Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits

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We assess the economic value of life-cycle air emissions and oil consumption from conventional vehicles, hybrid-electric vehicles (HEVs), plug-in hybrid-electric vehicles (PHEVs), and battery electric vehicles in the US. We find that plug-in vehicles may reduce or increase externality costs relative to grid-independent HEVs, depending largely on greenhouse gas and SO_2 emissions produced during vehicle charging and battery manufacturing. However, even if future marginal damages from emissions of battery and electricity production drop dramatically, the damage reduction potential of plug-in vehicles remains small compared to ownership cost. As such, to offer a socially efficient approach to emissions and oil consumption reduction, lifetime cost of plug-in vehicles must be competitive with HEVs. Current subsidies intended to encourage sales of plug-in vehicles with large capacity battery packs exceed our externality estimates considerably, and taxes that optimally correct for externality damages would not close the gap in ownership cost. In contrast, HEVs and PHEVs with small battery packs reduce externality damages at low (or no) additional cost over their lifetime. Although large battery packs allow vehicles to travel longer distances using electricity instead of gasoline, large packs are more expensive, heavier, and more emissions intensive to produce, with lower utilization factors, greater charging infrastructure requirements, and life-cycle implications that are more sensitive to uncertain, time-sensitive, and location-specific factors. To reduce air emission and oil dependency impacts from passenger vehicles, strategies to promote adoption of HEVs and PHEVs with small battery packs offer more social benefits per dollar spent.

The electrification of passenger vehicles has the potential to address three of the most critical challenges of our time: plug-in vehicles may (*i*) produce fewer greenhouse gas (GHG) emissions when powered by electricity instead of gasoline, depending on the electricity source; (*ii*) reduce tailpipe emissions, which impact people and the environment; and (*iii*) reduce gasoline consumption, helping to diminish dependency on imported oil. Recognizing these benefits, US policymakers have provided federal tax credits of up to \$7,500 per vehicle to encourage electrified transportation, with additional supporting policies enacted in many states (1, 2). Ideally, these policies would compensate for the externalities of energy use, such as damages to human health and to resources caused by emissions or oil consumption. Because such externality damages are not priced explicitly in the marketplace, they are not adequately accounted for in decision making, and users consume and emit more than they would have if they had born the full costs (3). Policymakers understand the impossibility of eliminating all externality damages; instead, laws favor determining which externality-reducing measures are worth paying for and which approaches reduce externality damages most efficiently.

In this study we assess, under a wide range of scenarios, how much externality damage reduction plug-in vehicles can offer in the US and at what cost. To answer this question, we gathered data on (*i*) the quantity and location of emissions released from tailpipes and from upstream processes to produce and operate vehicles, (*ii*) the externality costs of damages caused by the release of these emissions, and (*iii*) estimates of externalities and other costs to the US associated with oil consumption. We compare externality and oil consumption costs to the costs of owning and operating these vehicles and to subsidies designed to encourage their adoption. *SI Text* provides a detailed review of relevant literature.

Results

Emissions Damage Reduction Potential. We estimate life-cycle emissions damages for comparable new midsize vehicles, including a conventional vehicle (CV), a hybrid-electric vehicle (HEV), plug-in hybrid-electric vehicles (PHEV) with battery packs sized for storing 20 km (PHEV20) or 60 km (PHEV60) of grid electricity (with the remainder powered by gasoline), and a battery electric vehicle (BEV) with a 240-km pack (and no gasoline engine). We estimate location-specific externality damages for releases of CO, nitrogen oxides (NO_x), particulate matter (PM), SO_2, and volatile organic compounds (VOCs) using data from a 2010 National Research Council (NRC) study (3, 4) with their \$6 million estimate for value of statistical life, and we examine a range of estimates for damages from GHG emissions (3, 5). We combine these externality values with data on US driving patterns from the 2009 National Household Travel Survey (NHTS) (6) and data on manufacturing, fuel cycle, and operation emissions from Argonne National Laboratory (ANL) (7, 8) to estimate US life-cycle damages for each vehicle. Fig. 1 summarizes the results. In our base case, we assume average US values for emissions and damage valuation of electricity generation, oil refining, vehicle and battery production, driving location, and upstream supply chain emissions, we use a medium global valuation for GHG emissions, and we assume the battery will last the life of the vehicle. Although gasoline production and combustion produce significant emissions, battery and electricity production emissions are also substantial. We find that, in the base case, plug-in vehicles (PHEVs and BEVs) may produce more damage on average than today's HEVs. This fact is due in large part to SO_2 and GHG emissions from coal-fired power plants.

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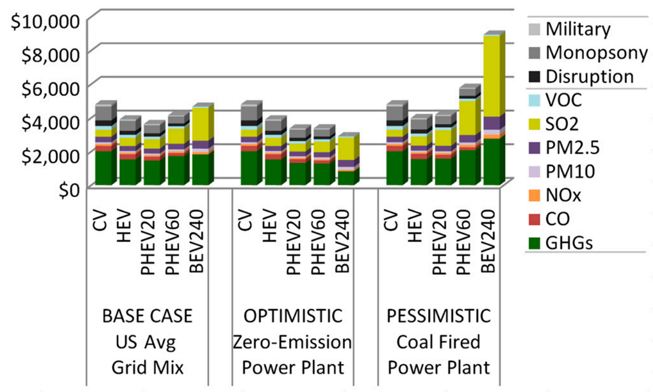

Fig. 1. Value of life-cycle emissions externality damages and oil premium costs from vehicles ($\$_{2010}$). PHEV$_x$, plug-in hybrid-electric vehicle with an x-km battery pack; BEV$_x$, battery electric vehicle with an x-km battery pack.

Power plant emissions associated with charging a plug-in vehicle could be higher or lower than today's US average grid mix, depending on region, time of day, regulations, such as caps on SO_2 emissions or renewable portfolio standards, and anticipated plant retirement and new plant construction. Additionally, considerable variation in electricity emissions factors exists for each charging location depending on the geographic boundary chosen for analysis (9). To put bounds on these factors, Fig. 1 presents a hypothetical optimistic case, where zero-emission electricity is used to charge the vehicle, and a pessimistic case, where coal-fired power plants are used to charge the vehicle. In the pessimistic case, the BEV could be responsible for more than a \$5,000 increase in lifetime damages over the HEV (all costs are in year 2010 US dollars, notated $\$_{2010}$). In the optimistic case, the BEV could reduce lifetime air emissions damages by about \$100. Although the costs of damages from vehicle-associated emissions are significant, the damage reductions that can be gained through electrification are small compared to the total cost of owning and operating a vehicle (10). Additional sensitivity cases are described in the *SI Text*.

Oil Premium. Because the US consumes about 23% of global oil production, US light-duty vehicles account for 45% of US oil consumption, and oil-fired power plants represent less than 1% of US electricity production, there is great interest in electrified transportation for displacing oil consumption (11, 12). The economic competitiveness of plug-in vehicles depends on gasoline prices; however, the economic cost to the US of its gasoline consumption includes at least three components beyond market price: (*i*) risk of losses due to oil supply disruptions, (*ii*) higher costs due to the effect of US demand on world oil prices, and (*iii*) the cost of existing policies meant to enhance oil security (13).

First, sudden disruptions of oil supply have the potential to cause price spikes. These spikes reduce US ability to generate economic output, cause temporary losses associated with dislocation and reallocation of resources, and cause additional wealth transfers to foreign countries. Brown and Huntington (14) estimate the externality portion of these costs at \$5.24 (with a range of \$1.16–\$15.01) per barrel (bbl) of imported oil by estimating disruption frequency and magnitude from historical data. The gasoline portion of this cost, allocated on an energy basis, is \$0.09 (\$0.02–\$0.28) per gallon.

The second component is the monopsony premium: Because the US demands a large portion of world oil consumption, if the US were to reduce oil consumption, world oil prices would likely fall, reducing the cost of the remaining oil consumed. Although this consideration is not an externality, it is a cost over which the US has some control. The effect on world oil prices of a drop in US demand depends on the reaction of oil producers, including the Organization of the Petroleum Exporting Countries. Leiby estimates the premium at \$10.26 (\$3.35–\$21.21) per bbl of oil, or \$0.22 (\$0.07–\$0.45) per gallon of gasoline (13).

The third component is cost of oil security policies, particularly military spending to protect oil supplies. The relevant literature and government rule-making have often assumed these costs to be nonlinear and coupled with other US strategic objectives, and they are often omitted from gasoline externality analyses (15–17). However, work by Delucchi and Murphy estimate the portion of these costs due to oil consumption from the Persian Gulf at \$0.03–\$0.16 per gallon of gasoline on average (18). We use the low end as an estimate of marginal cost in our base case, assuming that economies of scale result in marginal costs lower than average, and we examine a range in sensitivity analysis.

Fig. 1 shows the oil premium associated with supply disruption, monopsony power, and military spending added to air emission externality costs for each vehicle. With the oil premium added, the lifetime emissions externality and oil premium benefits of plug-in vehicles over HEVs remain small or negative. In the optimistic and pessimistic scenarios, plug-in vehicles provide up to \$1,000 in savings or up to \$4,000 in additional costs relative to HEVs, respectively. Although we account here for global damages from GHG emissions, we examine US oil premium costs, including costs of additional transfers to foreign countries. Implications and additional sensitivity cases are described in the *SI Text*.

Other Externalities and Factors. Environmental damages from oil extraction, such as the recent Gulf oil disaster, although costly, are nonetheless small when divided by the volume of crude oil consumed in the US (19). The largest vehicle externality costs are associated with congestion and accident rates (15, 19). If the marginal cost of driving is reduced (e.g., via electrification), people may drive more, increasing externalities associated with congestion, accidents, and emissions. However, it is not yet known how the limited range of plug-in vehicles may affect driving behavior. Other externalities, such as noise and water pollution are not considered here due to lack of data with sufficient resolution (we discuss the magnitude of these effects in the *SI Text*); nor do we place economic value on equity issues with externality burdens (20).

There may be additional arguments for supporting plug-in vehicles in the US, including the following: reducing the trade deficit by shifting from foreign to domestic fuel sources, enabling a distributed storage resource to balance intermittent renewable electricity (21), reducing oil revenues to states hostile to US interests (16), hedging against an anticipated oil-scarce or carbon-constrained future (22, 23), improving regulatory control over emissions associated with poor vehicle maintenance (24), generating positive externalities by encouraging innovation (25), encouraging domestic development of strategic technical competency and intellectual property, manufacturing learning curve effects, reducing nonfinancial political and human suffering effects from war and political instability (18), and promoting international environmental justice. Quantification of these factors and estimates of life-cycle benefits of electrification would facilitate comparisons, and we encourage such analysis.

Lifetime Ownership Costs and Damages. Fig. 2 summarizes lifetime private cost paid to own and operate each vehicle type plus the cost of the oil premium and damages caused by lifetime emissions charged to the owner at the time of purchase, assuming no change in driving patterns. In the base case, we use US average grid emissions, average gasoline prices in the period 2008–2010, a long battery life, scheduled maintenance costs estimated by Oak Ridge National Laboratories (26), charging infrastructure cost estimates based on installation data, and ANL estimates of vehicle costs in the year 2015. Although the lifetime costs of conventional, HEV, and PHEV20 are comparable, it is clear that the

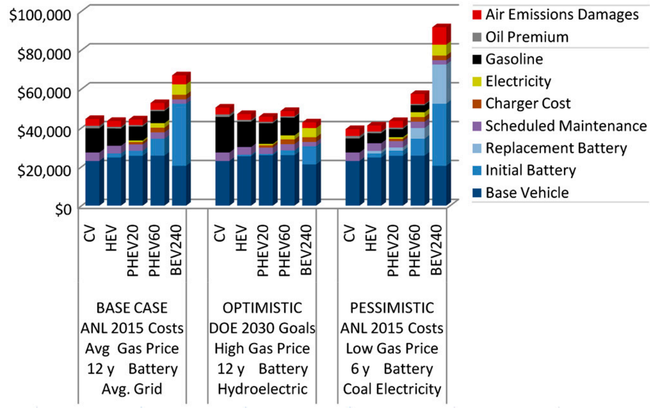

Fig. 2. Net present value of lifetime private ownership cost, emissions externality damages, and oil premium costs ($\$_{2010}$). ANL 2015 costs, Argonne National Laboratory cost estimates for the year 2015; DOE 2030 goals, US Department of Energy targets for vehicle cost in the year 2030; high, low, and average gas prices are for US weekly averages in 2008–2010; vehicle life is assumed to be 12 y.

high costs of vehicles with larger battery packs are not balanced by fuel cost savings or emissions damage and oil premium reduction. We compare an optimistic scenario, using the highest historical weekly US gasoline price, US Department of Energy targets for vehicle costs in 2030 (which ANL calls "very optimistic"), long battery life, and zero-emission charging. In the optimistic scenario, plug-in vehicles with large battery packs could offer lower damage at lower lifetime cost. But competitiveness in this case is driven by direct costs, not externality damages, and market forces would presumably drive adoption in such a case. Conversely, in a pessimistic scenario using low gasoline prices, shorter battery life, coal-powered charging, and ANL 2015 cost estimates, plug-in vehicles could produce more damages at substantially higher cost.

We also examine a range of other factors that affect costs and damages, such as urban vs. rural driving, oil supply source, refinery location, emissions valuation, oil premium estimates, and discount rate (see *SI Text*). Although large battery packs offer the largest emissions and oil consumption reductions at lowest cost in the most optimistic scenarios, they result in high costs and increased damages if not all of the right factors fall into place, including high gasoline prices and achievement of low battery costs, long battery life, and low electricity production emissions. In contrast, HEVs and PHEVs with small packs are robust, providing emissions reductions and oil displacement benefits at low cost with less infrastructure investment and lower uncertainty.

Discussion

Our results suggest that plug-in vehicles with large battery packs may either reduce or create more life-cycle damages than HEVs depending largely on GHG and SO_2 emissions from electricity and battery production. But even if future marginal electricity production and battery manufacturing processes have substantially lower emissions than today's averages, the emission damage and oil premium reduction potential of plug-in vehicles is small compared to ownership cost: Optimally efficient (Pigovian) fees charged to correct for externality damages would not provide much leverage for incentivizing the adoption of plug-in vehicles with large battery packs unless their costs drop to competitive levels. Even GHG emissions allowance charges as high as $100/t do not substantially change the financial incentives for electrification (27, 28).

BEVs have the potential to offer the greatest reductions in emissions and oil consumption at competitive cost if air emissions from electricity generation are substantially reduced, battery prices drop dramatically, gasoline prices rise, high-power charging infrastructure is sufficiently deployed, and battery life is increased beyond vehicle life. Strong policy and support for research and development are needed to pursue this optimistic future; however, such outcomes are not guaranteed because of uncertain technological, economic, and political factors. In the near term, larger battery packs come at higher costs with greater infrastructure requirements and diminishing returns on social benefits, and they may fail to reduce emissions damages if the vehicles are charged in coal-heavy regions or if batteries are replaced before the vehicle's end of life. In contrast, HEVs and PHEVs with small battery packs provide substantial emission damage reduction at low (or no) additional cost over their lifetime. In the future, if there are sufficient decreases in battery costs and increases in gasoline prices, the market may drive adoption of vehicles with larger battery packs. Until then, US policy would produce more benefit per dollar spent by supporting research on battery cost reduction, enforcing air emission reductions in power generation and transportation, and encouraging adoption of HEVs and small-capacity PHEVs (and potentially advanced conventional vehicles, not studied here). Some federal policies already follow this path. The Department of Energy's Advanced Research Projects Agency, Energy program, which was started with funds made available through the American Recovery and Reinvestment Act of 2009, has allocated significant resources to support the development of better and cheaper batteries. Similarly, the Environmental Protection Agency has issued the National Renewable Fuel Standards (first established by the Energy Policy Act of 2005) to regulate the carbon intensity of transportation fuels and is in the process of issuing several regulations to further reduce conventional air pollutants from electricity. These efforts are complemented by State Renewable Portfolio Standards, which have established targets for the percentage of electricity that must be generated with renewable fuels. HEVs have received significant support via tax credits from the federal government in the past years; however, they expired in 2010 and have been replaced by tax credits for plug-in vehicles. Although these policies encourage adoption of alternative vehicles, policies that address externalities directly (e.g., carbon taxes, cap and trade systems, or gasoline taxes) would have the added benefit of encouraging consumers to find the most efficient means of reducing damages, including purchasing smaller vehicles or reducing driving.

