. For moderate to long distances of 20–100 miles between charges, PHEVs release fewer GHG, but HEVs are generally less costly, even under a $100 carbon tax. High gas prices, improved battery technology with low cost or a high SOC swing, or low-carbon electricity combined with carbon tax policy can make PHEVs economically competitive over a wider range. However, large-capacity PHEVs are not the lowest cost alternative under any scenario.

3.4. Vehicle efficiency simulation

The PSAT simulation predicts a PHEV electrical efficiency η_{CD} of about 4.6–5.6 mile/kWh (equal to 178–215 Wh/mile) from battery to wheel, or about 4–5 mile/kWh (equal to 202–244 Wh/mile) from plug to wheel for the UDDS urban driving cycle, which is on the upper end of values previously reported in the literature. Since PHEVs have not been deployed on a large scale, uncertainty remains regarding the actual value of η_{CD} achieved. Several factors might have influenced the η_{CD} reported by PSAT. These include the possibility of omitted losses or loads (e.g. battery HVAC systems or other electrical loads) and our focus on an urban driving cycle. In addition to vehicle weight, driving systems and environment (temperature, terrain, vehicle hotel loads, driving characteristics) could also affect values of η_{CD}. Given the importance of efficiency predictions in determining economic and environmental implications, more data from PHEVs operating on the road are needed to reduce uncertainty.

4. Summary and conclusions

Our study results indicate that the impacts of battery weight on CD-mode electrical efficiency and CS-mode fuel economy are measurable, about a 10% increase in Wh/mile and an 8% increase in gallons per mile when moving from a PHEV7 to a PHEV60. This implies that the additional weight of a PHEV60 results in a 10% increase in operation-related costs and greenhouse gas emissions per mile relative to a PHEV7 for drivers who charge frequently (every 7 miles or less).

The best choice of PHEV battery capacity depends critically on the distance that the vehicle will be driven between charges. Our results suggest that for urban driving conditions and frequent charges every 10 miles or less, a low-capacity PHEV sized with an AER of about 7 miles would be a robust choice for minimizing gasoline consumption, cost, and greenhouse gas emissions. For less frequent charging, every 20–100 miles, PHEVs release fewer GHGs, but HEVs are less costly. An increase in gas price, a decrease in the cost of usable battery capacity, or a carbon tax combined with low-carbon electricity generation would increase PHEV cost competitiveness for a wide range of drivers. In contrast, a battery technology that increases specific energy would not affect net cost and GHG emissions significantly, and a $100 /ton carbon tax

[11] We assume life cycle emissions of 0.2 kg CO2-eq per kWh at the power plant (Samaras and Meisterling, 2008).

without a corresponding drop in carbon intensity of electricity generation would not make PHEVs significantly more competitive. These results suggest that research on PHEV battery technology improvements would be better targeted toward cost reduction than improvement of specific energy, and the effect of carbon taxes on the PHEV market will depend on their effect on the electricity generation mix, such as encouraging renewables, carbon capture and sequestration, and nuclear.

PHEVs perform best when the batteries are sized according to the charging patterns of the driver. Three potential complications arise when sizing PHEVs based on the number of miles that drivers travel: (1) if the variance in miles traveled per day is large, then a capacity designed for the average distance may be suboptimal; (2) it is unclear whether it is safe to assume that drivers will consistently charge their vehicles once per day—irregular charging behavior could lead to significantly longer distances between charges than the average daily distances would suggest; and conversely, (3) widespread installation of charging infrastructure in public parking places would enable charging more than once per day, enabling shorter distances between charges. But daytime versus nighttime charging, geographic location, and effects of marginal changes in electricity demand on the mix of energy sources could all affect implications associated with electrified transportation. Policy and planning should be employed to minimize negative impacts of PHEV adoption on the electricity grid.

Across the scenarios examined, the small-capacity PHEV outperforms larger capacity PHEVs on cost regardless of the consumer's discount rate, and the larger PHEV40 and PHEV60 are not the lowest lifetime cost options in any scenario, although they provide GHG reductions for some drivers and the potential to shift air pollutant emissions away from population centers. The dominance of the small-capacity PHEV over larger capacity PHEVs across the wide range of scenarios examined in this study suggests that government incentives designed to increase adoption of PHEVs may be best targeted toward adoption of small-capacity PHEVs by urban drivers who are able to charge frequently. Because nearly 50% of US passenger vehicle miles are traveled by vehicles driving less than 20 miles per day (Samaras and Meisterling, 2008; US DOT, 2003), there remains significant potential in targeting this subset of drivers. Since the goals of reducing cost, GHG emissions and fuel consumption are well-aligned for drivers who will charge frequently, economic interest may lead to environmental solutions for these drivers if policies promote appropriate infrastructure and initial sales. In addition to targeted financial incentives, appropriate policies could include government fleet purchases, support for public charging infrastructure, as well as consumer education and clear labeling of gasoline and electricity consumption of PHEVs.

Further research is needed to determine appropriate projections for the distribution of miles that PHEV drivers will travel between vehicle charges. Infrastructure advancements, such as automatic charging connections installed in garages or designated public parking spaces, may help to ensure frequent charging and increase the number of drivers for whom PHEVs are competitive. Because economic, environmental, and fuel consumption implications of PHEVs are sensitive to this variable, research to better understand and predict driver behavior is warranted. Finally, the role of government incentives and consumer preferences in bringing PHEV technology to market will have a substantial impact on PHEV designs chosen by automakers (Michalek et al., 2004). Examining the relative importance to consumers of attributes such as purchase cost, operating cost, fuel economy, performance, reliability, perceived sustainability and charging requirements will shed greater light on which vehicles may emerge as successful in the competitive marketplace.

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