Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy

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Supporting Online Information

Number of pages: 25

Number of figures: 2

Number of tables: 8

1. Life cycle assessment

This analysis investigates the life cycle greenhouse gas (GHG) emissions associated with plug-in hybrid electric vehicles (PHEVs) in the United States (US). 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 (*1-3*). A process-based methodology examines and quantifies resource inputs and environmental outputs associated with each stage of a product's life cycle. An EIO methodology can reduce the potentially sizable truncation error of omitted upstream impacts and the extensive data requirements of a process model by aggregating activities and impacts up to the economic sectoral level (*2, 4*). The Economic Input-Output Life Cycle Assessment model (EIO-LCA) is a linear input-output model that uses published input-output economic accounts of all the 491 sectors of the US economy and determines environmental discharges associated with a dollar value of economic activity in each sector (*5*). In order to reduce uncertainty associated with both process and EIO–based methods, the field of life cycle assessment is increasingly combining elements from both approaches, in what is termed a hybrid life cycle assessment (*6-9*). We use data from previous process LCAs, the EIO-LCA model (*5*), and the literature to provide a hybrid estimation of the life cycle GHG emissions of PHEVs.

Building on the relationship given in Facanha and Hovarth (*10*), life cycle GHG emissions for vehicles are calculated using the following equation:

$$GHG = \sum_{i=1}^{n} \frac{I_i}{L} * E_i \qquad (1)$$

Where

GHG = Life cycle GHG emissions [g CO_2 equivalent (100 yr) per km traveled]

n = Total number of inputs

I_i = Input (energy, gallons, $US)

E_i = GHG intensity of each input (g CO_2e / I_i units)

L = Lifetime of vehicle (km)

For example, consider the battery in a conventional HEV. We estimate the HEV has a lithium ion (Li-ion) battery with1.3 kWh of energy storage capacity (Table S3). Using the emissions factor in Table S2, 120 kg CO_2e are emitted to produce one kWh of Li-ion battery storage capacity. The battery is assumed to last the lifetime of the vehicle, 240,000 km (about 150,000 mi). Thus, life cycle GHG emissions of the battery input = (1.3) * (120*10^3) / 241,000 = 1 g CO_2e / km (see Table S8 for GHG emissions associated with each input).

The system boundary in Figure S1 illustrates the processes and inputs that are considered in the analysis. The emission factors for fuels and electricity are shown in Table S1. All values in this analysis are higher heating values (HHV).