Although an electrified transportation system coupled with low-emission electricity generation represents a promising path to achieving reductions of air emissions and petroleum consumption in the US, plug-in vehicles will have to compete on total cost of ownership in order to offer a realistic mass-market alternative and an efficient approach to achieving these reductions. US policy provides taxpayer support of research and development aiming to achieve cost parity together with subsidies to encourage deployment. However, current subsidies of up to $7,500 for vehicles with large battery packs are far larger than our optimistic estimates of externality benefits and represent GHG abatement costs well over $100/t in our base case (28). Subsidies would produce greater reductions of emissions damages and oil premium costs per tax dollar spent if targeted to HEVs and PHEVs with small battery packs. For example, in our base case, the current subsidy of up to $7,500 for up to 200,000 plug-in vehicles (2), implying a maximum total subsidy of $1.5 billion, could pay the purchase premium for 390,000 HEVs or 290,000 PHEV20s, reducing emissions externality damages and oil premium costs by $350 million or $330 million, respectively, compared to conventional vehicles. In contrast, $1.5 billion could pay the purchase premium for only 130,000 PHEV60s or 51,000 BEV240s, reducing damages and premium costs by $86 million or $7 million, respectively (lifetime fuel costs also vary). As battery technology improves, gasoline prices rise, the electricity grid improves, and constraints on GHG emissions become stringent, BEVs and PHEVs with large battery packs may become more cost effective at reducing damages. But today's HEVs and PHEVs with small battery packs offer more emissions reduction and petroleum displacement per dollar spent with less of a need for new infrastructure and with lower uncertainty about future costs and life-cycle implications.

These US-specific findings may not extend to other countries. For example, it is possible that, in some European countries, the combination of higher petroleum prices, lower-emission electricity, higher population density, greater use of diesel, and shorter driving distances could make plug-in vehicles more attractive both for ownership cost and externality damage reduction.

Methods

We use life-cycle assessment (LCA) to identify and compare the emissions of each vehicle in our study. LCA is framework for evaluating emissions inventories and their impacts in complex systems. We evaluate a well-to-wheel system boundary including raw materials extraction and processing, manufacturing, vehicle operation, vehicle end of life (reuse, recycling, incineration, or land filling), and transportation connections between processes. We estimate NO_x, SO_2, PM, CO, VOCs, and GHG air emissions, including CO_2, CH_4, and N_2O, converted to CO_2 equivalence using 100-y Intergovernmental Panel on Climate Change global warming potential values (29). Specific components in the life-cycle boundary are vehicle and battery manufacturing (assembly and upstream), energy production (petroleum refining, electricity generation, and upstream emissions), and the direct emissions from driving (tailpipe, tire wear, and brake wear).

Allocation methods can be critical to the results of life-cycle assessment. Often, there are multiple coproducts in a system. In these cases, energy and material consumption as well as wastes and emissions must be allocated among the multiple coproducts. Petroleum refineries are an example of systems where allocation is required. Gasoline, diesel, liquefied petroleum gas, kerosene, and many other products are produced within the refinery boundary. We allocate petroleum production emissions based on the energy content of the refinery coproducts (mass and volumetric allocation produce similar results; see *SI Text* for a discussion of alternative approaches).

Emissions quantities for vehicle and battery manufacturing were evaluated with an analysis tool called The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model 2.7a (7) and are determined from a materials-based life-cycle inventory that captures raw material extraction, material processing, manufacturing, and transportation for major vehicle systems including the body, powertrain, transmission/gearbox, chassis, traction motor, generator, and electronic controller. Furthermore, lifetime fluid use and battery manufacturing, including lead acid, nickel metal hydride (NiMH), and Li-ion chemistries are determined. The CV and HEV were evaluated, the HEV data were used as a proxy for PHEV and BEV base vehicle production, and batteries were considered independently. Emissions associated with production of a single battery pack were estimated using GREET, and battery replacement frequency was adjusted as a sensitivity parameter. We use the NiMH chemistry for our HEV model. To estimate emissions for the larger battery packs associated with PHEVs and BEVs, we scale the HEV Li-ion battery pack production emissions linearly with pack weight, sizing the packs to meet the stated range on the Environmental Protection Agency's urban dynamometer driving schedule (30). (The *SI Text* provides additional explanation of battery pack weight and sizing.)

The well-to-pump emissions of gasoline production were evaluated with the GREET 1.8d fuel-cycle model. GREET provides the ability to model many transportation fuel pathways, and conventional gasoline production is considered in this study. However, gasoline can be produced from a variety of sources including conventional crude and oil sands. In our sensitivity analysis, we consider 9.4% (current average US mix), 0%, and 100% of crude from oil sands, with the remainder from conventional crude in each case (8). These three scenarios are intended to provide bounds on average and marginal units of oil, which may vary in composition of source by location and over time. The GREET fuel-cycle model includes evaluation from extraction of crude product to processing and distribution of finished gasoline product. For feedstock production, recovery processes are determined for conventional crude, and bitumen extraction and upgrading (including hydrogen production) are evaluated for oil sands recovery (including surface mining and in-situ production). The feedstock production phase also includes transport from the recovery sites to US refineries, where processing to the finished gasoline product occurs. The fuel refining phase in GREET evaluates refinery energy use and processes, production of additives, and final transport and distribution to the pump.

Air emissions from electricity generation include direct emissions from combustion at the power plant and upstream emissions associated with fuel supply. We estimate direct emissions using the data from the NRC study (3), which in turn used the Emissions and Generation Resource Integrated Database (31). The NRC study includes data on NO_x, SO_2, PM_{10}, $PM_{2.5}$, and GHGs from coal and natural gas plants, which account for 70% of US electricity generation. We assume optimistically that the remaining 30% of plants produce energy with zero emissions. We estimate upstream emission factors per unit of coal or natural gas feedstock using GREET. We compute the average emissions per kilowatt hour generated in the US by weighting emissions from each plant by its production output. When determining impacts, we identify the plants with the 5th, 50th, and 95th percentile damages based on location.

Emissions from vehicle use depend on vehicle efficiency as well as the portion of propulsion energy powered by electricity versus gasoline. Although CVs and HEVs use only gasoline for propulsion and BEVs use only grid electricity, PHEVs use some of each. After a PHEV battery is fully charged, a PHEV will operate in charge-depleting mode (CD mode) until the battery's state of charge drops to a predetermined level, at which point the vehicle switches to charge-sustaining mode (CS mode). We use midsize vehicle models defined in GREET 1.8d to estimate vehicle efficiency, vehicle emissions, and battery pack size requirements (30). To estimate the portion of driving propelled by electrical power, we use the 2009 NHTS (6), which interviewed over 140,000 people across the US on details of their travel behavior. We extracted data on total daily distance traveled over the survey population weighted by vehicle to correct for demographic differences in the survey sample. We used the remaining data to calculate the portion of distance that would be traveled in CD vs. CS mode for each vehicle, assuming one charge per day and using vehicle efficiencies estimated in GREET. All daily travel shorter than the CD-mode range is traveled entirely in CD mode, whereas daily travel longer than the CD-mode range is traveled partly in CD mode and partly in CS mode.

To convert the estimated life-cycle air emissions to cost of damages, the Air Pollution Emission Experiments and Policy (APEEP) analysis model was used (3, 4). APEEP calculates the marginal human health and environmental damages from emissions of $PM_{2.5}$, PM_{10}, VOC, NO_x, and SO_2 on a dollar-per-ton basis. APEEP is an integrated assessment model that evaluates emissions in each US county with human and environmental exposure, physical effects, and the resulting monetary damages determined from peer-reviewed findings from broad disciplines. Physical effects include epidemiological outcomes (e.g., mortality, bronchitis, asthma, cardiac), crop loss, timber loss, materials depreciation, visibility, and forest re-creation. Ground level release heights are used to evaluate emissions from driving, whereas estimates at stack-height elevations are used to evaluate the emissions from electricity generation and petroleum refining. APEEP accounts for secondary PM production from sulfate, VOC, and ozone formation, and the costs of these secondary pollutants are attributed to the appropriate emissions. For example, most of the damages associated with SO_2 emissions are caused by exposure to secondary sulfate PM and ambient exposures to SO_2. For each county and each pollutant, APEEP estimates mortality, morbidity, and environmental damages. We use the highest value of statistical life: \$6 million ($\$_{2000}$) (4). Vehicles make up the largest source of CO emissions in the US, and APEEP does not evaluate this pollutant (32). To account for this emission, the median CO valuation cost from Matthews et al. (33) was employed and scaled with the APEEP county PM_{10} valuation costs, because CO, similar to PM_{10}, is primarily linked to cardiovascular effects. We examine a range of GHG cost estimates based on refs. 3 and 5, which include changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change.

Vehicle cost estimates for years 2015 and 2030 were adapted from the Argonne National Laboratory's 2009 report on transportation futures (34), which consist of targets set by the Department of Energy and estimates based on literature review and interviews with experts. The report estimates costs associated with a variety of subsystems and assumes that retail prices are 1.5 times costs for all vehicles. Estimates span those summarized in ref. 35. We adopt maintenance cost estimates from Oak Ridge National Laboratories (26), which lie within the range summarized in ref. 35, and our charger cost estimates are based on a range of unpublished data (see *SI Text*). For use-phase energy costs, we use maximum, minimum, and average costs from 2008–2010 from the Energy Information Administration. Lifetime operating costs are calculated using a base case nominal discount rate of $r_N = 8\%$ and assuming annual inflation price increases of $r_I = 3\%$, resulting in a real discount rate of $r_R = 4.9\%$. Air emissions externality and oil premium costs are discounted at the same discount rate as though the corresponding fees are charged to the consumer at the time of purchase for vehicle, battery, gasoline, and electricity, and all upstream fees are passed along to the consumer. All monetary values are converted to 2010 dollars using the Energy Information Administration Gross Domestic Product Price Deflator (36). More information on these methods, data sources, and relevant literature is available in the *SI Text*.

SUSTAINABILITY SCIENCE

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Supporting Information

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SI Text

This supplemental document presents data, assumptions, methods, and additional analysis for the primary document "Valuation of Plug-in Vehicle Life-Cycle Air Emissions and Oil Displacement Benefits." We begin by reviewing relevant literature for context. We then describe life-cycle emissions data followed by data for valuation of external damages caused by emissions and the oil premium. Finally, we present data on ownership costs, provide detail and analysis of results, and discuss conclusions and policy implications.

Literature Review

Comparing the life-cycle costs and emissions benefits of vehicle electrification requires an understanding of (*i*) life-cycle emissions reduction potential of electrified vehicles, (*ii*) the value of reduced damages associated with emissions reduction, and (*iii*) the lifetime cost of ownership for each vehicle alternative. We review relevant literature in the following sections. Literature on the premium associated with oil consumption is reviewed separately in the oil consumption valuation section.

Valuation of Emissions Damages from Vehicles. Air emissions externalities from personal vehicle travel have been evaluated typically focusing on morbidity, mortality, and environmental impacts. These studies vary in scope, including study location, pollutants assessed, and inclusion versus exclusion of upstream life-cycle implications. A number of studies focus on estimating only the direct externalities of driving. Small and Kazimi (1) estimate mortality and morbidity from particulates and ozone in the Los Angeles region at 2.05¢$_{1992}$ per vehicle kilometer traveled (VKT), where subscripts on currency symbols are used to indicate the reference year. Mayeres et al. (2) forecast air pollution costs [CO_2, CO, NO_x, SO_x, particulate matter (PM_{10}), and volatile organic compounds (VOCs)] in Brussels in 2005 at 21–24 mECU$_{1990}$/VKT (where ECU is the European currency unit) for cars and congestion costs as large as 1,387 mECU$_{1990}$/VKT. Their study also quantifies costs associated with accidents (98–158 mECU$_{1990}$/VKT) and noise (1–6 mECU$_{1990}$/VKT). Maddison et al. (3) estimate external costs of air emissions (NO_x, SO_x, PM_{10}, VOCs including benzene, and lead) in the United Kingdom at 0.02–0.04 £$_{1993}$/VKT for light-duty vehicles, and they go on to report congestion externalities through lost time evaluation as large as 36 £$_{1990}$/VKT. McCubbin and Delucchi (4) estimate air pollution-related costs at 0.58–7.71 ¢$_{1992}$ per vehicle mile traveled (VMT) for US light-duty gasoline vehicles, quantifying mortality and chronic illness damages for ozone, CO, NO_2, particulates, and toxic pollution. Citing their earlier work (5), Delucchi and Lipman (6) report that the benefit of battery electric vehicles (BEVs) over conventional vehicles (CVs) is 0.4–3.7 ¢$_{2000}$/VMT, and that external costs are small compared to other costs. Furthermore, Lipman and Delucchi (7), using estimates from Delucchi (8), include greenhouse gas (GHG) and oil-use (0.053–0.427 \$$_{2000}$ per gallon) as well as air pollution and noise damages (0.14–5.26 ¢$_{2000}$ per gallon) in a life-cycle cost analysis of internal combustion engine vehicles (ICEVs) and hybrid-electric vehicles (HEVs). Sen et al. (S9) estimate air pollution costs (CO, NO_x, particulates, and hydrocarbons) in Delhi at 0.28–0.31 Rupees (Rs) for gasoline cars and 1.03–2.74 Rs for diesel cars. Mashayekh et al. (10) evaluate the top 86 US metropolitan regions and determine that CO_2, NO_x, VOCs, CO, SO_x, particulates, and NH_3 produce external costs of \$145 million per day in 2007 across the country plus an additional \$24 million per day due solely to congestion. Hill et al. (11) estimate that total climate change and health-related costs for gasoline are about \$$_{2008}$ 0.71/gal and higher for corn ethanol. Thomas (12) calculates US urban air pollution, greenhouse gas, and oil displacement costs from 2000 to 2100 by evaluating alternative vehicle fleet penetration, estimating that exposure to VOCs, CO, NO_x, PM, and SO_2 from the 2010 US passenger vehicle fleet produces approximately \$30 billion in healthcare costs and forecasting costs to 2100 using scenarios for alternative vehicle technology adoption.

A few studies have considered life-cycle air emissions externalities by evaluating services in larger transportation systems. Early in the development of economic input–output environmental assessment, Matthews et al. (13) evaluated the US transportation sector and showed that the inclusion of upstream transportation services increases external costs by as much 45%. Evaluating SO_2, CO, NO_2, VOC, PM_{10}, and GHGs, Matthews et al. (13) details the upstream supply chain activities that exist to support transportation services and their potential major emissions contributions in the life cycle. Recognizing the need to compare different vehicle and fuel technologies within a life-cycle framework, The National Research Council (NRC) (14) developed external cost estimates for passenger and freight modes at each of the approximately 3,000 US counties. The gasoline and diesel vehicle costs range from 1.3–1.8 ¢$_{2007}$/VMT for light-duty automobiles to 3.23–10.41 ¢$_{2007}$/VMT for heavy-duty vehicles, for driving in 2005. They also report damages for grid-independent HEVs at 1.22 ¢$_{2007}$/VMT, grid-dependent HEVs at 1.46 ¢$_{2007}$/VMT, and electric vehicles at 1.72 ¢$_{2007}$/VMT, assuming average electricity. Lastly, by applying life-cycle inventories to cities, Chester et al. (15) estimates external costs for passenger transportation in the San Francisco, Chicago, and New York City metropolitan areas at 0.5–64 ¢$_{2008}$ per vehicle trip, depending on vehicle location, age, speed, and driving time.

The variation in external cost estimates across these studies, even when comparing air emissions exclusively, is the result of a myriad of factors. These include the vehicles evaluated (year, emission profiles), pollutants considered, population demographics (impacts to the people exposed), valuation scheme (unit external cost assessed based on impact literature for a particular region), driving characteristics (free flow or congestion), and life-cycle considerations (only tailpipe emissions vs. inclusion of emissions associated with upstream activities required for transportation services). Furthermore, some studies include human health impacts exclusively (and choose a value of statistical life), whereas others capture climate change, vegetation, visibility, material, and aquatic damages, to name a few.

In our study, we adopt the scope and framework of the NRC study (14) for externality valuation, accounting for life-cycle emissions of NO_x, SO_2, PM, CO, VOCs, and GHGs including CO_2, CH_4, and N_2O for each vehicle type; accounting for damages associated with environmental impact, mortality, and morbidity (using a \$6 million value of statistical life); and assessing location-specific damages in the regions where emissions take place. We assume that other externalities associated with driving, such as congestion costs (16, 17), will not be substantially different as a result of powertrain choice, and thus we do not include such factors in the assessment.

