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

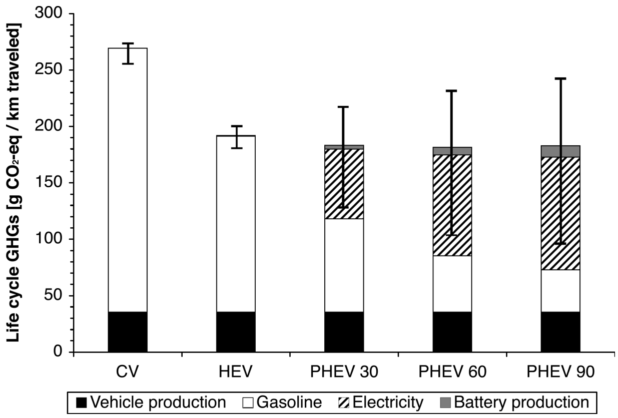

FIGURE 1. Life cycle GHG emissions (g CO_2-eq/km) of conventional vehicles (CVs), hybrid electric vehicles (HEVs), and plug-in hybrids (PHEVs) with all-electric ranges of 30, 60, or 90 km. Life cycle GHG intensity of electricity is 670 g CO_2-eq/kWh (186 g/MJ; U.S. average scenario). Uncertainty bars 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 10 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-

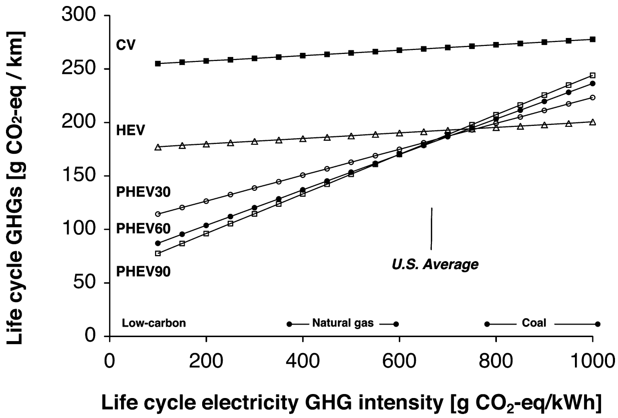

FIGURE 2. Life cycle GHG emissions from vehicles shown as a function of the life cycle GHG intensity of electricity generation. Electricity is used during production of the vehicles, and the slight slope of the CV and HEV lines reflect GHG intensity of electricity used during production. The chart indicates 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.

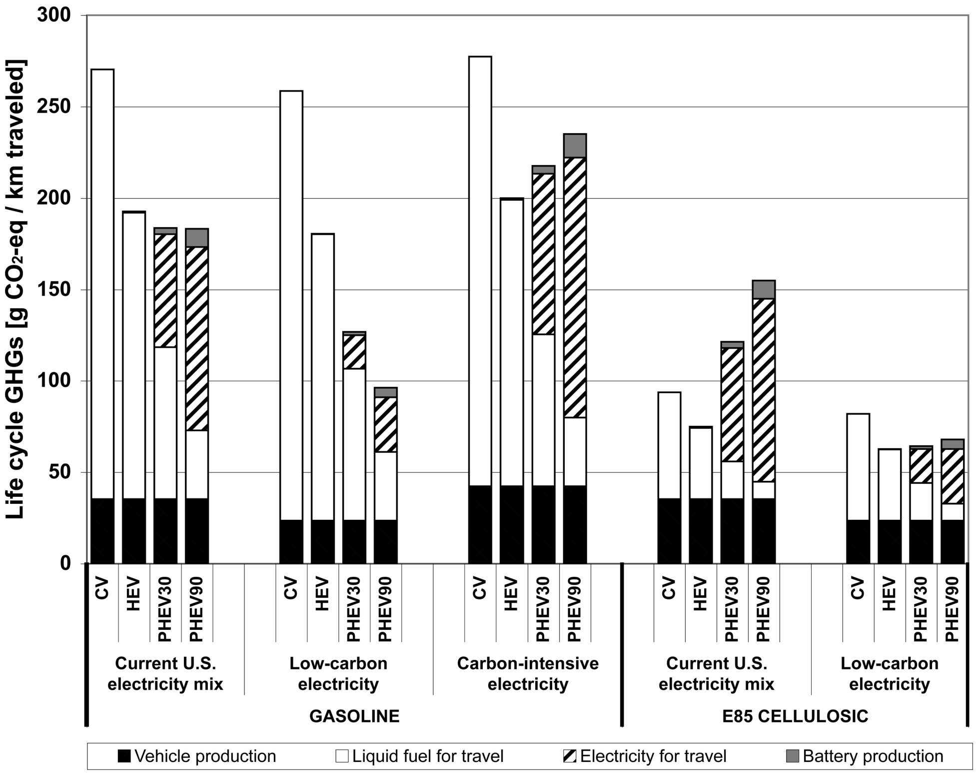

FIGURE 3. Life cycle GHG emissions sensitivity of CVs, HEVs, and PHEVs with 30 and 90 all-electric km ranges under different fuel and electricity carbon intensities. Life cycle carbon intensity of electricity assumed to be 670, 200, and 950 g CO_2-eq/kWh for U.S. average, low-carbon, and carbon-intensive 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.