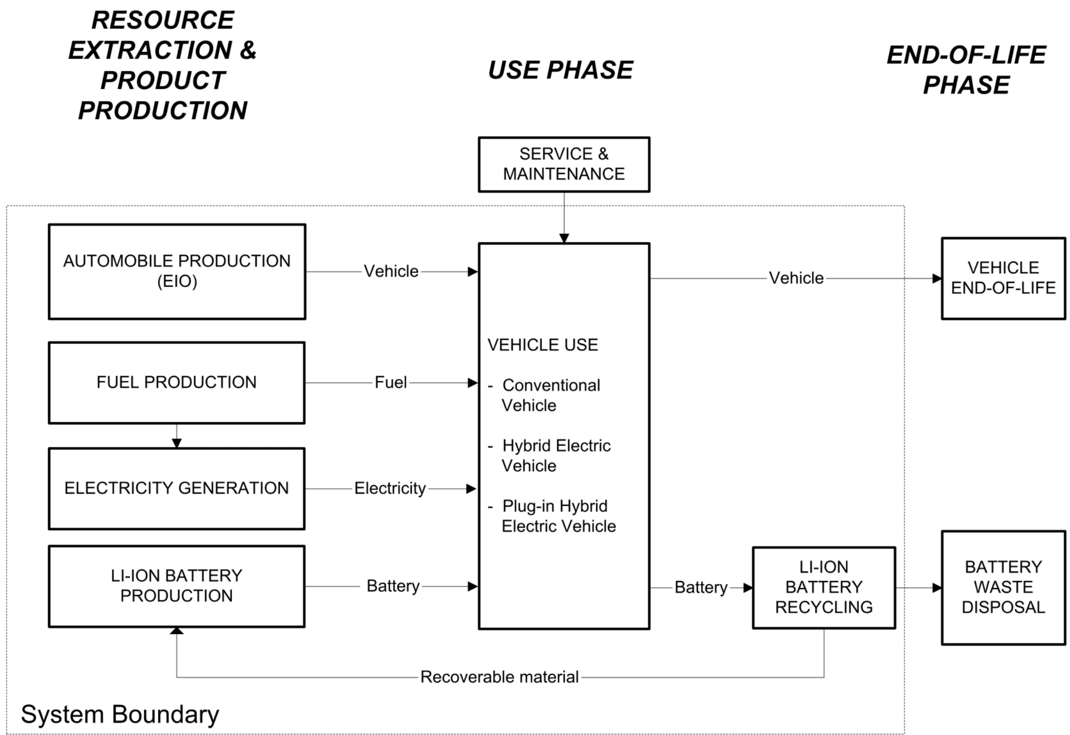

Figure S1. System boundary. Where noted, the Economic Input-Output Life Cycle Assessment (EIO-LCA) model was used.

Table S1. Assumptions used regarding GHG emissions from various energy sources and carriers. Vehicle and battery impacts are given in Table S2.

	Carbon intensity of energy source (g CO_2e / MJ HHV)	Source
Electricity		
Current US direct emissions (at power plant from fuel combustion)	171 (615 g / kWh)	(*11*)
Upstream emissions	15 (54 g / kWh)	(*11, 12*)
US average (life cycle)	186 (670 g / kWh)	
Low-carbon portfolio (life cycle)	56 (200 g / kWh)	Table S6
Carbon-intensive portfolio (life cycle)	250 (950 g / kWh)	Adapted from (*13, 14*)
Diesel		
Site emissions (fuel combustion)	69	(*15, 16*)
Upstream emissions	18	(*16*)
Gasoline		
Site emissions (fuel combustion)	67	(*15, 16*)
Upstream emissions	19	(*16*)
Ethanol		
Site emissions (fuel combustion)	0	
Upstream emissions (corn-based)	73	(*17*)
Upstream emissions (low-input biomass)	10	(*18*)

Notes: CO_2e = carbon dioxide equivalents; direct and upstream emissions numbers may not match total due to rounding.

2. Production phase

2.1 Vehicle production

The PHEVs considered in this analysis are assumed to be similar to an existing HEV, a Toyota Prius, with additional battery capacity to enable plug-in capabilities in a parallel configuration. There have been several aftermarket conversions of Prius HEVs to PHEVs and it is assumed that the introduction of a sedan PHEV will build upon an HEV design. In an alternative PHEV series configuration not considered in this analysis, propulsion is solely powered by electricity and liquid fuel combustion is used to maintain the battery's charge (*19*). PHEVs in a series configuration may require a larger battery and a smaller combustion engine than a parallel configuration (*19*). Following the work of Lave and MacLean (*20*), this study used the Toyota Corolla for the baseline conventional vehicle (CV). The Corolla has similar characteristics, dimensions, and curb weight to the Toyota Prius (*21*).

An EIO methodology relies on benchmark accounts of economic activity from defined economic sectors from the US Department of Commerce, and hence uses producer prices (as opposed to retail prices) as inputs. The EIO-LCA model reports economic and emissions data in five-year increments, and data from 1997 were the latest available. In the automobile manufacturing sector, producer price is approximately 80% of the retail price (*22*), and producer price indices are 141.7 and 133.7 for 1997 and 2006 respectively (*23*). Thus, we estimate that the Toyota Corolla, which retails in 2006 for $16,100 (*24*), has a producer price of about $13,500 in 1997. The EIO-LCA model reports that 102,000 MJ of primary energy are consumed and 8.5 tonnes of CO_2e are emitted during the manufacturing of this Toyota Corolla-type vehicle.

We have augmented the EIO-LCA data to estimate GHGs from vehicle manufacturing under the different scenarios of CO_2 intensities of electricity considered in this analysis (see main document, and 'Powering the vehicle' section below). To produce the Corolla-like vehicle, EIO-LCA reports that about 6,100 kWh of electricity are purchased in the economy. Assuming life cycle GHG emissions are 670 g CO_2e per kWh of electricity in 1997 (Table S1), GHG emissions from the electricity life cycle account for about half of the total emissions from vehicle manufacturing. The augmented emissions are calculated by first subtracting GHG emissions due to electricity (at 670 g CO_2e per kWh) from total GHG emissions from vehicle manufacturing. GHG emissions due to electricity are added back on, according to the carbon intensity of interest (see Table S1 for scenarios).