Emission Reduction Potential of Electrified Vehicles. Several studies estimate the emissions reductions that can be achieved with electrified vehicles. Lipman and Delucchi provide a recent review for GHG emissions (18). The Electric Power Research Institute (EPRI) conducted a two-part study with the National Resources Defense Council on the potential of plug-in hybrid-electric vehicles (PHEVs) to reduce use-phase GHGs and air pollutants (19). Their study included detailed projections of vehicle time-of-day charging, regional market penetration, plant dispatch policy, plant retirement, new plant construction, technological advancement, and public policy. Under these assumptions, the study estimates GHG reduction potential of 163–612 million metric tons (t) per year by 2050 depending on penetration and grid mix scenarios (19). The electricity used to charge PHEVs in the study's future scenarios is assumed to be 33–84% less carbon intensive than the current US generation portfolio (20). Samaras and Meisterling (20) estimate that life-cycle GHG emissions associated with PHEVs may be 32% lower than conventional vehicles under an average US grid mix, but only slightly lower than HEVs. However, net emissions depend critically on the source of electricity generation: Life-cycle emissions under coal electricity are estimated at 9–18% higher than HEVs, whereas a low carbon electricity generation mix could reduce GHG emissions by 30–47% over HEVs. Bradley and Frank (21) review PHEV GHG reductions ranging from 27–67%. Sioshansi and Denholm (22) apply optimization dispatch models, finding that marginal emissions associated with charging plug-in vehicles may depend strongly on vehicle charge timing. Thompson et al. (23) modeled air quality impacts of PHEVs charged overnight in a regional grid and found both improvements and worsening of air quality indicators, depending on spatial and temporal patterns. Peterson et al. (24) modeled CO_2, NO_x, and SO_2 net emissions in the New York and PJM Interconnection electricity grids and found net reductions in CO_2 and NO_x, but either small or large increases in SO_2 depending on stringency of SO_2 emissions caps. Finally, Argonne National Laboratory (ANL) has conducted a range of studies on life-cycle emissions associated with vehicle use as well as vehicle and fuel production, and they have collected the resulting models into an analysis tool called The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model, or GREET (25). In particular, a 2010 well-to-wheels analysis (26) identifies vehicle efficiency and tailpipe emissions using the Powertrain Systems Analysis Toolkit, also developed at Argonne.

In our study, we adopt GREET and the vehicle profiles defined by ANL, which provide documentation of vehicle specifications, efficiency, and emissions for estimating characteristics of each vehicle alternative.

Cost of Electrified Vehicles. As with many new technologies, early adopters and enthusiasts will provide niche market demand for electrified transportation, even if costs of electrified vehicles are substantially higher. However, in order for plug-in vehicles to achieve broad market success, they must be cost competitive with other conventional and advanced transportation options. Because of high uncertainty, cost estimates often examine a range of potential battery prices and fuel costs. Delucchi and Lipman (6) review several cost estimates for BEVs, PHEVs, and fuel cell vehicles. For example, Kromer and Heywood (27) estimate future price premiums for PHEVs and BEVs, and Delucchi and Lipman (5) estimate costs for battery electric vehicles with various battery pack sizes. Argonne's 2009 vehicle futures study (28) estimates vehicle systems costs for CVs, HEVs, PHEVs, BEVs, and other vehicles in 2015, 2030, and 2045 using literature review and expert interviews, and they compare estimates to Department of Energy (DOE) program goals. Scott et al. (29) found that the maximum PHEV premium consumers would be willing to pay relative to other types vehicles would range from $0–$4,600. Lemoine et al. (30, 31) estimated that batteries prices would have to fall to less than $600/kWh for PHEVs and $200/kWh for BEVs to be competitive with HEVs and CVs. Shiau et al. (32) estimated that PHEV battery pack prices below $400/kWh are needed for optimized plug-in vehicles to be competitive with HEVs if consumers use discount rates above 10%. Karplus et al. (33) modeled costs and emissions and found that PHEV cost premiums of 15% above CVs were favorable for adoption but current premiums were around 30–80%. Shiau et al. (34) found that small PHEVs with a 7-mi all-electric range could be competitive with current HEVs if charged frequently (assuming sufficient battery life), whereas increasing battery size to extend electric range only achieves economic competitiveness under optimistic assumptions. Finally, an NRC report (35) estimated the costs of PHEV batteries at $625–$850/kWh at the pack level. The NRC forecasted that PHEVs with 40-mile battery packs are unlikely to achieve cost effectiveness before 2040 with gasoline prices below $4.00/gal, however, PHEVs with 10-mile battery packs will likely fare better (35). Most studies examining PHEV costs (32, 34, 36, 37) find that PHEVs become more competitive as they drive more of their miles on electricity but become less competitive as more batteries are added. Hence frequent charging increases the economic viability of PHEVs, if battery life is not compromised. All of these studies imply that economic competitiveness of PHEVs depends on inexpensive, reliable batteries and relatively expensive gasoline.

In our study, we adopt ANL's cost estimates (28), which provide a comprehensive and detailed cost breakdown for projections over several decades, and we use DOE targets for sensitivity analysis. These estimates span the range of electric vehicle cost premium estimates reviewed by Delucchi and Lipman (6).

Cost Effectiveness of Emissions Reduction. The cost of reducing GHGs with electrified transportation is a critical factor to maximize the effectiveness of policy objectives. Lutsey and Sperling (38) constructed a cost supply curve of transportation GHG mitigation options and found that most cost effective options involved improving conventional vehicle efficiency, while excluding PHEVs due to cost considerations. Kammen et al. (39) estimated the cost effectiveness of GHG abatement with PHEVs by dividing the additional subsidy required to make PHEVs competitive after discounted fuel cost savings are included by the estimated GHG savings. The authors conclude that costs of GHG mitigation with PHEVs are well over $100/t-$CO_2$e. Studies by Shiau et al. (32) and Argonne National Laboratories (28) also state that the cost of GHG mitigation with PHEVs and BEVs is well over $100/t, and CO_2 taxes below $100/t offer little leverage for improving cost competitiveness of PHEVs. However, Kammen et al. (39) notes that

> While we focus on PHEVs' value as a strategy to abate GHGs, PHEVs also offer social benefits through reduced petroleum consumption and reduced urban air pollution that many other GHG abatement options will not. Any comparison of PHEVs with other abatement technologies on the basis of the metric $/tCO2eq is therefore incomplete. However, we consider only GHGs and leave other air pollutants for future research.

It is our intention in this work to address this research gap by assessing cost-effectiveness of combined air pollution and oil consumption reduction benefits of electrified vehicles in addition to GHG reduction benefits.

US Public Policy. Since 2005, the US Congress has enacted several laws that include support and restrictions for alternative vehicles and fuels. The Energy Policy Act of 2005 included provisions to support alternative vehicles through tax credits as well as mandated that ethanol and other renewable fuels be blended with gasoline. Tax credits were created to support ethanol and biodiesel fuels. The 2007 Energy Independence and Security Act (EISA) expanded the renewable fuel mandate and increased the Corporate Average Fuel Economy (CAFE) standards. EISA set a goal of 35 mi/gal by 2020. The American Recovery and Reinvestment Act of 2009 included provisions to support alternative fuels and advanced vehicles. Such incentives included tax credits for the purchase of electric vehicles as well as support for research and development of batteries that can be used in advanced vehicles.

In addition to efforts by Congress, several states have enacted regulation to reduce GHG emissions. Most notable are the efforts in California. In 2006, the California legislature passed Assembly Bill 32, the Global Warming Solutions Act. Through this act, the legislature set a cap for GHG emissions by 2020. Under this law, the California Air Resources Board (CARB) was directed to identify emission reduction mechanisms. Since then, CARB has been working to amend the Low Emission Vehicle Program with the goal of developing more stringent tailpipe and GHG emissions standards for new passenger vehicles. CARB has a zero emission vehicle program to support deployment of plug-in hybrid vehicles, battery electric vehicles, and hydrogen fuel cell vehicles, and CARB has also developed the Low Carbon Fuel Standard, which established a goal of reducing by 10% the carbon intensity of transportation fuels sold in the state by 2020. CARB and its partners (the California Environmental Protection Agency, the University of California, and the California Energy Commission) have been working to identify the fuels that can meet such standards. The fuels under consideration include compressed natural gas, biofuels, and electricity for plug-in vehicles, among others.

Life-Cycle Emissions Inventory

We use life-cycle assessment (LCA) methods to identify and compare the emissions of conventional vehicles, HEVs, PHEVs, and BEVs. LCA provides a systematic inventory and impact assessment of the full environmental implications of products across life-cycle stages: materials extraction and production, manufacturing, use, and the ultimate fate of the product (reuse, recycling, incineration, or land filling). For this study, we estimate emissions of nitrogen oxides (NO_x), sulfur dioxide (SO_2), PM, CO, VOCs, and GHG emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). We normalize CO_2, CH_4, and N_2O to CO_2-equivalence using the 100-y Intergovernmental Panel on Climate Change AR4 global warming potential values adopted by GREET (40). Data for some of these pollutants were not available for some life-cycle stages, as minor emissions are not always reported. For those stages where a specific pollutant is not reported, a value of zero is assumed. The life-cycle boundary includes emissions from vehicle and battery manufacturing (assembly and upstream emissions), energy production (petroleum refinery, electricity generation, and upstream emissions), and the direct emissions from driving (tailpipe and particulates from brake wear).

Allocation of petroleum refinery emissions is based on the energy content of the refinery coproducts. Allocation methods can be important to the results of life-cycle assessment. Often, there are multiple coproducts in a system. In these cases, energy and material consumption as well as wastes and emissions must be allocated among the multiple coproducts. Petroleum refineries are an example of systems where allocation is required. Gasoline, diesel, liquefied petroleum gas, kerosene, and many other products are produced within the refinery boundary. In this study, allocation by energy output is used, which is consistent with prior work on the life cycle of petroleum products (25, 41–43). Allocation by mass, volume, or product supplied is also possible but would not affect the results of this study. Increasingly, system expansion and consequential analysis have been gaining popularity within the life-cycle community. Use of system expansion has been identified to be most important for agricultural systems, where widely different coproducts are produced that may have significant impacts on global markets (see for example ref. 44). Performing an appropriate consequential system expansion analysis requires the use of detailed economic models and/or computable general equilibrium models with associated uncertainties. Similarly, refinery constraints limit the impacts of changes in coproduct breakdown. A truly consequential analysis would require the use of detailed refinery models that are currently unavailable in the public domain. Hence, refinery product allocation by system expansion is beyond the scope of this paper.

Vehicle and Battery Manufacturing. Vehicle and battery manufacturing energy consumption and emissions were evaluated with GREET 2.7a. The model performs a materials-based life-cycle inventory that captures raw material extraction, material processing, manufacturing, and disposal. The materials are evaluated by each vehicle system including body (steel, aluminum, copper/brass, magnesium, glass, plastic, rubber), powertrain system (steel, iron, aluminum, copper/brass, plastic, rubber, perfluorosulfonic acid, carbon paper, polytetrafluoroethylene, platinum), transmission system/gearbox (steel, copper, iron, aluminum, plastic, rubber), chassis (steel, iron, aluminum, copper/brass, plastic, rubber), traction motor (steel, aluminum, copper/brass), generator (steel, aluminum, copper/brass), and electronic controller (steel, aluminum, copper/brass, rubber, plastic). Similar to vehicle components, a materials-based assessment is performed for battery manufacturing, including lead-acid (plastic, lead, sulfuric acid, fiberglass, water), nickel metal hydride (NiMH) (iron, steel, aluminum, copper, magnesium, cobalt, nickel, rare earth metals, plastic, rubber), and lithium ion (Li-ion) (lithium oxide, nickel, cobalt, manganese, graphite/carbon, binder, copper, aluminum, plastics, steel, thermal insulation, electronic parts) chemistries. Lifetime vehicle fluid use is also evaluated, including ethylene glycol (engine coolant), engine oil, power steering fluid, brake fluid, transmission fluid, and methanol (windshield fluid). GREET 2.7a provides the ability to evaluate cars and sport utility vehicles, and the former was chosen for this assessment. Both a conventional internal combustion engine vehicle (CV) and an HEV were evaluated with the HEV used as a proxy for PHEV and BEV base vehicle production, prior to the batteries. For both vehicles, conventional materials were assumed (GREET 2.7a provides the ability to model lightweight materials as well) producing a 3,330 lb weight for the CV and a 2,810 lb weight for the HEV (3,200 and 2,632 lb excluding the batteries).

Although GREET models the CV with a 16-kg lead-acid battery, two alternative battery types were considered for the HEV: a 38-kg NiMH pack and a 15.3-kg Li-ion pack (both producing 23 kW peak battery power). Emissions associated with production of a single battery pack were estimated using GREET, and battery replacement frequency was adjusted as a sensitivity parameter to estimate lifetime emissions. We use the NiMH chemistry for our HEV model. To estimate emissions for the larger battery packs associated with PHEVs and BEVs, which are not available in GREET, we scale the HEV Li-ion battery pack production emissions linearly with pack weight. In particular, the PHEV and BEV designs in GREET use the Saft VL41M cell with a specific energy of 135 Wh/kg (26). We interpolate using reported battery pack energy values (26) to estimate 2010 rated pack capacity as 4.6, 15.9, and 66.1 kWh for the PHEV20, PHEV60, and BEV240, respectively (where $PHEV_x$ and BEV_x indicate vehicles with battery packs sized for x km of usable electrical energy). These packs were sized to meet the stated range on the Environmental Protection Agency's urban dynamometer driving schedule (UDDS) (real-world driving conditions will typically result in reduced range; ref. 26). We therefore estimate battery production emissions from PHEV20, PHEV60, and BEV240 by multiplying GREET HEV Li-ion production emissions by 2.23, 7.66, and 31.78, respectively.

Using material inputs, GREET 2.7a evaluates energy inputs and air emission outputs at each life-cycle stage. The results for CV, NiMH-HEV, and Li-ion-HEV are presented in Tables S1–S3. For air emissions, GHGs, VOCs, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x are reported. Tables S1–S3 summarize the final air emissions per vehicle lifetime. In each table, air emissions results are shown for battery assembly, battery upstream, vehicle assembly, and vehicle upstream groupings. The assembly life-cycle components are the final stages of manufacturing where processes materials are turned into finished products. The upstream life-cycle components include processing of raw materials into finished materials for assembly. Ultimately, when evaluating the external costs of vehicle manufacturing, emissions from vehicle and battery components are considered separately due to differences in location. Disposal and recycling emissions are excluded from the assessment due to the complexities in material reuse modeling and process uncertainty depending on secondary markets.

GREET 2.7a pulls from the GREET 1.8d fuel-cycle model to evaluate energy consumption emissions (e.g., diesel fuel combustion or electricity generation). GREET 1.8d evaluates electricity generation mixes as the percentage of oil, natural gas, coal, nuclear, biomass, and others, and hydroelectric power is assumed to be represented by the "others" category. Our base case assumes an average US grid mix for emissions associated with power generation supplied to manufacturing and upstream facilities. The low case assumes all electricity is from hydroelectric sources, and the high case assumes all electricity is from coal.

GHG emissions estimates for Li-ion batteries given by GREET are used for our base case for consistency. The GREET estimates are lower than estimates by Zackrisson et al. (45) and higher than estimates by Samaras and Meisterling (20), Majeau-Bettez et al. (46), and Notter et al. (47). Differences in study system boundaries and other input assumptions are likely responsible for the variability in the estimates. We bound these results in our sensitivity analyses through variation of grid mix supply to production facilities. Tables S1–S3 show battery and vehicle assembly and upstream emissions determined from GREET for the three vehicle and battery types of interest. Global warming potential values of 25 for CH_4 and 298 for N_2O have been used in determining CO_2 equivalence.