Acknowledgments

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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.

Literature Cited

(1) U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2004*; EPA: Washington, DC, 2006.
(2) Demirdoven, N.; Deutch, J. Hybrid cars now, fuel cell cars later. *Science* **2004**, *305* (5686), 974–976.
(3) Farrell, A. E.; Plevin, R. J.; Turner, B. T.; Jones, A. D.; O'Hare, M.; Kammen, D. M. Ethanol can contribute to energy and environmental goals. *Science* **2006**, *311* (5760), 506–508.
(4) Maclean, H. L.; Lave, L. B. Life cycle assessment of automobile/fuel options. *Environ. Sci. Technol.* **2003**, *37* (23), 5445–5452.
(5) Schmer, M. R.; Vogel, K. P.; Mitchell, R. B.; Perrin, R. K. Net energy of cellulosic ethanol from switchgrass. *Proc. Natl. Acad. Sci.* **2008**, *105* (2), 464–469.
(6) Frank, A. A. Plug-in hybrid vehicles for a sustainable future. *Am. Sci.* **2007**, *95* (2), 158–165.
(7) Bradley, T. H.; Frank, A. A. Design, demonstrations and sustainability impact assessments for plug-in hybrid electric vehicles. *Renew. Sustain. Energy Rev.* **2007,** doi: 10.1016/j.rser.2007.05.003.
(8) U.S. Department of Transportation. *2001 National Household Travel Survey*; DOT: Washington, DC, 2004.
(9) Wirth, T. E.; Gray, C. B.; Podesta, J. D. The future of energy policy. *Foreign Affairs* **2003**, *82* (4), 132–155.
(10) EPRI. *Comparing the benefits and impacts of hybrid electric vehicle options*; 1000349; EPRI: Palo Alto, CA, 2001; pp 1–264.
(11) EPRI. *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles*; TR 1009299; EPRI: Palo Alto, CA, 2002.
(12) Kintner-Meyer, M.; Schneider, K.; Pratt, R. *Impacts assessment of plug-in hybrid vehicles on electric utilities and regional U.S. power grids, Part 1: Technical analysis*; Pacific Northwest National Laboratory: Richland, WA, 2006.
(13) Kliesch, J.; Langer, T., *Plug-in hybrids: An environmental and economic performance outlook*; American Council for an Energy Efficient Economy, 2006.
(14) Kempton, W.; Archer, C. L.; Dhanju, A.; Garvine, R. W.; Jacobson, M. Z. Large CO_2 reductions via offshore wind power matched to inherent storage in energy end-uses. *Geophys. Res. Lett.* **2007**, *34*, (2)., L02817.
(15) EPRI. *Environmental assessment of plug-in hybrid electric vehicles, Volume 1: Nationwide greenhouse gas emissions*; 1015325; EPRI: Palo Alto, CA, 2007.
(16) ISO. *ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework*; Geneva, 2006.
(17) Hendrickson, C.; Horvath, A.; Joshi, S.; Lave, L. Economic input-output models for environmental life-cycle assessment. *Environ. Sci. Technol.* **1998**, *32* (7), 184A–191A.
(18) Hendrickson, C.; Lave, L.; Matthews, H. S., *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach*; Resources for the Future: Washington, DC, 2006.
(19) *Economic Input-Output Life Cycle Assessment Model*; Carnegie Mellon University Green Design Institute; http://www.eiolca.net (accessed March 22, 2007).
(20) Joshi, S. V. Product environmental life cycle assessment using input-output techniques. *J. Ind. Ecol.* **2000**, *3* (2–3), 95–120.
(21) Suh, S.; Lenzen, M.; Treloar, G. J.; Hondo, H.; Horvath, A.; Huppes, G.; Jolliet, O.; Klann, U.; Krewitt, W.; Moriguchi, Y.; Munksgaard, J.; Norris, G. System boundary selection in life-cycle inventories using hybrid approaches. *Environ. Sci. Technol.* **2004**, *38* (3), 657–664.
(22) IPCC. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel of Climate Change*; Cambridge University Press: Cambridge, UK and New York, 2001.
(23) Lave, L. B.; MacLean, H. L. An environmental-economic evaluation of hybrid electric vehicles: Toyota's Prius vs. its conventional internal combustion engine Corolla. *Trans. Res. Part D-Transport. Environ.* **2002**, *7* (2), 155–162.
(24) Schmidt, W. P.; Dahlqvist, E.; Finkbeiner, M.; Krinke, S.; Lazzari, S.; Oschmann, D.; Pichon, S.; Thiel, C. Life cycle assessment of lightweight and end-of-life scenarios for generic compact class passenger vehicles. *Int. J. LCA* **2004**, *9* (6), 405–416.
(25) Lipman, T. E.; Delucchi, M. A. A retail and lifecycle cost analysis of hybrid electric vehicles. *Trans. Res. Part D-Transport. Environ.* **2006**, *11* (2), 115–132.
(26) EPRI. *Advanced Batteries for Electric Drive Vehicles*; TR 1009299; EPRI: Palo Alto, CA, 2004.
(27) Rydh, C. J.; Sandén, B. A. Energy analysis of batteries in photovoltaic systems. Part I: Performance and energy requirements. *Energy Convers. Manage.* **2005**, *46* (11–12), 1957–1979.
(28) Burke, A. F. Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles. *Proc. IEEE* **2007**, *95* (4), 806–820.
(29) Wang, M. *Development and use of GREET 1.6 fuel-cycle model for transportation fuels and vehicle technologies*; ANL/ESD/TM-163; Argonne National Laboratory: Argonne, IL, 2001.
(30) EIA. *Annual Energy Review 2005*; DOE/EIA-0384(2005); U.S. Department of Energy, 2006.
(31) Jaramillo, P.; Griffin, W. M.; Matthews, H. S. Comparative life cycle air emissions of coal, domestic natural gas, LNG, and SNG for electricity generation. *Environ. Sci. Technol.* **2007**, *41* (17), 6290–6296.
(32) Meier, P. J.; Wilson, P. P. H.; Kulcinski, G. L.; Denholm, P. L. US electric industry response to carbon constraint: a life-cycle assessment of supply side alternatives. *Energy Policy* **2005**, *33* (9), 1099–1108.
(33) Kim, S.; Dale, B. E. Life cycle inventory information of the United States electricity system. *Int. J. LCA* **2005**, *10* (4), 294–304.
(34) The Dollars and Sense of Hybrids. *Consumer Reports* **2006**, (April), 18–21.
(35) EPA. *Fuel economy labeling of motor vehicles: Revisions to improve calculation of fuel economy estimates*; EPA: Washington, DC, 2006.
(36) U.S. DOE. *Tracking new coal fired power plants, coal's resurgence in electric power generation*; U.S. Department of Energy, National Energy Technology Laboratory, January 24, 2007.
(37) Morrow, W. R.; Griffin, W. M.; Matthews, H. S. Modeling switchgrass derived cellulosic ethanol distribution in the United States. *Environ. Sci. Technol.* **2006**, *40* (9), 2877–2886.
(38) Tilman, D.; Hill, J.; Lehman, C. Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science* **2006**, *314* (5805), 1598–1600.
(39) Lubowski, R. N.; Vesterby, M.; Bucholtz, S.; Roberts, M. J. *Major uses of land in the United States, 2002*; Economic Research Service, USDA, 2006.
(40) Hamelinck, C. N.; van Hooijdonk, G.; Faaij, A. P. C. Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term. *Biomass Bioenergy* **2005**, *28* (4), 384–410.
(41) Lynd, L. R. Overview and evaluation of fuel ethanol from cellulosic biomass: Technology, economics, the environment, and policy. *Ann. Rev. Energy Environ.* **1996**, *21*, 403–465.