Table S2 summarizes the life cycle inventory for vehicle production. These results are consistent with previous vehicle production emissions estimates (*25-29*).

2.2 Battery production

Rydh and Sandén (*30*) completed an analysis of the energy required to produce a lithium-ion battery. They considered a SAFT Li-ion VL50E cell with a metal oxide-based cathode (Co, Mn, Al). In our study, we assume battery production occurs in the US, and no impacts from battery transport have been included. We apply the GHG emission factors from Table S1 to the energy carriers from Rydh and Sandén; they report 75% of total energy required for battery production is primary fuel for electricity, and conversion efficiency of primary fuel to electricity is 35% (*30*). We assume the remaining energy is from diesel for mining operations. Diesel life cycle GHG emissions are listed in Table S1. If natural gas instead represents a large fraction of energy inputs to the battery life cycle, impacts would decrease slightly. The battery life cycle inventory results are summarized in Table S2. The focus on materials production and battery manufacture in the Rydh and Sandén study omits other supply chain impacts from battery manufacturing, which could increase life cycle impacts from batteries. Additionally, if the batteries are produced in Asia, battery impacts would be affected by the carbon intensity of the electricity used in production and to a lesser extent, the increased impacts from ocean freight.

The GREET 2.7 model estimates vehicle cycle impacts, while the GREET 1.7 model (*16*) is a separate tool that estimates fuel cycle impacts. GREET 2.7 also estimates impacts from battery manufacturing (*31*). If this model is employed, impacts from battery manufacturing are lower. However, the lithium-ion battery background data in the GREET 2.7 model is still under development and the model developers have identified this part of the model as requiring additional information. Given the data limitations with the GREET 2.7 model regarding lithium-ion batteries, we use impacts as reported by Rydh and Sandén in our assessment.

Table S2. Energy and GHG emissions associated with vehicle and Li-ion battery production. Rydh and Sandén (2005) report that 75% of the energy used in Li-ion battery production is primary fuel for electricity generation; we assume the remainder (non-electricity) is from diesel.

	Unit		Source
Vehicle production			
Energy use	MJ / vehicle	102,000	(*5*)
GHG emission	kg CO_2e / vehicle	8,500	(*5*)
Battery production			
Energy density	kWh / kg battery	0.1	(*30, 32, 33*)
Energy required for materials and manufacturing	MJ / kWh battery capacity	1,700	(*30*)
GHG emissions	kg CO_2e / kWh battery capacity	120	Energy used is 75% electricity, 25% diesel (*30*); CO_2 intensity from Table S1

The impacts of battery production for each vehicle configuration are shown in Table S3. Estimated impacts from NiMH battery production, adapted from Rydh and Sandén (*30*), are approximately double those of Li-ion and are shown in Table S3. As discussed, improvements in battery technologies and manufacturing could potentially reduce the GHG impacts. Alternatively, one or more battery replacements during the vehicle useful life will increase total life cycle impacts. If the battery is deep-cycled (battery is consistently discharged to 80% DOD), it may last about 2,500 cycles (*34*) (about 10 years if the battery is cycled 5 times per week, however, aging is a concern for Li-ion battery technology). In addition, the source of materials for the batteries affects impacts of manufacturing. Sensitivities of manufacturing impacts in relation to the amount of recycled material inputs utilized are presented in Table S4.

Table S3. Energy and GHGs from Li-ion storage battery production for HEVs and PHEVs. Total battery capacity is 20% greater than energy required for PHEV propulsion to allow for sufficient capacity to operate as a HEV at 80% DOD. The table also shows impacts from NiMH battery production, which is more energy intensive per kWh of battery capacity than Li-ion.

	Unit	CV	HEV	PHEV 30	PHEV 60	PHEV 90
Electric range of battery	km	-	0	30	60	90
Energy required (from battery) for PHEV range	kWh	-	0	5.4	10.7	16.1
		-				
Total battery capacity to enable 80% DOD	kWh	-	1.3	6.7	13.4	20.1
		-				
Li-ion						
Battery mass	kg	-	16	84	168	252
		-				
Production	MJ / battery	-	2,210	11,400	22,800	34,200
	kg CO_2e / battery		160	810	1,610	2,420
	MJ / km	-	0.01	0.05	0.09	0.14
	g CO_2e / km	-	1	3	7	10
NiMH						
Battery mass	kg	-	36	190	370	560
		-				
Production	MJ / battery	-	4,200	22,000	43,000	64,000
	kg CO_2e / battery		300	1,600	3,100	4,600
	MJ / km	-	0.02	0.09	0.18	0.27
	g CO_2e / km	-	1	6	13	19

Table S4. Li-ion battery impacts over the vehicle life cycle when battery is produced with recycled or virgin materials, using ranges reported by Rydh and Sandén (*30*).