Petroleum Refining. The well-to-pump emissions of gasoline production are evaluated with the GREET 1.8d fuel-cycle model. GREET provides the ability to model many transportation fuel pathways, and conventional gasoline production is considered in this study. However, gasoline can be produced from a variety of sources including conventional crude and oil sands. GREET specifies that, in 2010, 9.4% of US gasoline is produced from oil sands. Oil sands extraction and processing is significantly more energy and emissions intensive than conventional crude. GREET 1.8d reports that fossil energy requirements are over twice as large for oil sands than conventional crude, greenhouse gas emissions are 1.7 times as large, and other air emissions are up to 1.2 times as large. Three pathways are considered for gasoline production: 9.4%, 0%, and 100% of crude from oil sands, with the remainder from conventional crude in each case. These three scenarios are intended to provide bounds on average and marginal units of oil, which may vary in composition of source by location and over time. The GREET fuel-cycle model includes evaluation from extraction of crude product to processing and distribution of finished gasoline product. For feedstock production, recovery is captured for conventional crude, and bitumen extraction and upgrading (including hydrogen production) are evaluated for oil sands recovery (surface mining and in situ production). The feedstock production phase also includes transport from the recovery sites to US refineries where processing to the finished gasoline product occurs. The fuel refining phase in GREET evaluates refinery energy use and processes, production of additives (if applicable), and final transport and distribution to the pump. GREET 1.8d allows for the customization of several critical input parameters that define the feedstock-to-fuel pathways. A 50/50 mix of surface mining and in situ recovery methods are assumed for oil sands. For hydrogen and steam production in oil sands recovery processes, natural gas is used. A fuel sulfur level of 26 ppm is specified and hydrogen is produced with natural gas in refinery processes. In general, GREET default US parameters for 2010 were used with customization of the share of oil sands products in crude oil feed to refineries. The emissions at each phase are shown in Table S4, with our base case highlighted.

Electricity Generation. Air emissions from electricity generation include direct emissions from combustion at the power plant and upstream emissions associated with fuel supply. We estimate direct emissions using the data from the recent NRC report on externalities of energy production (14), which in turn used the Emissions and Generation Resource Integrated Database (48). The NRC report included data on NO_x, SO_2, PM_{10}, $PM_{2.5}$, and GHGs from coal and natural gas plants, which account for 70% of US electricity generation. These data were reported as mass of pollutant per megawatt hour of electricity generated. We assume optimistically that the remaining 30% of plants produce energy with zero emissions. We also estimate upstream emission factors per unit of coal or natural gas feedstock using GREET, which provides estimates of NO_x, SO_2, CO, PM_{10}, $PM_{2.5}$, and GHGs from production, processing, and transport of coal and natural gas. These data are reported as mass of pollutant per unit of fuel energy and then converted to a per unit of output basis using the efficiency for individual power plants, as obtained from the NRC power plant data (14). The NRC report did not provide data on CO and VOC emissions from power plants. As a result, CO and VOC emissions from electricity generation in this study only include the CO and VOC emissions from the upstream stages. Electricity generation is a minor source of these pollutants: Less than 1% of national CO emissions and less than 0.5% of national VOC emissions come from power generators (49); the exclusion of direct emissions from power plants is not expected to significantly impact our results.

We compute the average emissions per kilowatt hour generated in the US by weighting emissions from each plant by its production output. Marginal emissions associated with the specific plants that supply marginal PHEV or BEV electricity demand in a particular location and in future scenarios may be higher or lower than the average grid mix. To bound these scenarios, we identify the plants with 5th, 50th, and 95th percentile damage intensity by first computing total externality damages per kilowatt hour generated from each plant, then ordering the plants by damage intensity, and finally selecting the plants associated with the 5th, 50th, and 95th percentile kilowatt hour generated by damage intensity. Because the ordering of plants depends on the value of damages assigned to GHG emissions, we compute 5th, 50th, and 95th percentile plants for each GHG damage value used in the study. Table S5 summarizes the data with our base case highlighted. The 95th percentile plant will not necessarily have higher emissions than the 50th percentile plant for each pollutant, but the overall value of damages from emissions per kilowatt hour from the 95th percentile plant are higher than damages from the 50th percentile plant.

Vehicle Use. Emissions from vehicle use depend on vehicle efficiency as well as the portion of propulsion energy powered by electricity vs. gasoline. Whereas CVs and HEVs use only gasoline for propulsion and BEVs use only grid electricity, PHEVs use some of each. After a PHEV battery is fully charged, it will operate in charge-depleting mode (CD mode) until the battery's state of charge drops to a predetermined level, at which point the vehicle switches to charge-sustaining mode (CS mode). Average propulsion energy in CS mode comes entirely from gasoline, and the vehicle operates like an HEV. In CD mode, the vehicle may have an all-electric or a blended control strategy. The all-electric control strategy takes all propulsion energy from the battery pack and consumes no gasoline in CD mode. The blended control strategy permits the vehicle to use some gasoline in CD mode where useful to improve overall efficiency. The blended strategy also allows smaller battery packs and motors to be used because they need not be sized for peak power demand.

We use midsize vehicle models defined in GREET 1.8d to estimate vehicle efficiency, vehicle emissions, and battery pack size requirements (26). The conventional vehicle is a baseline ICEV, and we do not consider advanced ICEVs in this study. The HEV is a split drivetrain with an NiMH battery and a single planetary gear set, similar to the Toyota Prius. The PHEV20 is a split drivetrain with an Li-ion battery pack sized for enough energy to support 20 km of all-electric travel on the UDDS driving cycle. The vehicle is assumed to have a blended control strategy, so CD-mode range is longer than 20 km, but the electrical system provides energy for 20 km worth of propulsion on the UDDS driving cycle. We use the efficiency values for the GREET PHEV10 (miles) as an estimate of efficiency for the PHEV20 (kilometers) in this study. The PHEV60 is a series drivetrain with an Li-ion battery pack sized to provide enough energy to support 60 km of all-electric travel. The control strategy is all-electric. We use efficiency values for the GREET PHEV40 (miles) as an estimate of efficiency for the PHEV60 (kilometers) in this study. Finally, the BEV has an Li-ion battery pack sized for 240 km (150 mi) of travel.

To estimate the portion of driving propelled by electrical power, we use the 2009 National Household Travel Survey (NHTS), which interviewed over 140,000 people across the US on details of their driving behavior on the day surveyed (50). We extracted data on total daily distance traveled over the survey population, weighted by vehicle to correct for demographic differences in the survey sample, and removed all data points with daily travel distances over 1,000 mi (1,600 km, or less than 0.1% of the data) to avoid some outlier long-trip entries with likely data entry errors. We used the remaining data to calculate the portion of distance that would be traveled in CD vs. CS mode for each vehicle, assuming one charge per day and using vehicle efficiencies estimated in GREET. All trips shorter than the CD-mode range are traveled entirely in CD mode, whereas trips longer than the CD-mode range are traveled partly in CD mode and partly in CS mode. The Argonne report (26) estimates losses associated with real-world driving, so that, even though a PHEV_x has a battery pack sized for x km of electric travel on standard test driving cycles, in practice it will experience less than x km of range due to losses associated with aggressiveness and start-stop conditions of real driving cycles (see ref. 26 for details). For the PHEV20, the CD-mode range is longer than the all-electric range (20 km) despite these losses because gasoline is also used in CD mode. For the PHEV60, the CD-mode range is shorter due to losses, which are particularly pronounced in the series drivetrain. Table S6 summarize the vehicle characteristics, Fig. S2 shows the effect of NHTS data truncation, and Table S7 summarizes lifetime energy consumption and emissions, with our base case highlighted, using the data in Table S6.

Air Emissions Externality Valuation

All monetary values in this study were converted to year 2010 US dollars using the Energy Information Administration Gross Domestic Product (GDP) Price Deflator unless otherwise noted (51). To convert the estimated air emissions to cost of damages, the Air Pollution Emission Experiments and Policy (APEEP) analysis model was used. APEEP is designed to calculate the marginal human health and environmental damages corresponding to emissions of $PM_{2.5}$, PM_{10}, VOC, NO_x, and SO_2 on a dollar-per-ton basis (52). The APEEP model evaluates emissions in each US county with its exposure, physical effects, and resulting monetary damages. APEEP evaluates emissions at different release heights: the ground-level subset is used to evaluate emissions from driving, whereas estimates at stack-height elevation are used to evaluate the emissions from electricity generation and petroleum refining. For each county and each pollutant, APEEP estimates mortality, morbidity, and environmental (e.g., visibility, crop loss, forest recreation, timber loss, materials depreciation, etc.) damages. We use APEEP costs with a statistical value of life of \$6 million ($\$_{2000}$) (52). All values in the APEEP model are given in 2000 dollars and were converted to 2010 dollars.

CO valuation is not included in the APEEP model, however, vehicles are the largest source of CO emissions in the US (49). Like PM_{10}, CO is primarily linked to cardiovascular effects, followed by secondary effects from ground-level ozone (53, 54). CO valuation costs from Matthews and Lave (55) were employed in this analysis. The median value of \$570/t of CO ($\$_{1992}$) was scaled with the PM_{10} valuation costs for each county given in the APEEP model following $CO_{county} = CO_{median} \times (PM_{county}/PM_{median})$. This value is high compared to the range of $\$_{1991}$ 10–90/t reported by Delucchi (56). The Matthews and Lave (55) range ($\$_{1992}$ 1.1–1,160/t) encapsulates Delucchi's range (56) and is less than CO control costs reported by Wang et al. (57) of $\$_{1989}$ 1,550–5340/t with a median of $\$_{1989}$ 2,950/t. GHG costs are from the NRC study and based on a literature survey and estimates from the US Interagency Working Group on Social Cost of Carbon (58). Converted to 2010 dollars, the low, medium, and high valuation of GHG emissions are \$14, \$42, and \$140 per metric ton, respectively. These costs are intended to reflect global damages, but marginal damages remain uncertain and could be larger (59). If only US-specific damages are desired, then the Interagency Working Group estimates 7–23% of the global values should be used (58).

Valuation of Vehicle and Battery Manufacturing Externalities. The vehicle and battery external cost valuation cases are based on the emissions reported in Tables S1–S3 and their potential release in automobile manufacturing-related counties for assembly and all US counties for upstream processes.

For direct emissions from vehicle and battery assembly, we estimate damages associated with the location of automobile and parts manufacturing counties identified through US census data where vehicle and parts manufacturing occurs. The use of census data, which tags facilities and employees to counties affiliated with vehicle manufacturing sectors, was originally employed by NRC (14). This approach identifies approximately 1,700 unique counties out of the roughly 3,100 in the US. Emissions from each county are weighted by the number of automotive manufacturing employees from that county, and we use the weighted average as a base case. For bounding cases, we multiply the relevant emissions by damage costs for each pollutant in each county (14, 52), order the counties by damage intensity, and take the 5th and 95th percentile weighted county as bounding cases.

Because many of the upstream emissions from vehicle and battery assembly are associated with similar processes to assembly (auto parts manufacturing, etc.), we use the same weighted 1,700 auto manufacturing counties to estimate base case upstream emissions damages. For high and low bounding estimates for upstream damages, emissions are evaluated at all of the 3,100 US counties (unweighted), and the 5th and 95th percentile counties are selected for bounding. Although it is likely that upstream processes occur outside of the US at some point in the global supply chain, the impact potential captured by evaluating all US counties includes counties with very low and high populations, which provides a reasonable estimate for bounds globally.

The APEEP unit cost data (14, 52) does not include valuation of carbon monoxide. CO valuation costs from Matthews et al. (13) were employed and for each case scaled from the median value of \$520 ($\$_{1990}$) based on the PM_{10} ratio for the particular case and its median value, as described previously. Case-specific GHG emissions were determined from the valuation literature survey performed by NRC (14). Additionally, for bounding, our low emissions case assumes that the electricity mix used to power the assembly and upstream facilities is zero emissions, whereas the high emissions case assumes the electricity is from coal. Tables S8–S11 summarize results, with our base case highlighted.

Valuation of Petroleum Refining Externalities. Similar to vehicle and battery manufacturing, gasoline production and upstream emission externality valuation are evaluated independently. The gasoline production refinery emissions are evaluated at each of the 135 petroleum refineries in the US based on NRC (14) (this approach was employed in NRC to evaluate both refinery and upstream emissions; we have chosen to evaluate the upstream independently with a different approach). At each of the refineries, the emission externality unit values are multiplied by the emissions "fuel refining" component reported in Table S4, producing a total cost at each location. Refineries are then rank ordered, and the total cost is used to determine the 5th, 50th (median), and 95th percentile cases for gasoline refining. Using the refinery operable capacities, a weighting is determined as the fraction of total US production. The weighting vector for the refineries is multiplied and then summed for each unit externality refinery cost to determine the weighted average case. The 9.4% oil sands crude share is used for the base case and the same approach described is employed when 0% or 100% oil sands cases are evaluated.

Note that the unit costs determined from APEEP for the refinery locations at each case do not change with the percentage of oil sands crude. This result is because the crude entering the refinery is effectively the same. CO_2e costs ($\$_{2010}$/t) are varied in the GHG valuation scenario at \$14 (low), \$42 (medium, base), \$140 (high), or \$0 (zero).

The values of upstream emissions prior to the petroleum refinery are estimated using several approaches. NRC (14) valued upstream emissions at gasoline refinery locations. This approach is likely an overestimate because gasoline refinery locations are often situated in or near high-population centers, where the fuel is consumed, whereas the upstream emissions for gasoline production can occur anywhere between oil production sites and the refinery. For conventional crude in the US, GREET 1.8d specifies a default of 7% of oil imported from Alaska, 8% from Canada and Mexico, 50% from offshore countries, with the remainder extracted domestically. The challenge of pinpointing where upstream emissions are occurring was managed by evaluating three scenarios. First, the 135 petroleum refinery counties were used but were assumed to overestimate impacts. Second, oil and gas extraction were assumed to occur in the same regions. Sixty percent of natural gas is produced in Louisiana, New Mexico, Oklahoma, Texas, Wyoming, and Colorado (60). The natural gas producing counties in these six states were determined, producing roughly 400 unique US counties for petroleum upstream valuation. Lastly, all 3,100 US counties were evaluated, a likely overestimate because large cities are captured in this sample where upstream processes would not occur. The second approach was chosen as the most representative for capturing the range in upstream locations. Although only US counties are considered, the range includes near-zero impact locations to high-impact locations bounding processes in non-US regions. The unit valuation costs are summarized in Table S13, with our base case highlighted.

Valuation of Electricity Generation Externalities. Power plant emission valuation was conducted using data from the NRC report (14). Valuation estimates for each power plant were available for SO_2, NO_x, PM_{10}, and $PM_{2.5}$. Upstream emissions from the production, processing and transport of coal and natural gas are also included in this analysis. The Energy Information Administration (EIA) maintains county-level coal production data (61), which was used to develop the emission costs of coal production, processing, and transport. EIA does not maintain county-level natural gas production data. County-level natural gas production data from the six top producing states (Louisiana, New Mexico, Oklahoma, Texas, Wyoming, and Colorado) were obtained from state agencies (62–67) and used to develop the costs from natural gas production, processing, and transport. These total county-level costs were rank ordered, and the 5th and 95th percentile values (based on cumulative production) for the upstream emissions were computed, as shown in Table S14. Notice that, in some cases, the value of an individual pollutant is lower in the 95th percentile value than in the 5th percentile value. The 5th and 95th percentile values were obtained using the total valuation of all pollutants, so individual pollutants may present these characteristics. It should also be noted that, because the upstream emission factors are constant for all the counties, the valuation of GHG emissions does not affect the 5th and 95th percentile values for the criteria air pollutants.

In addition to NO_x, $PM_{2.5}$ (from combustion at the power plant), SO_2, PM_{10}, and CO (for the upstream stages), we developed scenarios at different carbon costs: \$0, \$14, \$42, and \$140 per metric ton of GHG. Bounds were developed for each carbon cost scenario by aggregating the total externality costs (adding the individual pollution costs in a dollar per kilowatt hour basis) of each plant, sorting from lowest to highest, and selecting the 5th, 50th, and 95th percentile kilowatt hour generated. A weighted average plant was estimated using the percentage of electricity generated by each plant. Pollutant valuation numbers can be found in Table S15, with our base case highlighted.

Valuation of Driving Externalities. APEEP county-specific valuation data was used to determine high- and low-case scenarios for damages caused by emissions during driving (tailpipe, brake wear, and tire wear). To develop these values, an aggregated total externality value (in dollars per mile) was developed for each county using the emission factors for conventional vehicles shown in Table S7, the counties were ordered by net damage per mile, and the 5th and 95th percentile counties were used to represent low- and high-damage counties, respectively, for all vehicle types. The pollutant valuation estimates used for driving emissions can be seen in Table S16.