(42) Kalogo, Y.; Habibi, S.; Maclean, H. L.; Joshi, S. V. Environmental implications of municipal solid waste-derived ethanol. *Environ. Sci. Technol.* **2007**, *41* (1), 35–41.

(43) Kempton, W.; Tomic, J. Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. *J. Power Sources* **2005**, *144* (1), 268–279.

(44) Morgan, M. G. Don't grandfather coal plants. *Science* **2006**, *314* (5802), 1049–1049.

(45) Morgan, M. G.; Apt, J.; Lave, L. *U.S. Electric Power Sector and Climate Change Mitigation*; Pew Center on Global Climate Change: Washington, DC, 2005.

(46) EIA. *Annual Energy Outlook with Projections to 2030*; U.S. Department of Energy, 2007.

(47) EPRI. *Environmental assessment of plug-in hybrid electric vehicles, Volume 2: United States air quality analysis based on AEO-2006 assumptions for 2030*; 1015326; EPRI: Palo Alto, CA, 2007.

(48) EPA. *Life Cycle Assessment: Principles and Practice*; EPA/600/R-06/060; U.S. Environmental Protection Agency: Washington, DC, 2006.

(49) Lave, L. B.; Hendrickson, C. T.; McMichael, F. C. Environmental Implications Of Electric Cars. *Science* **1995**, *268* (5213), 993–995.

(50) Stephan, C. H.; Sullivan, J. Environmental and Energy Implications of Plug-In Hybrid-Electric Vehicles. *Environ. Sci. Technol.* **2008**, *42* (4), 1185–1190.

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