	Unit	HEV	PHEV 30	PHEV 60	PHEV 90
Battery impacts: as assumed (1700 MJ/kWh$_e$ capacity)	g CO_2e / km	1	3	7	10
Battery impacts: all recycled material inputs (1510 MJ/kWh$_e$ capacity)	g CO2$_e$ / km	1	3	6	9
Battery impacts: all virgin material inputs (1870 MJ/kWh$_e$ capacity)	g CO2$_e$ / km	1	4	7	11

3. Powering and operating the vehicle

The use phase includes energy and emissions from vehicle operations as well as from vehicle service, fixed costs such as insurance and other services, and upstream impacts from fuel production (*35*). In comparing the CV, HEV and PHEVs, this analysis omits impacts from vehicle service, maintenance, and other fixed costs, assuming these to either be similar across vehicle technologies, or that differences have a negligible impact in comparison with the use phase (*26*). HEVs and PHEVs may require fewer oil changes (and other services) for the IC motor as it endures fewer operating hours, but the differences in GHG impacts are likely to be small compared to the overall life cycle.

3.1 Liquid Fuel

Upstream GHG emissions associated with gasoline were estimated to be about 0.67 kg of CO_2e per liter of fuel (19 g CO_2e / MJ) using the GREET 1.7 model (*16*). If EIO-LCA would be employed to estimate upstream impacts from gasoline, fuel distribution impacts must be added to the upstream impacts from petroleum refining (10). Life cycle emissions from corn and cellulosic ethanol reported in Table S1 are estimated from Farrell *et al.* (*17*) and Schmer *et al.* (*18*), respectively. Schmer *et al.* include carbon abatement through soil carbon storage in their estimate. Tilman *et al.* have also recently shown that carbon negative fuels can be produced from a diverse mix of plants grown on degraded soil (*36*). Farrell *et al.* estimate cellulosic ethanol production emits 10 g / MJ (converted to HHV), but do not include soil carbon storage. Spatari *et al.* (*37*) performed a life cycle assessment of cellulosic ethanol from switchgrass, and estimated life cycle emissions at 20 g / MJ ethanol (converted to HHV). They did not include soil carbon storage, which depends on past and future management practices.

8.9 million barrels of motor gasoline per day were supplied to the US transportation sector in 2004, representing 17 quadrillion BTU (17 EJ) of energy annually (*38*). Net imports of crude oil and petroleum products in 2004 were 22 and 4 quads respectively. Hence motor gasoline in the transport sector, which is primarily used by automobiles and light trucks, represented about 65% of US petroleum imports in 2004 on an energy basis. Diesel fuel represents a negligible fraction of US automobile and light truck fuel use and was omitted.

Storage batteries with higher capacities have increased weight and volume, which may require additional structural support weight in the vehicle body. This increased weight of battery packs and potential vehicle modifications may alter both liquid fuel and electricity propulsion requirements for PHEVs. The magnitude of the changes in net fuel consumption is uncertain, as larger batteries and electric motors may compensate for the additional mass through increased drivetrain or motor efficiency, and potentially less mass required for other engine components (*39*). As stated in the text, effective fuel consumption is assumed to remain the same as PHEV battery capacity increases in order to be consistent with earlier studies which model varying levels of battery capacity within the same vehicle class.

Preliminary estimates of how weight affects HEV fuel economy have been made by Reynolds and Kandlikar (*40*). Zervas and Lazarou (*41*) detail how reductions in vehicle weight affect CO_2 emissions from transport in the context of European Union policy. In the regression presented by Reynolds and Kandlikar, increasing vehicle weight by 100 kg increases fuel consumption by 0.72 liters per 100 km for an HEV. When engine power (kW) is added as a predictor variable in that study, the HEV result is not statistically significant. Detailed modeling of the effect of increased weight requirements on PHEV fuel consumption is an opportunity for continuing future research.