Oil Consumption Valuation

The US oil premium is a measure of some of the major costs to the US associated with oil consumption that are not captured in the commodity price. Leiby (68) identifies three categories of costs associated with the economic cost of importing petroleum into the US: (*i*) risk caused by potential sudden oil supply disruptions to US economic output, (*ii*) higher world oil prices resulting from US imports (monopsony), and (*iii*) the cost of existing oil security policies, such as associated military spending and maintenance of the strategic petroleum reserve. We examine each of these in turn. Leiby (68) cautions that

> The oil import premium is an informative measure of long-standing interest, but is not intended to provide complete guidance on oil security policy. The oil premium is not a measure of the full social costs of oil imports or use, or the full magnitude of the oil dependence and security problem. Rather, it is a measure of the quantifiable per-barrel economic costs which the US could avoid by a small-to-moderate reduction in oil imports.

Supply Disruptions. Sudden disruptions to the supply of oil have externality effects in the form of (*i*) reductions in US economic output resulting from higher prices of a necessary commodity, (*ii*) temporary losses associated with dislocation and lags in reallocation of resources in response to a sudden spike, and (*iii*) additional wealth transfers to foreign countries due to the spike. These costs are computed by estimating the probability of supply disruptions using historical data and the impact of supply disruptions (69). Not all of the corresponding costs are externalities. As Brown and Huntington (69) explain

> When buying oil products (or oil-using goods), individuals should recognize that possible oil supply shocks and higher prices could harm them personally. So the expected transfer on the marginal purchase is not an externality. On the other hand, individuals are unlikely to take into account how their purchases may affect others by increasing the size of the price shock that occurs when there is a supply disruption. So the latter portion is an externality.

The externality portion of these effects estimated by Brown and Huntington are shown in Table S17 (69). Leiby estimates these costs for imports at \$2.51–\$9.00/bbl with a medium estimate of \$5.40/bbl (68). We use midpoint average estimates by Brown and Huntington (69) as our base case.

Market Power. Because the US is such a large consumer of oil, accounting for 22% of world oil consumption in 2009 (70), US consumption volume has an effect on world oil prices. This effect is not an externality; however, it is an additional cost that the US has the power to control to some degree, because reduction of US imports would reduce the world price of oil, thus reducing the cost paid for remaining imports (exercising this control creates a market distortion and is generally not globally efficient). The level of price reduction depends on assumptions about market responses to reductions in US demand, including reactions by the Organization of the Petroleum Exporting Countries (OPEC). Leiby's range of estimates are \$3.35–\$21.21/bbl, with a medium estimate of \$10.26/bbl (68). We use Leiby's medium estimate as our base case.

Greene (71) also estimates excess losses during a supply disruption due to the market power of OPEC. Although these are not security externalities and do not necessarily reduce US GDP, Greene argues that they are costs to the US, in particular in terms of long-term oil independence, because the world's 10 largest oil companies own 80.6% of the world's proven reserves, and nine of the 10 are state-owned OPEC companies (71). These costs, although large, are not externality costs and are not likely to be substantially changed by marginal changes in US consumption, so we do not count separately the costs of OPEC's ability to exercise market power in our study.

Oil Security Policy. Net petroleum and petroleum product imports to the US represented about 52% of total oil consumption in 2009 (72). The US energy security issues associated with petroleum dependence typically include the costs of maintaining the strategic petroleum reserve (SPR), the potential economic threats to US national security, the use of oil supplies as leverage by external states to achieve foreign policy goals, the use of oil revenues by rouge states to pursue policies unfavorable to the US, the use of oil revenues to finance terrorism, and the military costs of defending the transportation of oil from the Persian Gulf (68, 73).

Although costs of maintaining the SPR may be considered part of oil security policy, Leiby (68) states

> While the optimal size of the SPR, from the standpoint of its potential influence on US costs during a supply disruption, may be related to the level of US oil consumption and imports, its actual size has not appeared to vary in response to recent changes in the volume of oil imports. Therefore, we adopt the [static SPR] approach and assume no change in the SPR from its current size. However, the role of the SPR in addressing shock effects and reducing disruption costs is explicitly accounted in the estimates.

Additionally, the fiscal year (FY)2010 appropriation to maintain and partially expand the SPR was \$244 million, and the SPR held 727 million barrels of oil (74). Yet, with expansion plans canceled, the FY2011 request is only \$139 million, with the FY2012 request reduced further. The high estimate of SPR maintenance costs are negligible relative to total oil expenditures and consumption. We follow Leiby's approach and ignore direct changes to SPR spending due to marginal changes in oil consumption.

The use of oil supplies as leverage by external states to achieve foreign policy goals, the use of oil revenues by rouge states to pursue policies unfavorable to the US, and the use of oil revenues to finance terrorism are difficult to quantify as damage functions. However, Crane et al. argue that the use of oil supplies as foreign policy coercion has never been successful, due to a global market for oil (73). They also argue that successful terrorist attacks can require very low financial support, so reductions in oil demand alone is unlikely to dramatically reduce this risk. Oil revenues have enhanced the capabilities for some rogue countries to pursue unfavorable policies, however the externality portion of these costs on a barrel of oil has not been estimated in the literature and is an important area for further research.

The US military provides security for oil transit in the Persian Gulf as well as protection of production facilities, oil companies, infrastructure, and regimes friendly to US oil production interests (75). Crane et al. estimated that, if all US military expenditures associated with defending the procurement and transit of imported oil from the Persian Gulf were eliminated, the budgetary savings would range between \$75.5 and \$91 billion ($\$_{2009}$) (73). Delucchi and Murphy (75) estimated the amount the US federal government would be expected to reduce its military commitment in the Persian Gulf if the US highway transportation sector did not use oil as between \$6 and \$25 billion annually, emphasizing that the "analysis is more illustrative than rigorously quantitative." Stern (76) uses a method of cost accounting for force projection in the Persian Gulf, which results in a much higher cost than previous estimates. Although military expenditures associated with oil security are large, marginal changes in oil consumption do not necessarily result in proportional reductions in military spending because military spending is likely a nonlinear function of oil consumption. Delucchi and Murphy (75) argue that marginal costs could be higher than average costs because "if the oil defense cost per gallon is proportional to the price of oil per gallon, then given that the price of oil increases with quantity, the defense cost per gallon will increase with quantity." In contrast, Brown and Huntington (69) argue "the direction of [oil security] policy is not likely to be greatly affected by marginal changes in oil consumption," and the National Research Council (14) argues "it is unlikely that whatever spending is specific to securing the [oil] supply routes would change appreciably for a moderate reduction in oil flowing from that region to the United States. [The National Highway Traffic Safety Administration (NHTSA)] rule making for CAFE standards (41) adopts a similar base case approach. In other words, several works in the literature assume the marginal cost is essentially zero," and "a twenty percent reduction in oil consumption, for example, would likely have little impact on the strategic positioning of military forces in the world." There does not appear to exist definitive data to resolve these views; however, we do not believe that the defense cost per gallon is necessarily proportional to the price of oil per gallon. Rather, we view the primarily nonlinearity as caused by economies of scale and the presence of multiple strategic objectives. Defending a region or supply route that produces even a small amount of oil requires at minimum a substantial level of infrastructure and manpower investment. If the volume of oil passing through the region or route increases slightly, marginal additional support may be required, but this would not likely be proportional to the cost required to set up the minimum initial infrastructure needed to establish a meaningful presence. Nonetheless, it is likely that the marginal attributable costs of providing security for oil supply lines, although lower than average, is not zero. We adopt Delucchi and Murphy's low estimate of average military costs (75) as our base case estimate of marginal costs, and we examine the full range, including zero marginal cost, in sensitivity.

Net oil Premium. Table S18 summarizes coproduct output from petroleum refineries in the United States. To compute the value of the oil premium to be allocated to gasoline, it is possible to conduct a system expansion to estimate the change in oil consumption in the United States caused by a reduction in gasoline consumption and the relevant effects to global oil markets, production, and consumption. This consequential analysis has been proposed by some in the life-cycle community, however its use is not agreed upon, and there are several arguments about when it is appropriate to perform consequential analysis (77). We encourage such analysis. Absent availability of such an assessment, however, it is common in life-cycle assessment studies to allocate upstream factors to downstream coproducts by mass, volume, energy, or economic value of the coproduct outputs (43). Table S18 computes allocation of the oil premium, in dollars per barrel of oil, to each coproduct output, in cents per gallon, on a mass, energy, and volumetric basis. Results for gasoline are similar across all three allocation approaches, and we select energy allocation.

Table S20 summarizes the supply disruption, monopsony, and military estimates of the oil premium using the energy-based allocation to gasoline. We use the medium estimate as our base case and examine the range in sensitivity analysis.

Vehicle Ownership Cost

We adopt the vehicle cost estimates for years 2015 and 2030 from the Argonne National Labs 2009 report on transportation futures (28), which consist of (*i*) estimates based on literature review and interviews with experts and (*ii*) targets set by the Department of Energy. The Argonne report calls the DOE targets "very optimistic." The report estimates costs associated with a variety of subsystems and assumes that retail prices are 1.5 times costs for all vehicles. Relevant factors are summarized in Table S19 with our base case highlighted. The range of price premium associated with BEVs in the ANL report span the range of estimates reviewed in ref. 6.

For use-phase energy costs, we use maximum, minimum, and average costs from 2008–2010 from the EIA. Lifetime operating costs are calculated using a nominal discount rate of $r_N = 8\%$ and assuming annual inflation price increases of $r_I = 3\%$, resulting in a real discount rate of $r_R = 4.9\%$.

For scheduled maintenance costs, we adopt estimates from Oak Ridge National Laboratory, based on prior estimates from EPRI, and we assume lifetime maintenance costs are divided evenly over the 12 y of vehicle life in order to compute net present value (78). These estimates, summarized in Table S22, are within the range of those reviewed in ref. 6.

Charger costs were estimated based on examination of unpublished data on charger installation costs from Idaho National Laboratory, Duke Energy, Coulomb Technologies, and Clean Fuel Connections. We examine only the cost of level-2 chargers because the difference in cost for installing a level-1 vs. level-2 circuit is small enough that consumers who need to install a new circuit are likely to select level 2 in many cases. We ignore the cost of workplace and public charging infrastructure and assume that all drivers charge only at home, which may underestimate costs, especially for BEVs which depend on charger availability. We assume that BEV and PHEV60 drivers will install new level-2 charging infrastructure at home to provide a sufficient charging rate to fully charge the battery overnight. We assume that half of PHEV20 drivers will use already-existing level-1 outlets at their home parking location and will not require new charging infrastructure (because level 1 provides a sufficient rate to charge the smaller battery pack in the PHEV20), whereas the other half install new level-2 lines (although level 1 is sufficient, new installations are likely to be level 2 because difference in new installation cost between level 1 and level 2 is typically small). Costs vary substantially if installation is in a single family home vs. multiunit dwelling, if an attached or detached garage or carport is present, whether an electrical panel upgrade is needed, and how much trenching, boring, concrete, and stucco work is required to complete the installation. Our assumed costs, summarized in Table S23, are intended only as a rough estimate, and more work is needed to assess average and variation in future costs of charging equipment and installation.

Detailed Results

Base Case. Our base case scenario is defined in Table S24. US average values are used for electricity grid mix, refinery direct and upstream emissions, manufacturing direct and upstream emissions, manufacturing electricity source, vehicle driving location, and gasoline and electricity prices. The medium estimate for GHG damages is used. GREET vehicle characteristics for 2010 are used, and batteries are assumed to last the life of the vehicle. The 5% best location for electricity upstream is assumed because upstream emissions from electricity are believed to be released primarily in locations farther from population centers (this assumption has a negligible effect on results). We assume 9.4% of oil supply is from oil sands because this is the current US average reported in GREET. Literature review vehicle costs for 2015 and medium estimates of the oil premium are used.

Air emissions and oil premium costs for this scenario are listed in Table S25 and displayed graphically in Figs. S3–S5. In the base case, a large portion of emissions damages are associated with vehicle operation and emissions associated with battery production are significant for BEVs. The majority of damages are caused by GHGs and SO_2 releases. Plug-in vehicles operating in all-electric mode produce no tailpipe emissions but still emit PM in tire and brake wear, thus the vehicle operation phase is not zero. SO_2 is currently capped under US law, which means that releases associated with charging electrified vehicles may be shifted from other potential demand rather than newly created. As such, it is possible that costs associated with charging PHEVs are related to compliance costs (e.g., costs to retrofit plants, shift to low-sulfur coal, or shift loads in order to comply with regulation) rather than new damages. These costs are not captured in current permit prices, which are low due to a nonbinding cap. As the cap is reduced, compliance costs will increase. The act of shifting loads to comply with emission caps may increase or decrease damages, depending on where the emissions are moved. Tracking down these shifts would be difficult. Despite these caveats, our base case provides a reasonable estimate of damages associated with the average production of electricity in the US today, and damages and compliance costs of marginal electricity production are bounded by our sensitivity cases.

Tailpipe emissions factors from GREET used in this study do not account for increases in emissions that occur over the vehicle life due to wear, poor maintenance, or deliberate tampering. Because emissions associated with electricity production are easier to police than tailpipe emissions, it is expected that average tailpipe emissions in a fleet of vehicles will be higher than those estimated based on new vehicles, depending on future laws and enforcement; however, what factor of increase is relevant and how it may vary by location and by powertrain type is not obvious. Beaton et al. (79) used on-road measurements to identify vehicles that fail emission control inspection tests (due to deliberate or unintentional tampering or missing equipment) as contributing the lion's share of emissions. Accounting for such phenomena may improve relative benefit of plug-in vehicles. Similarly, battery degradation affects electrical charge and discharge efficiency and battery power and energy capabilities over time. These effects increase electricity consumption, decrease the electrical range of vehicles, and increase the portion of trips powered by gasoline; however, these effects are likely smaller than potential increases in tailpipe emissions unless strict regulation and enforcement reduce aging issues with gasoline-powered vehicles. We leave assessment of these age-, maintenance-, and tampering-related factors for future work.

Damages associated with base vehicle production are significant but are relatively constant across vehicle types. Damages associated with battery production are significant for large battery packs in the PHEV60 and BEV240. These damages, based on GREET data, are somewhat lower than estimates from Zackrisson et al. (45) and higher than estimates from Samaras and Meisterling (20), Majeau-Bettez et al. (80), and Notter et al. (47). We use GREET as our base case for consistency and examine lower production emissions in a sensitivity analysis. Gasoline production emissions and tailpipe emissions are larger for conventional vehicles, and electricity production emissions are larger for plug-in vehicles. The majority of air emission damages from each source are caused by GHGs and SO_2; however, CO and PM have nonnegligible impact for tailpipe emissions, and PM is also important in manufacturing. The APEEP model uses a simple approach to account for secondary PM formation from VOCs (52) that recent research suggests may underestimate the secondary PM formed from motor vehicles by a factor of 10 (81). Such an increase would be significant but would not change our key conclusions.

In our base case, we consider US-specific oil premium costs together with global externality costs of GHG emissions (other air emissions costs are specific to the US, but this captures the vast majority of global damages from US emissions). Although this framing would not offer a consistent scope for a social cost-benefit analysis, we present it as the most relevant case for considering additional costs above ordinary prices that the US may wish to mitigate. In a US-specific accounting frame, the price of GHG emissions would be reduced. The interagency working group estimates that 7–23% of global damages from GHGs would occur in the US (58), thus the component of costs attributed to GHGs would be reduced by 77–93%. Such a frame would not account for global GHG damages caused by US actors. In a global accounting frame, costs to the US associated with transfers to foreign countries, such as those represented in the monopsony premium, would not be included, but benefits to and costs borne by other countries as a result of US oil consumption would need to be included. Such a frame would ignore many US financial interests of reducing petroleum consumption. Use of either of these frames would be expected to reduce the differences between the vehicle alternatives examined and further strengthen our key conclusions. We include global costs of GHG emissions and US-specific oil premium costs in our base case to express global interest in emissions damage reduction but national interest in economic losses due to oil consumption. Our sensitivity cases examine a range of GHG and oil premium costs that encompass alternative framings.

Ownership costs include the cost of purchasing the initial vehicle and battery, purchasing replacement batteries as needed over the vehicle life, purchasing fuel to operate the vehicle over its life, purchasing a charger (if relevant), and paying for scheduled maintenance. Table S26 summarizes these costs for the base case, using an 8% nominal discount rate plus 3% inflation for future gasoline and electricity purchases over a 12-y life. Our base case assumes that the battery lasts the life of the vehicle, so battery replacement costs are zero (lead-acid starter battery replacements are ignored). Fig. S6 summarizes these ownership costs plus emissions damages. Net costs of the CV, HEV, and PHEV20 are comparable, whereas vehicles with larger battery packs come at substantially higher cost.

Sensitivity Analysis. Fig. S7 summarizes a sensitivity analysis for a series of univariate parametric studies for life-cycle air emissions and oil premium costs. The base case is repeated on the left for reference, and the remaining cases show how much net increase or decrease is observed by each scenario. Power plant cases (grid mix) have a substantial impact on emissions associated with electrified vehicles. Whereas an average grid mix predicts about a \$1,000 increase in air emission and oil premium costs over the life for BEVs above those of HEVs, these BEV costs could be \$1,000 lower than HEV if electricity comes from hydroelectric sources or \$4,000 higher than HEV if electricity comes from coal. Across these cases, potential air emission and oil premium cost reduction from electrification beyond HEVs is small compared with lifetime ownership costs. If GHG emissions are valued at high (\$140/t) or low (\$14/t) levels, these costs change considerably and trends are amplified; however, differences in lifetime air emission and oil premium costs across electrified vehicles remain within \$2,000 over the life. The discount rate, which represents the rate consumers might apply to value future fees incurred from hypothetical (Pigovian) taxes on air emission externalities plus oil premium fees, also affects overall cost, with high discount rates favoring conventional and low discount rates favoring electrified vehicles. Urban driving locations, high-damage refinery locations, and higher estimates of oil disruption and monopsony premiums also improve benefits of electrification, whereas shorter battery life makes electrification worse, and varying the grid mix used to power manufacturing facilities could increase or decrease emissions associated with electrified vehicles. The remaining sensitivity cases have little effect on comparison of emissions damages across vehicles, and, across all cases, the air emission and oil premium cost reduction potential of plug-in vehicles compared to HEVs is small (or negative) compared with the cost of ownership.

Fig. S8 summarizes sensitivity analysis for a series of univariate parametric studies for net present value of lifetime ownership costs plus air emissions externality and oil premium costs. Most cases that primarily increase or decrease damages have little effect on overall cost comparisons. Reduced battery life significantly increases the cost of vehicles with large battery packs. Reduced vehicle costs, increased gasoline costs, and low discount rates create more favorable conditions for electrified vehicles. Electricity prices have little effect on lifetime costs.

We have not explicitly included a shorter-range BEV alternative in the sensitivity analysis for several reasons: First, shorter ranges for BEVs cover a smaller portion of the distribution of NHTS daily trips, so the assumption of constant driving patterns is weaker for shorter-range BEVs, and allocation of these vehicles to a specific subset of drivers and/or trips is necessary to understand their impact because they cannot function as full replacements for all primary vehicles. This limitation exists to some degree with all BEVs, but the assumption that each vehicle is allocated to an "average driver" from the NHTS data is weaker for short-range BEVs. Additionally, we aim to be consistent with our use of data sources across all vehicle types, and the ANL data are based on only one BEV with a 150-mi (240-km) pack. Shorter-range BEVs can be expected to have impact that is bounded by longer-range BEVs and the PHEV60, less its gasoline-associated impact.

We do not address externalities associated with noise and water pollution. Estimates of the value of noise and water pollution from transportation do exist in the literature (3, 5, 82), but these estimates are not sufficient to capture implications over the entire life cycle (including refineries, power plants, factories, and upstream implications), nor do they provide sufficient resolution to differentiate between the powertrain alternatives or geographic variation in this study. Litman and Doherty (82) estimate noise costs at \$0.011/mi (\$$_{2007}$) for an average car vs. \$0.004/mi for an electric car on an average driving time and location. At these rates, an electric vehicle could provide about \$800 of additional benefit over the life at our base discount rate, but this estimate does not include noise costs from power plants, refineries, factories, and other upstream factors, and it is not clear how much noise reduction value HEV and PHEVs may offer. Water pollution can also be significant. Litman and Doherty (82) estimate that water pollution costs from oil (including crankcase oil, transmission, hydraulic, brake fluid, and antifreeze) are at least \$0.014/mi for conventional vehicles and may be cut in half for electric vehicles. This estimate provides another \$800 of potential benefit but again does not account for water pollution from refineries, power plants, factories, or other upstream locations.

Conclusions and Policy Implications.

The findings in this study suggest that, using US average estimates, damages from life-cycle emissions of BEVs and PHEVs with large battery packs may be larger than damages from HEVs and PHEVs with small battery packs due largely to GHG and SO_2 emissions from electricity and battery production. Even if future marginal grid mix and battery manufacturing processes have lower emissions than today's averages, emission damage reduction potential of plug-in vehicles is small compared with ownership cost, and Pigovian taxes designed to correct for externality damages would not be expected to provide much leverage for driving the adoption of plug-in vehicles. Likewise, oil premium costs associated with gasoline consumption are significant, yet differences in these costs among vehicle alternatives remain small compared to differences in lifetime ownership costs. Therefore, electrified vehicles must offer a competitive cost of ownership before they can provide a socially efficient alternative in the United States.

BEVs have the potential to offer the greatest reduction in air emission and oil premium costs at a competitive cost of ownership if vehicle costs drop substantially, gasoline prices rise, emissions from power generation are reduced, and batteries are improved to last the life of the vehicle. As such, continued research to reduce battery cost and policy to reduce emissions from power generation are warranted. However, there is no guarantee that the necessary technical, economic, and political factors will align to achieve this optimistic future, and, in a pessimistic case, BEVs could cause more damages at substantially higher costs. In contrast, HEVs and PHEVs with small battery packs provide meaningful reductions in emission damages and oil premium costs at low (or no) additional lifetime ownership costs compared to conventional vehicles. These vehicles offer a more robust strategy to reducing emissions in the short term at lower cost and lower risk of paying high cost only to end up increasing life-cycle damages. For a given level of social spending, more damage reduction can be achieved by funding adoption of HEVs and PHEV20s than by subsidizing a smaller number of PHEV60s and BEVs. It is likely that advanced high-fuel-economy conventional vehicles, which were not examined in this study, also provide externality reductions at competitive costs. In the future, if there are sufficient decreases in battery costs, increases in gasoline prices and battery life, and reductions of emissions from the electricity grid, then policy to encourage adoption of vehicles with larger battery packs may be justified. Until then, it seems that policy focused on social welfare would be more efficient by encouraging adoption of HEVs and small-capacity PHEVs combined with policy to reduce grid emissions and support research to reduce the cost of batteries for all electrified vehicles. Of course, policies that address externalities directly (e.g., carbon taxes, cap and trade policy, and gasoline taxes) have the added benefit of encouraging consumers to purchase smaller vehicles and reduce driving, which would have benefits outside the scope of our study.

These US-specific results may not hold in other countries. For example, it is possible that in some European countries, the combination of higher gasoline prices, lower-emission electricity grid mix, greater population density (with associated emissions damage implications), greater use of diesel instead of gasoline (with associated particulate emissions), and shorter driving distances could make plug-in vehicles more attractive both for ownership costs and damage reduction, and emissions damage reduction potential could be larger in comparison to differences in ownership costs. Additionally, the externality study presented here examines only economic efficiency and does not assess equity, distributional impact, or social and environmental justice. It is possible that some policies may be warranted to manage issues with fairness in distribution of damages, rather than simply reducing damages to economically efficient levels. We also do not examine other externalities, such as congestion and accident rates, that may be affected by changes in driving behavior due to differences in vehicles (lower operating cost, reduced range, etc.).

There are several arguments that might be made for supporting adoption of BEVs and PHEVs with large battery packs despite these results. These may include the potential for greatly increased tailpipe emissions from poorly maintained vehicles or a desire for strategic positioning in the face of anticipated possible futures that may include oil scarcity, significantly higher oil prices, anticipated higher probability of supply disruptions than estimated, anticipated breakthrough battery technology, and shifts in geopolitical factors. For instance, there is concern that if shifts to electrified vehicles are in fact inevitable due to oil scarcity, development of intellectual property related to vehicle electrification within the US could position the US more favorably to compete in future markets. Also, electrified vehicles provide a mechanism for shifting away from consumption of foreign oil to consumption of domestic electricity without some of the potential difficulties in trade negotiations that would be caused by more direct efforts to shift the trade deficit. These shifts could potentially create more US jobs and could have value to the US; however, the benefits of such efforts have yet to be quantified and weighed against costs. It is our hope that the study presented here will encourage further studies to quantify such potential strategic benefits and will sharpen the discussion about the value of potential benefits of vehicle electrification and rational, strategic policy responses.

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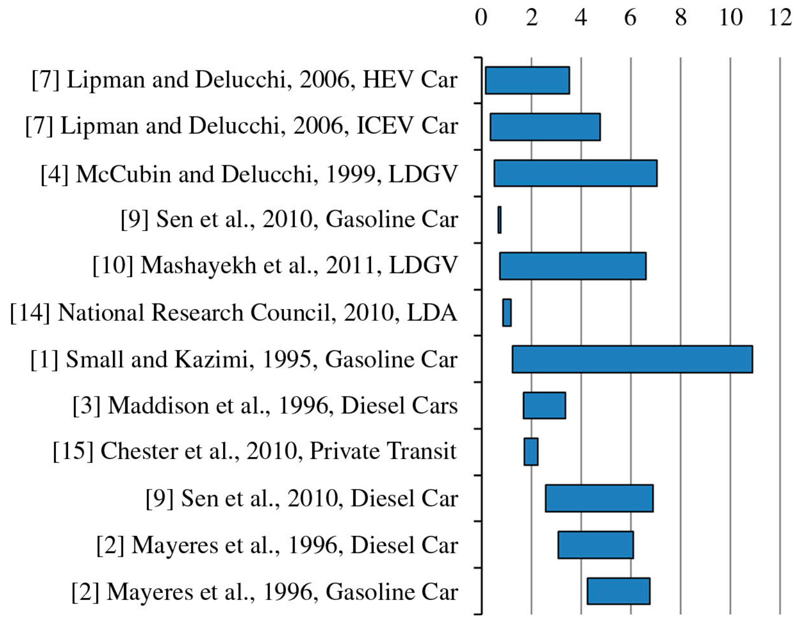

Fig. S1. Comparison of existing air pollution external damage estimates normalized to ¢$_{2010}$/VKT. (Costs are converted from their base currency and year to dollars with the following factors: 1.7 £$_{1993}$ per \$$_{1993}$, 1.3 ECU$_{1990}$ per \$$_{1990}$, 44 Rs$_{2005}$ per \$$_{2005}$.) ECU, European currency unit; LDGV, light-duty gasoline vehicle; LDA, light-duty automobile.

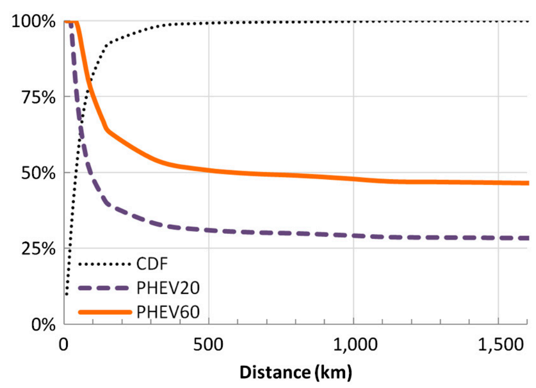

Fig. S2. Portion of distance traveled in CD-mode as a function of distance of data truncation. Cumulative distribution function (CDF) indicates portion of driving days with distance shorter than the associated distance (50).

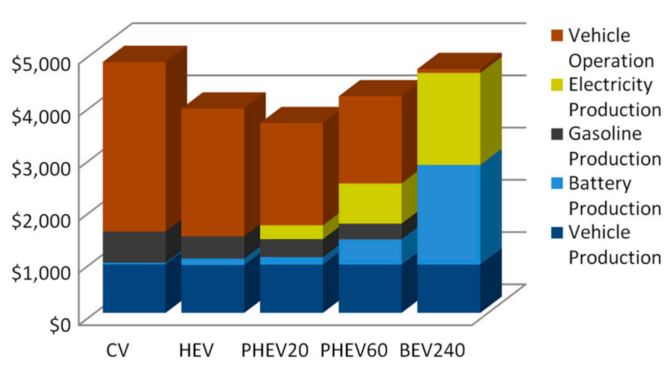

Fig. S3. Base case air emissions and oil premium costs by source (\$$_{2010}$ per vehicle lifetime). PHEV and BEV numbers indicate battery range in kilometers.

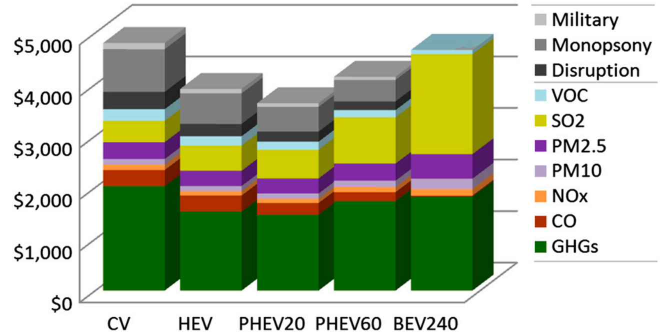

Fig. S4. Base case air emissions and oil premium costs by type ($\$_{2010}$ per vehicle lifetime). PHEV and BEV numbers indicate battery range in kilometers.

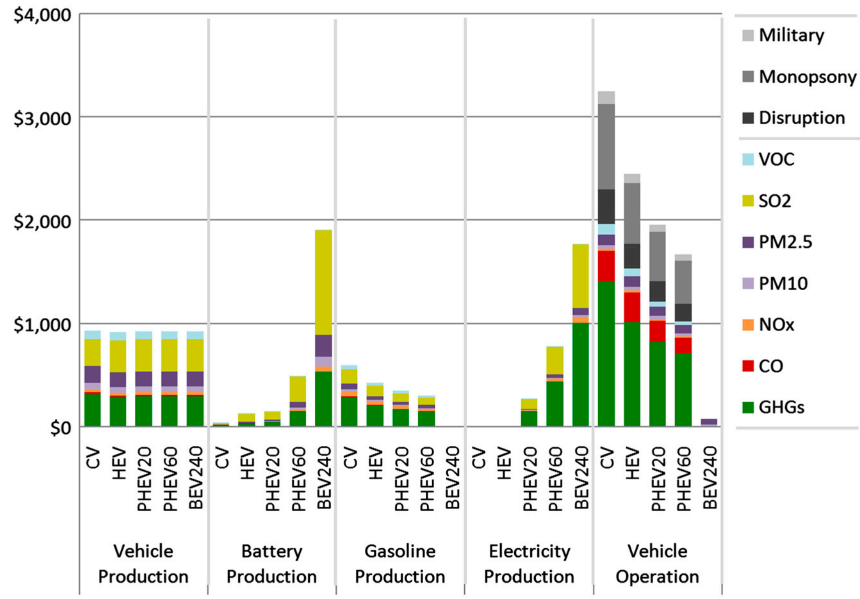

Fig. S5. Breakdown of base case air emissions and oil premium costs ($\$_{2010}$ per vehicle lifetime). PHEV and BEV numbers indicate battery range in kilometers.

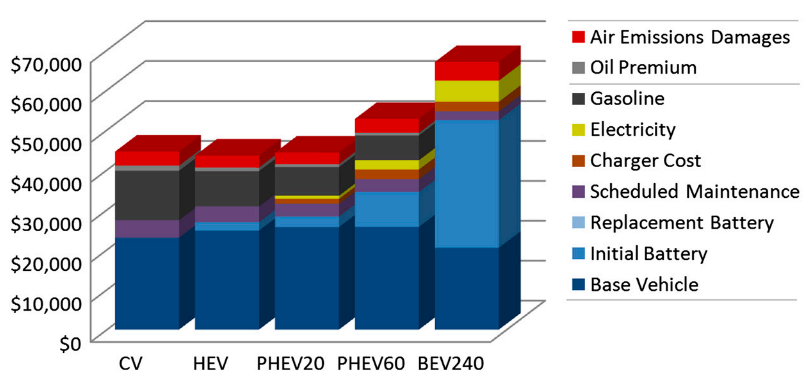

Fig. S6. Net present value of base case lifetime vehicle ownership costs plus air emissions and oil premium costs ($\$_{2010}$ per vehicle lifetime). PHEV and BEV numbers indicate battery range in kilometers.