3.2 Electricity used to power PHEV

In addition to CO_2 emissions from combustion exhaust, greenhouse gases are produced and released during power plant fuel production, processing, and transport. This analysis considers three scenarios for life cycle GHG intensities of electricity – a system that is similar to the current US average, a low-carbon scenario, and a carbon-intensive scenario. Kim and Dale (*12*) report electricity life cycle GHG emissions to be 193 g CO_2 equivalents per MJ electricity (MJe) generated in the US in 2000 (695 g CO_2e / kWh).

The Energy Information Agency's (EIA) Annual Energy Review for the year 2000 reports direct (combustion exhaust only) CO_2 intensity of electricity production was 178 g CO_2 / MJe (640 g / kWh) (*38*). Using the figures from Kim and Dale, and EIA, we calculate upstream emissions of 15 g CO_2e / MJe (55 g / kWh), adding an additional 9% of the direct emissions. This calculation is performed with year 2000 data, since Kim and Dale performed their life cycle assessment for the year 2000. To estimate life cycle emissions in the year 2004, we assume the upstream emissions were also 9% of the direct emissions. EIA reports direct emissions were 171 g CO_2 / MJe (615 g CO_2 / kWh) in 2004. Thus, for the US average scenario, we estimate upstream emissions of 15 g CO_2e / MJe (54 g / kWh) produced, and total life cycle emissions of 186 g CO_2e / MJ (670 g / kWh) of electricity produced.

The *carbon-intensive* scenario represents a case where coal (the most carbon-intensive fuel) is the predominant fuel for electricity generation, and emits 950 g CO_2e / kWh. This figure could represent the combustion and upstream impacts of a mix of existing less efficient subcritial coal plants and additions of more efficient supercrtical coal plants (*13, 14*). If solely less efficient, existing coal plants are used to charge PHEVs, the carbon-intensive electricity scenario would have higher GHG intensity. The *low-carbon* scenario describes an electricity system where renewables, nuclear, or coal with carbon capture and sequestration account for a large share of the generation, thus making the total life cycle GHG intensity of electricity low, at 200 g CO_2e / kWh. The GHG impacts from electricity generation infrastructure are generally negligible compared to combustion emissions, with the exception of low-carbon generation (which have little or no combustion emissions) (*42*). Table S6 outlines a representative electricity mix for the *low-carbon* scenario and contains direct and upstream impacts of electricity generation, including generation infrastructure. The life cycle GHG emissions of our electricity scenarios do not include transmission and distribution infrastructure.

The actual GHG intensity of the electricity used to recharge PHEV batteries will depend on the mix of generation types dispatched, which varies by region, season, and time of day. In this analysis, we calculate life cycle emissions assuming various electricity GHG intensities. Thus, we demonstrate the effects of various generation fuels and fuel mixes charging PHEVs. Life cycle global warming potential (GWP, measured in CO_2 equivalents using GHG conversion factors from the IPCC for 100 year time frame (*43*)) was estimated for each scenario, as listed in Table S1. As population densities change regionally in the future, electricity demands (including potential PHEV demands) will be correlated. Much modeling effort can be expended to produce detailed life cycle inventories for changes in electricity demand and population. Although such efforts are useful, this analysis uses simple scenarios to illustrate the effect of different electricity GHG intensities on the life cycle GWP of PHEVs.

It is assumed that gasoline consumption for the conventional vehicle (CV) is 0.08 l/km (30 mpg), and hybrid (both HEV and PHEV) vehicle fuel consumption is 0.05 l/km (45 mpg) for gasoline-powered transport (*44, 45*). To calculate plant-to-wheel electricity required, we use the 0.18 kWh/km requirement for a compact sedan (includes regenerative braking benefits and efficiency losses in the battery and charger) from the

Electric Power Research Institute (*46*). We also use 9% losses in electricity transmission and distribution from the EIA (*38*). These result in 0.20 kWh of electricity from the power plant required for a PHEV to travel one km using electricity as the energy source. Table S5 reviews assumptions for fuel and electricity consumption during travel. Both liquid fuel and electricity consumption per km will vary with different types of vehicles, characteristics, and driving styles.

Table S5. Parameters for liquid fuel and electricity consumption during travel.