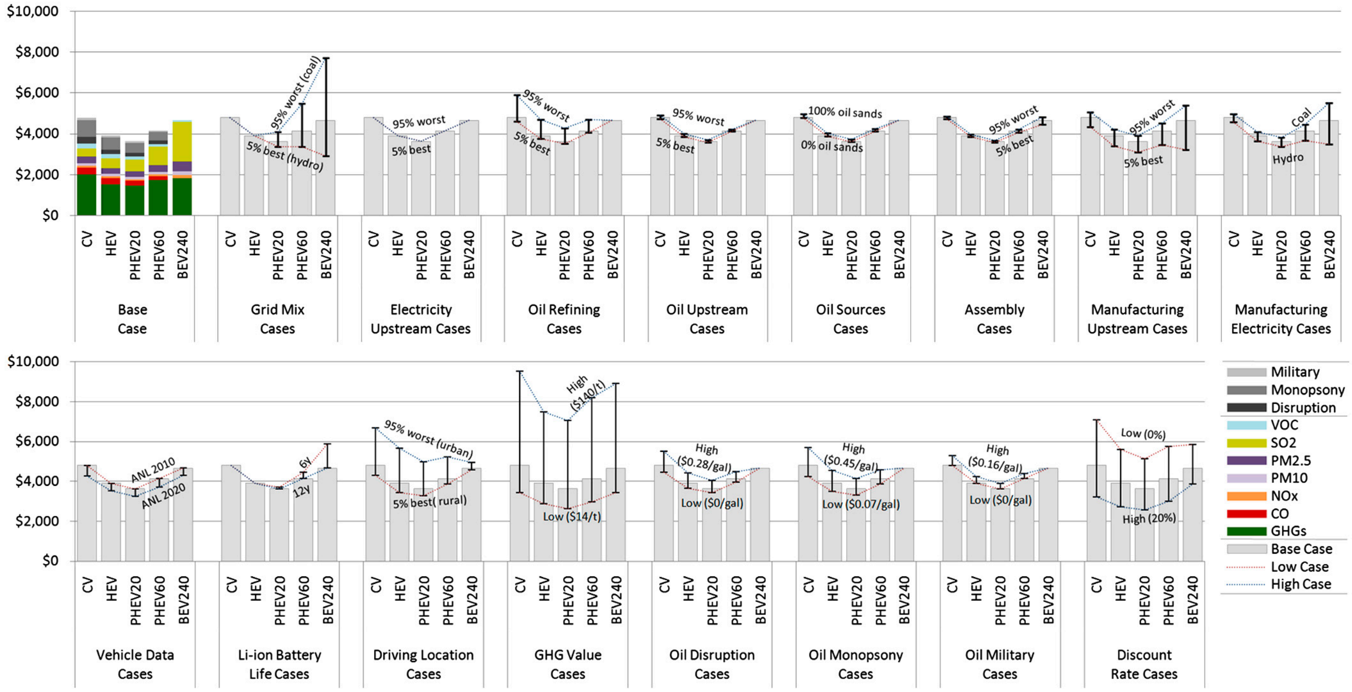

Fig. S7. Lifetime air emission and oil premium costs with sensitivity analysis ($\$_{2010}$ per vehicle lifetime). PHEV and BEV numbers indicate battery range in kilometers. (The base case shows the breakdown of emissions damages. The remaining sensitivity cases show an outline of the base case in gray with error bars displaying the change in total damages under the alternative scenarios indicated.)

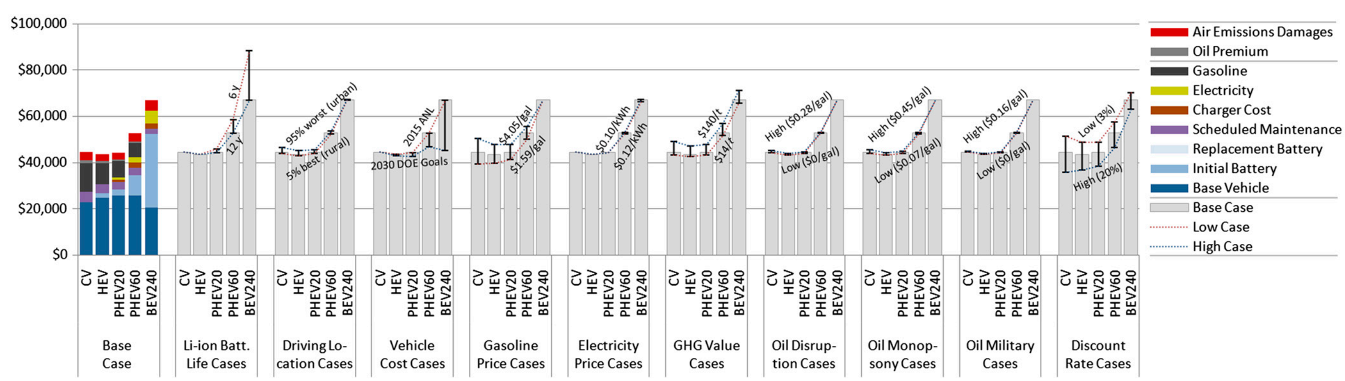

Fig. S8. Net present value of lifetime ownership costs plus air emission and oil premium costs with sensitivity analysis ($\$_{2010}$ per vehicle lifetime). PHEV and BEV numbers indicate battery range in kilometers. (The base case shows the breakdown of lifetime costs and damages. The remaining sensitivity cases show an outline of the base case in gray with error bars displaying the change in total costs under the alternative scenarios indicated.)

Table S1. Lifetime emissions (grams) summary for an ICEV with a lead-acid battery

	Battery assembly	Battery upstream	Vehicle assembly	Vehicle upstream	Total
Base case (US avg grid mix)					
CO_2	326,472	31,939	927,115	6,299,055	7,584,582
CH_4	440	101	1,582	11,032	13,154
N_2O	4.6	0.4	13	70	88
CO_2e	338,837	34,572	970,605	6,595,582	7,939,596
VOC	29	7.2	1,817	31,166	33,019
CO	87	18	362	39,473	39,941
NO_x	356	59	2,100	9,495	12,009
PM_{10}	430	119	1,511	11,039	13,099
$PM_{2.5}$	113	44	560	4,494	5,211
SO_x	782	446	2,945	17,812	21,985
Low case (hydroelectric supply)					
CO_2	0	20,758	500,209	4,462,802	4,983,768
CH_4	0	86	785	8,528	9,398
N_2O	0	0.2	4.8	43	48
CO_2e	0	22,972	521,271	4,688,758	5,233,001
VOC	0	6.2	1,778	31,002	32,787
CO	0	15	249	38,985	39,249
NO_x	0	47	1,634	7,493	9,174
PM_{10}	0	105	949	8,622	9,675
$PM_{2.5}$	0	40	464	3,873	4,377
SO_x	0	420	1,922	13,426	15,768
High case (coal electric supply)					
CO_2	522,422	38,650	1,183,441	7,401,062	9,145,574
CH_4	569	105	1,817	11,772	14,263
N_2O	5.2	0.4	14	73	92
CO_2e	538,194	41,397	1,233,111	7,717,018	9,529,721
VOC	41	7.6	1,832	31,232	33,112
CO	103	18	384	39,566	40,072
NO_x	548	65	2,351	10,575	13,540
PM_{10}	839	133	2,047	13,342	16,361
$PM_{2.5}$	218	48	645	5,065	5,975
SO_x	1,369	465	3,712	21,102	26,648

The battery assembly and upstream emissions reported are for the GREET default three batteries per vehicle lifetime.

Table S2. Lifetime emissions (grams) summary for an HEV with n NiMH battery

	Battery assembly	Battery upstream	Vehicle assembly	Vehicle upstream	Total
Base case (US avg grid mix)					
CO_2	653,892	721,252	927,115	5,654,728	7,956,987
CH_4	880	1,096	1,582	9,708	13,267
N_2O	9.3	9.6	13	63	95
CO_2e	678,657	751,511	970,605	5,916,055	8,316,828
VOC	59	78	1,817	30,952	32,905
CO	174	916	362	34,642	36,094
NO_x	713	849	2,100	8,677	12,338
PM_{10}	861	1,011	1,511	9,414	12,797
$PM_{2.5}$	227	313	560	3,873	4,973
SO_x	1,567	10,531	2,945	21,499	36,542
Low case (hydroelectric supply)					
CO_2	0	159,669	500,209	3,940,502	4,600,380
CH_4	0	342	785	7,363	8,490
N_2O	0	1.6	4.8	38	44
CO_2e	0	168,696	521,271	4,135,756	4,825,723
VOC	0	27	1,778	30,799	32,605
CO	0	766	249	34,186	35,201
NO_x	0	237	1,634	6,809	8,680
PM_{10}	0	272	949	7,157	8,378
$PM_{2.5}$	0	118	464	3,295	3,876
SO_x	0	9,187	1,922	17,401	28,510
High case (coal electric Supply)					
CO_2	1,046,359	1,058,315	1,183,441	6,683,496	9,971,612
CH_4	1,140	1,319	1,817	10,401	14,677
N_2O	10	11	14	65	101
CO_2e	1,077,950	1,094,424	1,233,111	6,963,017	10,368,502
VOC	82	98	1,832	31,014	33,025
CO	207	944	384	34,729	36,264
NO_x	1,097	1,180	2,351	9,686	14,314
PM_{10}	1,681	1,716	2,047	11,563	17,006
$PM_{2.5}$	436	493	645	4,405	5,979
SO_x	2,742	11,539	3,712	24,572	42,566

The battery assembly and upstream emissions reported are for the GREET default two batteries per vehicle lifetime. Battery values reported here are scaled for battery life sensitivity cases.

Table S3. Lifetime emissions (grams) summary for an HEV with a Li-ion battery

	Battery assembly	Battery upstream	Vehicle assembly	Vehicle upstream	Total
Base Case (US avg Grid Mix)					
CO_2	113,925	339,183	927,115	5,734,388	7,114,611
CH_4	153	530	1,582	9,847	12,113
N_2O	1.6	4.5	13	63	83
CO_2e	118,240	353,791	970,605	5,999,467	7,442,103
VOC	10	34	1,817	30,964	32,825
CO	30	103	362	35,251	35,746
NO_x	124	414	2,100	8,766	11,405
PM_{10}	150	514	1,511	9,559	11,734
$PM_{2.5}$	40	170	560	3,931	4,700
SO_x	273	2,226	2,945	21,814	27,258
Low case (hydroelectric supply)					
CO_2	0	97,016	500,209	3,995,382	4,592,607
CH_4	0	205	785	7,469	8,459
N_2O	0	1.1	4.8	38	44
CO_2e	0	102,474	521,271	4,193,458	4,817,203
VOC	0	12	1,778	30,809	32,600
CO	0	38	249	34,788	35,075
NO_x	0	151	1,634	6,871	8,656
PM_{10}	0	195	949	7,270	8,414
$PM_{2.5}$	0	86	464	3,344	3,894
SO_x	0	1,647	1,922	17,657	21,226
High case (coal electric supply)					
CO_2	182,303	484,531	1,183,441	6,778,030	8,628,306
CH_4	199	626	1,817	10,550	13,192
N_2O	1.8	4.9	14	66	87
CO_2e	187,807	501,661	1,233,111	7,061,558	8,984,138
VOC	14	43	1,832	31,027	32,915
CO	36	115	384	35,339	35,874
NO_x	191	557	2,351	9,790	12,889
PM_{10}	293	818	2,047	11,739	14,897
$PM_{2.5}$	76	247	645	4,471	5,440
SO_x	478	2,661	3,712	24,932	31,783

The battery assembly and upstream emissions reported are for the GREET default one battery per vehicle lifetime. Battery values reported here are scaled for battery life sensitivity cases.

Table S4. GREET results for conventional gasoline to US refineries (grams per million British thermal units of finished gasoline product)

	CO_2	CH_4	N_2O	CO_2e	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC	CO
0% oil sands										
Feedstock production	5,131	93	0.09	7,486	28	2.7	1.7	11	3.7	6.3
Fuel refining	11,138	14	0.15	11,536	17	4.1	2.1	12	23	5.9
Total	16,268	107	0.24	19,022	45	6.8	3.7	24	27	12
9.4% oil sands										
Feedstock production	3,956	91	0.08	6,263	28	2.6	1.6	12	3.6	6.1
Fuel refining	11,111	14	0.15	11,508	17	4.1	2.1	12	23	5.9
Total	15,068	105	0.22	17,771	46	6.7	3.7	24	27	12
100% oil sands										
Feedstock production	16,416	110	0.22	19,244	27	3.9	2.0	8.4	4.5	7.6
Fuel refining	11,392	15	0.15	11,801	17	4.1	2.1	12	23	5.9
Total	27,808	125	0.37	31,045	44	8.0	4.1	21	27	14

Table S5. Emissions from power generation (grams of pollutant per megawatt hour)

			Direct emissions					Upstream emissions						
GHG value case	Upstream location case	Net damages case	GHG, CO_2e	NO_x	PM_{10}	$PM_{2.5}$	SO_2	GHG, CO_2e	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC
Zero	5% best	5% best	0	0	0	0	0	0	0	0	0	0	0	0
Zero	5% best	50% median	894,914	1,348	188	128	329	44,349	25	139	1,622	404	68	73
Zero	5% best	95% worst	896,832	2,079	570	499	11,627	44,444	25	139	1,626	405	69	73
Zero	5% best	weighted avg	575,841	872	143	119	2,392	37,105	24	106	924	230	53	49
Zero	95% worst	5% best	0	0	0	0	0	0	0	0	0	0	0	0
Zero	95% worst	50% median	636,248	45	58	57	6	113,089	91	261	10	6	135	67
Zero	95% worst	95% worst	809,372	1,252	562	431	9,395	40,111	23	126	1,467	365	62	66
Zero	95% worst	weighted avg	575,841	872	143	119	2,392	37,105	24	106	924	230	53	49
Low	5% best	5% best	0	0	0	0	0	0	0	0	0	0	0	0
Low	5% best	50% median	1,113,857	1,810	4	4	3	114,343	92	264	10	6	137	68
Low	5% best	95% worst	901,170	1,606	382	353	10,799	44,744	25	140	1,637	407	69	74
Low	5% best	weighted avg	575,841	872	143	119	2,392	37,105	24	106	924	230	53	49
Low	95% worst	5% best	0	0	0	0	0	0	0	0	0	0	0	0
Low	95% worst	50% median	910,850	1,448	236	155	2,473	45,139	25	75	1,651	411	70	75
Low	95% worst	95% worst	1,388,666	977	233	212	4,018	68,462	39	113	2,504	623	106	113
Low	95% worst	weighted avg	575,841	872	143	119	2,392	37,105	24	49	924	230	53	49
Medium	5% best	5% best	0	0	0	0	0	0	0	0	0	0	0	0
Medium	5% best	50% median	935,561	2,427	351	214	730	46,431	26	145	1,698	423	72	77
Medium	5% best	95% worst	917,482	1,837	654	551	9,334	45,470	26	142	1,663	414	70	75
Medium	5% best	weighted avg	575,841	872	143	119	2,392	37,105	24	106	924	230	53	49
Medium	95% worst	5% best	0	0	0	0	0	0	0	0	0	0	0	0
Medium	95% worst	50% median	951,970	1,534	122	109	600	47,217	27	148	1,727	430	73	78
Medium	95% worst	95% worst	1,017,587	1,695	374	374	7,298	50,459	28	158	1,846	459	78	83
Medium	95% worst	weighted avg	575,841	872	143	119	2,392	37,105	24	106	924	230	53	49
High	5% best	5% best	0	0	0	0	0	0	0	0	0	0	0	0
High	5% best	50% median	823,780	1,584	22	10	2	147,352	119	340	12	8	176	88
High	5% best	95% worst	876,417	1,902	539	356	11,249	43,776	25	137	1,601	399	68	72
High	5% best	weighted avg	575,841	872	143	119	2,392	37,105	24	106	924	230	53	49
High	95% worst	5% best	0	0	0	0	0	0	0	0	0	0	0	0
High	95% worst	50% median	863,164	3,330	148	148	54	154,860	125	357	13	8	185	92
High	95% worst	95% worst	995,350	2,465	1,124	707	11,866	49,612	28	155	1,815	452	77	82
High	95% worst	weighted avg	575,841	872	143	119	2,392	37,105	24	106	924	230	53	49

Table S6. Portion of distance driven in CD mode

	PHEV20	PHEV60
Drivetrain	split	series
CD control strategy	blended	all-electric
CD-mode range	20.6 km	40.9 km
Portion of distance traveled in CD mode	28%	47%

NHTS data truncated at 1,000 mi (1600 km).