	Unit	Value	Source
Liquid-fuel powered travel			
Conventional vehicle	MJ / km	2.5	
	l gasoline / km (mi / gal)	0.08 (30)	(*44*)
HEV and PHEV	MJ / km	1.7	
	l gasoline / km (mi / gal)	0.05 (45)	(*44, 45*)
Electricity-powered travel and electric drive system (plant-to-wheel)			
Electricity consumption during electric powered travel, including charging/discharging losses	kWh / km (kWh / mi)	0.18 (0.29)	(*46*)
Transmission and distribution efficiency	(Plant-to-plug)	0.91	*(11)*
Electricity required to power travel (plant-to-wheel)	kWh / km	0.20	
Battery depth-of-discharge (DOD)		0.8	(*32*)

Table S6. A hypothetical electricity mix to represent the low-carbon portfolio considered. An electricity mix with life cycle emissions of 200 g CO_2e / kWh could be constructed with many different combinations, including some sources not considered below (e.g. solar thermal, tidal, and geothermal). This low-carbon portfolio is used to illustrate a potential generation mix with life cycle emissions of 200 g CO_2e / kWh. We are not arguing that the future electricity mix will match this scenario, but the portfolio presented may be one possibility. CCS = Carbon capture and storage; PV = photovoltaic (direct conversion of sunlight to electricity). Coal and natural gas carbon content from EPA (*47*); Efficiency of fossil fuel generation and CCS emissions from IECM (*13*); Upstream emissions from coal and natural gas from Jaramillo *et al.* (*14*); Nuclear, hydro, wind, and PV from Weisser (*48*).

Fuel (source)	Direct (g CO_2 / kWh)	Upstream (g CO_2e / kWh)	Total life cycle emissions (g CO_2e / kWh)	% of electricity generated
Coal	800	50	850	10%
Coal w/ CCS	100	50	150	25%
Natural gas	400	75	475	15%
Nuclear	0	10	10	25%
Hydro	0	8	8	5%
Wind	0	15	15	15%
PV	0	60	60	5%
GHG intensity of mix			**200**	

4. Driving patterns

Vehicles that travel less than 50 km per day are responsible for about 60% of daily kilometers (km) traveled by passenger vehicles (*49*). To determine the fraction of PHEV travel powered by electricity (as opposed to liquid fuel on-board), a cumulative distribution of daily vehicle kilometers traveled has been constructed (Figure S2) from the US Department of Transportation National Household Travel Survey (*50*). This distribution reports the percentage of total vehicle kilometers that are from vehicles traveling less than a given distance on any given day. National Household Travel Survey Data is available at http://nhts.ornl.gov. To determine the miles (km) traveled by each unique passenger vehicles per day, we used the NHTS DAYPUB database with national weights.

Table S7 shows fractions of vehicle travel powered by gasoline, for the different vehicle configurations considered.

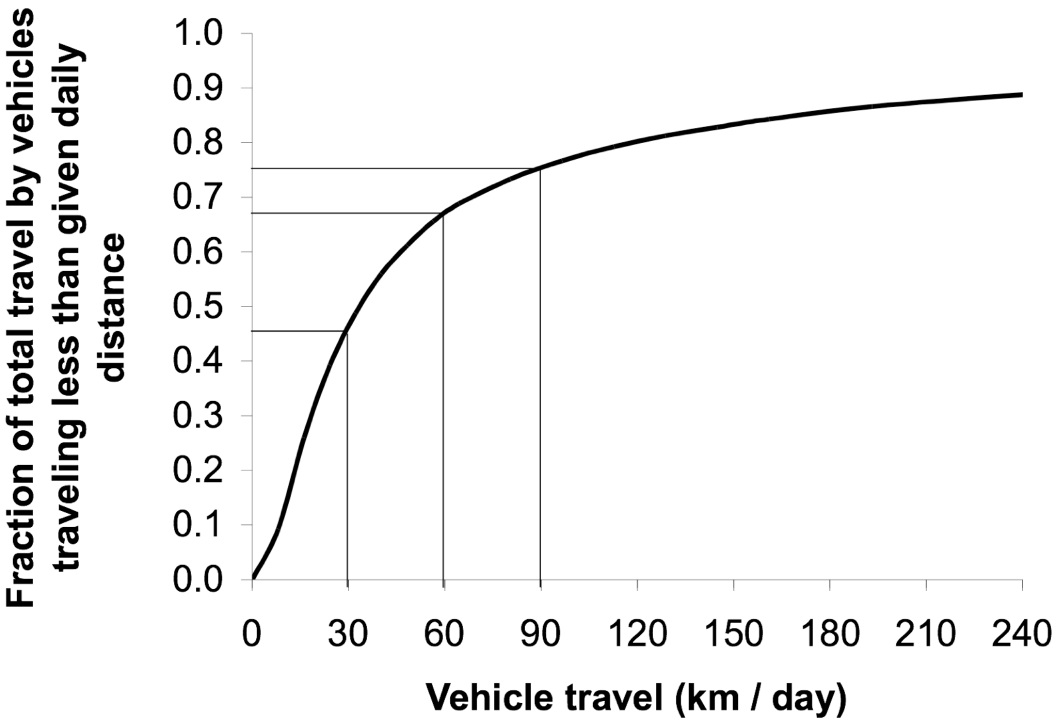

Figure S2. Cumulative distribution of daily passenger vehicle travel (km / day). By estimating the kilometers traveled by each vehicle per day, the percent of travel that could potentially be powered with electricity with the various PHEV configurations can be obtained. The distribution was constructed with data from the National Household Travel Survey (*50*).

Table S7. Fraction of total vehicle kilometers powered by electricity (α) and gasoline (1-α). Most likely results from the distributions are shown in this table.

	CV	HEV	HEV30	HEV60	HEV90
α	0	0	0.47	0.68	0.76
1-α	1	1	0.53	0.32	0.24

5. Results

By summing the production impacts in Table S2 and the use-phase impacts from equation 1 of the main text, the total life cycle impacts are presented in Table S8. The results provide a framework for policy and targeted improvement across these vehicle technologies. As with CVs and HEVs, emissions from PHEVs are sensitive to changes in fuel economy. If kWh/km requirements for PHEVs improve by 20% while holding liquid fuel economy constant for all vehicles, life cycle GHGs from PHEVs are 10-13% lower than HEVs. Conversely, a 20% improvement in liquid fuel economy across the vehicle technologies results in HEVs having 4-13% lower life cycle GHGs than plug-in hybrids. Sensitivity of total life cycle GHG impacts to changes in electricity propulsion requirements, fuel economy, and E85 cellulosic ethanol is shown in Table 1 of the main text. Finally, the adoption rate of biofuels and flex-fuel vehicles, changes in the electricity mix, and changes in driving patterns will also influence the potential benefits of a plug-in hybrid automobile fleet.

Table S8: Life cycle energy use and GHG emissions from conventional vehicles, hybrids, and plug-in hybrids using current US Average GHG intensity of electricity.

		Units	CV	HEV	PHEV 30	PHEV 60	PHEV 90
Production phase	Vehicle	MJ / km	0.4	0.4	0.4	0.4	0.4
		g CO_2e / km	35	35	35	35	35
	Battery	MJ / km	-	0.01	0.05	0.09	0.14
		g CO_2e / km	-	1	3	7	10
Use phase	Gasoline: site	MJ / km	2.6	1.8	0.9	0.6	0.4
		g CO_2e / km	177	118	63	38	28
	Gasoline: upstream	MJ / km	0.6	0.4	0.2	0.1	0.1
		g CO_2e / km	57	38	20	12	9
	Electricity: site	MJ / km	-	-	0.7	1.0	1.2
		g CO_2e / km	-	-	57	82	92
	Electricity: upstream	MJ / km	-	-	0.1	0.1	0.1
		g CO_2e / km	-	-	5	7	8
Total impact	Energy Use	MJ / km	3.6	2.6	2.3	2.2	2.2
	GHG emissions	g CO_2e / km	269	192	183	181	183

This study did not consider two-way power flows between the vehicle and the grid (V2G), in which the vehicle battery could provide ancillary services or other power to the grid in exchange for revenue (*51*). A V2G system could also potentially provide storage and dispatch capabilities for intermittent renewable energy sources (*52*), and Kempton *et al.* calculated that large offshore wind resources off the Eastern US coast matched the power demand for end uses in East coast states (*53*). The net GHG benefits of a V2G system would depend on the GHG intensity of electricity used for charging and the GHG intensity of the electricity displaced by two-way power flows, and is an interesting topic for future research.

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