Table S7. Lifetime energy consumption and tailpipe emissions for each vehicle type

	Energy consumption					GHG emissions				Air pollution emissions				
Source, year	Gasoline efficiency (CS mode), mi/gal	Gasoline efficiency (CD mode), mi/gal	Electrical efficiency (CD mode), mi/kWh	Electricity use, kWh	Gasoline use, gal	CO_2, t	CH_4, t	N_2O, t	Net GHGs (CO_2e), t	CO, t	NO_x, t	PM_{10}, t	$PM_{2.5}$, t	VOC, t
CV														
GREET1.7 (2010)	23.50	—	—	0	6,383	56.1	0.0016	0.0018	56.7	0.5238	0.0104	0.0043	0.0022	0.0228
GREET1.7 (2020)	23.90	—	—	0	6,276	55.1	0.0015	0.0018	55.7	0.5190	0.0104	0.0043	0.0022	0.0225
GREET1.8d (2010)	24.81	—	—	0	6,046	53.1	0.0016	0.0018	53.7	0.5238	0.0104	0.0043	0.0022	0.0228
GREET1.8d (2015)	27.20	—	—	0	5,514	48.4	0.0016	0.0018	49.0	0.5223	0.0104	0.0043	0.0022	0.0227
GREET1.8d (2020)	29.45	—	—	0	5,094	44.7	0.0015	0.0018	45.3	0.5190	0.0104	0.0043	0.0022	0.0225
ANLWTW(2008)	28.50	—	—	0	5,262	46.2	0.0015	0.0018	46.8	0.5238	0.0104	0.0043	0.0022	0.0228
HEV														
GREET1.7 (2010)	34.78	—	—	0	4,313	37.9	0.0007	0.0018	38.5	0.5238	0.0087	0.0043	0.0022	0.0162
GREET1.7 (2020)	36.33	—	—	0	4,129	36.3	0.0007	0.0018	36.8	0.5190	0.0087	0.0043	0.0022	0.0161
GREET1.8d (2010)	34.73	—	—	0	4,319	37.9	0.0007	0.0018	38.5	0.5238	0.0087	0.0043	0.0022	0.0161
GREET1.8d (2015)	38.09	—	—	0	3,939	34.6	0.0007	0.0018	35.2	0.5223	0.0087	0.0043	0.0022	0.0161
GREET1.8d (2020)	41.23	—	—	0	3,638	32.0	0.0007	0.0018	32.5	0.5190	0.0087	0.0043	0.0022	0.0161
ANLWTW(2008)	45.10	—	—	0	3,326	29.2	0.0007	0.0018	29.8	0.5238	0.0087	0.0043	0.0022	0.0162
PHEV 20														
GREET1.7 (2010)	34.78	—	2.07	21,840	3,168	27.8	0.0005	0.0013	28.3	0.3847	0.0064	0.0040	0.0019	0.0119
GREET1.7 (2020)	36.33	—	2.11	21,475	3,033	26.6	0.0005	0.0013	27.1	0.3812	0.0064	0.0040	0.0019	0.0118
GREET1.8d (2010)	36.62	73.90	5.21	9,295	3,509	30.8	0.0005	0.0013	31.2	0.3751	0.0062	0.0039	0.0019	0.0115
GREET1.8d (2015)	42.77	76.56	5.23	9,250	3,068	26.9	0.0005	0.0013	27.4	0.3740	0.0062	0.0039	0.0019	0.0115
GREET1.8d (2020)	46.66	86.06	5.22	9,272	2,797	24.6	0.0005	0.0013	25.0	0.3717	0.0062	0.0039	0.0019	0.0115
ANLWTW(2008)	44.73	64.42	5.22	9,279	3,062	26.9	0.0005	0.0013	27.3	0.3751	0.0062	0.0039	0.0019	0.0116
PHEV 60														
GREET1.7 (2010)	34.78	—	2.07	48,427	1,774	15.6	0.0003	0.0007	15.8	0.2154	0.0036	0.0036	0.0016	0.0067
GREET1.7 (2020)	36.33	—	2.11	47,617	1,698	14.9	0.0003	0.0007	15.2	0.2135	0.0036	0.0036	0.0016	0.0066
GREET1.8d (2010)	27.65	510.23	2.90	27,312	3,039	26.7	0.0004	0.0010	27.0	0.2802	0.0047	0.0037	0.0017	0.0086
GREET1.8d (2015)	32.66	526.30	3.02	26,250	2,590	22.8	0.0004	0.0010	23.1	0.2794	0.0047	0.0037	0.0017	0.0086
GREET1.8d (2020)	35.98	529.12	3.09	25,667	2,362	20.8	0.0004	0.0010	21.1	0.2777	0.0047	0.0037	0.0017	0.0086
ANLWTW(2008)	34.22	522.05	3.02	26,245	2,479	21.8	0.0004	0.0010	22.1	0.2802	0.0047	0.0037	0.0017	0.0087
BEV 240														
GREET1.7 (2010)	—	—	2.42	70,510	0	0	0	0	0	0	0	0.0031	0.0011	0
GREET1.7 (2020)	—	—	2.46	69,330	0	0	0	0	0	0	0	0.0031	0.0011	0
GREET1.8d (2010)	—	—	2.73	62,337	0	0	0	0	0	0	0	0.0031	0.0011	0
GREET1.8d (2015)	—	—	3.08	55,301	0	0	0	0	0	0	0	0.0031	0.0011	0
GREET1.8d (2020)	—	—	3.46	49,234	0	0	0	0	0	0	0	0.0031	0.0011	0
ANLWTW(2008)	—	—	2.91	58,488	0	0	0	0	0	0	0	0.0031	0.0011	0

For GREET models, refer to ref. 25. For the ANLWTW model, refer to ref. 26.

Table S8. Vehicle assembly emissions valuation cases ($\$_{2010}$/t)

Location	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC
Base case emissions						
5% best	68	1,994	817	4,962	1,824	1,716
50% median	548	2,305	5,466	29,493	3,830	2,338
95% worst	713	3,622	7,889	60,052	18,448	3,624
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
Low emissions						
5% best	54	1,937	681	4,261	1,919	1,591
50% median	129	2,704	1,481	9,270	7,088	2,527
95% worst	760	3,200	7,979	63,770	18,209	3,281
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
High emissions						
5% best	111	752	1,134	6,050	3,033	717
50% median	120	3,149	1,425	9,739	6,875	2,703
95% worst	760	3,200	7,979	63,770	18,209	3,281
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400

CO_2e costs ($\$_{2010}$/t) are varied in the GHG valuation scenario at \$14 (low), \$42 (medium, base), \$140 (high), or \$0 (zero).

Table S9. Battery assembly emissions valuation cases ($\$_{2010}$/t)

Location	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC
Base case emissions						
5% best	79	2,380	937	5,937	1,936	2,065
50% median	134	1,543	1,546	11,730	7,829	1,497
95% worst	627	3,730	6,960	51,878	19,196	3,732
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
Low emissions						
5% best	N/A	N/A	N/A	N/A	N/A	N/A
50% median	N/A	N/A	N/A	N/A	N/A	N/A
95% worst	N/A	N/A	N/A	N/A	N/A	N/A
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
High emissions						
5% best	53	1,060	649	3,338	2,934	1,021
50% median	145	3,298	1,677	11,208	7,155	2,916
95% worst	591	9,337	6,860	47,888	17,173	8,766
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400

CO_2e costs ($\$_{2010}$/t) are varied in the GHG valuation scenario at \$14 (low), \$42 (medium, base), \$140 (high), or \$0 (zero). N/A, not applicable.

Table S10. Vehicle upstream emissions valuation cases ($\$_{2010}$/t)

Location	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC
Conventional vehicle						
Base case emissions						
5% best	49	182	637	4,127	2,720	395
50% median	109	3,021	1,426	8,158	7,131	882
95% worst	500	3,623	6,560	48,848	16,962	4,681
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
Low emissions						
5% best	49	182	637	4,127	2,720	395
50% median	111	1,561	1,458	10,667	7,018	1,039
95% worst	627	1,309	8,226	56,613	14,325	5,328
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
High emissions						
5% best	66	1,512	859	3,732	2,163	371
50% median	106	2,445	1,392	8,231	7,464	817
95% worst	643	5,158	8,426	56,061	13,066	5,508
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
Hybrid electric vehicle						
Base case emissions						
5% best	43	854	564	2,861	2,734	276
50% median	98	3,279	1,284	8,543	6,803	923
95% worst	832	4,083	10,904	65,414	10,935	6,260
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
Low emissions						
5% best	52	1,541	687	3,600	2,204	368
50% median	110	2,769	1,440	8,157	7,295	838
95% worst	643	5,158	8,426	56,061	13,066	5,508
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
High emissions						
5% best	76	1,542	999	3,870	2,113	392
50% median	96	2,705	1,261	9,378	6,842	921
95% worst	508	2,917	6,660	48,368	16,787	4,636
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
Plug-in hybrid electric vehicle						
Base case emissions						
5% best	80	971	1,044	3,887	2,357	377
50% median	98	3,279	1,284	8,543	6,803	923
95% worst	508	2,917	6,660	48,368	16,787	4,636
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
Low emissions						
5% best	55	1,776	726	4,497	1,794	452
50% median	96	2,226	1,258	9,478	7,048	956
95% worst	643	5,158	8,426	56,061	13,066	5,508
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
High emissions						
5% best	76	1,542	999	3,870	2,113	392
50% median	96	2,705	1,261	9,378	6,842	921
95% worst	508	2,917	6,660	48,368	16,787	4,636
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400

CO_2e costs ($\$_{2010}$/t) are varied in the GHG valuation scenario at \$14 (low), \$42 (medium, base), \$140 (high), or \$0 (zero).

Table S11. Battery upstream emissions valuation cases ($\$_{2010}$/t)

Location	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC
Pb acid for conventional vehicle						
Base case emissions						
5% best	74	1,534	967	3,807	2,153	389
50% median	189	2,070	2,483	16,333	6,163	1,560
95% worst	449	3,168	5,887	43,486	17,322	4,198
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
Low emissions						
5% best	66	1,512	859	3,732	2,163	371
50% median	97	2,768	1,268	8,125	6,898	863
95% worst	449	3,168	5,887	43,486	17,322	4,198
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
High emissions						
5% best	61	1,909	801	5,074	1,970	507
50% median	97	2,768	1,268	8,125	6,898	863
95% worst	449	3,168	5,887	43,486	17,322	4,198
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
NiMH battery for HEV						
Base case emissions						
5% best	60	1,435	783	3,713	2,170	368
50% median	88	2,272	1,149	7,876	6,809	774
95% worst	508	2,917	6,660	48,368	16,787	4,636
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
Low emissions						
5% best	86	2,335	1,121	6,603	2,099	670
50% median	94	2,560	1,236	8,359	6,773	827
95% worst	508	2,917	6,660	48,368	16,787	4,636
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
High emissions						
5% best	70	1,490	911	3,646	2,165	370
50% median	94	2,560	1,236	8,359	6,773	827
95% worst	468	5,435	6,135	41,304	16,818	4,182
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
Li-ion battery for PHEV						
Base case emissions						
5% best	64	1,895	838	5,319	1,963	533
50% median	85	2,206	1,117	7,744	6,910	760
95% worst	788	1,167	10,333	54,940	16,624	5,207
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
Low emissions						
5% best	60	1,435	783	3,713	2,170	368
50% median	101	2,888	1,325	9,201	6,732	919
95% worst	788	1,167	10,333	54,940	16,624	5,207
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400
High emissions						
5% best	66	1,512	859	3,732	2,163	371
50% median	280	6,610	3,676	27,241	4,210	2,610
95% worst	788	1,167	10,333	54,940	16,624	5,207
Avg all counties	184	2,009	2,418	16,241	7,131	1,579
Avg auto counties	448	2,577	4,763	31,966	12,735	2,400

CO_2e costs ($\$_{2010}$/t) are varied in the GHG valuation scenario at \$14 (low), \$42 (medium, base), \$140 (high), or \$0 (zero).

Table S12. Gasoline production refinery emissions valuation cases ($\$_{2010}$/t)

Location	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC
5% best	45	951	552	2,807	1,754	273
50% median	130	3,000	1,463	11,398	3,289	1,094
95% worst	3,828	667	39,578	235,784	144,782	21,860
Weighted avg	648	2,006	6,712	43,844	18,016	4,136

Table S13. Gasoline production upstream emissions valuation cases ($\$_{2010}$/t)

Location	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC
0% oil sands						
5% best	36	612	478	1,996	3,387	197
50% median	153	1,904	2,009	11,965	3,705	1,154
95% worst	998	5	13,091	103,298	20,948	9,812
Weighted avg	241	2,877	3,160	21,868	7,489	2,092
9.4% oil sands						
5% best	50	1,178	660	3,162	1,759	313
50% median	153	1,904	2,009	11,965	3,705	1,154
95% worst	998	5	13,091	103,298	20,948	9,812
Weighted avg	241	2,877	3,160	21,868	7,489	2,092
100% oil sands						
5% best	32	726	422	1,945	3,560	193
50% median	92	2,709	1,211	8,234	2,221	800
95% worst	549	1,374	7,197	42,517	35,894	4,035
Weighted avg	241	2,877	3,160	21,868	7,489	2,092

For each of the oil sands scenarios (0%, 9.4%, and 100%) shown, CO_2e costs ($\$_{2010}$/t) are varied in a GHG valuation scenario at $14 (low), $42 (medium, base), $140 (high), or $0 (zero).

Table S14. Valuation of upstream emissions for coal and natural gas (¢$_{2010}$/GJ of fuel)

Pollutant	Natural gas		Coal	
	Low, 5%	High, 95%	Low, 5%	High, 95%
NO_x	0.81	4.39	4.56	4.01
$PM_{2.5}$	0.00	0.00	0.00	0.00
SO_2	102.93	232.67	4.19	19.52
PM_{10}	0.00	0.00	0.06	0.33
CO	0.16	0.92	0.71	0.62

Table S15. Power plant pollutant valuation ($\$_{2010}$/MWh)

			Direct emissions						Upstream emissions							
GHG value case	Upstream location case	Net valuation case	GHG	NO_x	PM_{10}	$PM_{2.5}$	SO_2	Total	GHG	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC	Total
Zero	5% best	5% best	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zero	5% best	50% median	0.00	1.50	0.09	1.28	2.59	5.46	0.00	0.00	0.10	0.96	0.92	0.14	0.02	2.14
Zero	5% best	95% worst	0.00	4.04	0.21	3.78	73.88	81.92	0.00	0.00	0.10	0.96	0.93	0.14	0.02	2.15
Zero	5% best	weighted avg	0.00	1.37	0.07	1.20	15.50	18.14	0.00	0.00	0.08	0.55	0.53	0.13	0.01	1.29
Zero	95% worst	5% best	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zero	95% worst	50% median	0.00	0.04	1.23	19.68	1.36	22.31	0.00	0.02	1.01	0.03	0.11	0.56	0.12	1.84
Zero	95% worst	95% worst	0.00	1.55	0.36	5.80	76.61	84.32	0.00	0.01	0.19	5.29	9.58	0.76	0.17	15.98
Zero	95% worst	weighted avg	0.00	1.37	0.07	1.20	15.50	18.14	0.00	0.00	0.07	0.67	0.65	0.10	0.01	1.50
Low	5% best	5% best	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low	5% best	50% median	15.49	3.82	0.00	0.02	0.01	19.34	1.59	0.00	0.18	0.01	0.01	0.45	0.02	2.26
Low	5% best	95% worst	12.54	3.24	0.15	2.92	75.73	94.57	0.62	0.00	0.10	0.97	0.93	0.14	0.02	2.79
Low	5% best	weighted avg	8.01	1.37	0.07	1.20	15.50	26.15	0.52	0.00	0.08	0.55	0.53	0.13	0.01	1.81
Low	95% worst	5% best	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low	95% worst	50% median	12.67	1.10	0.03	0.31	5.12	19.23	0.63	0.01	0.21	5.95	10.78	0.85	0.19	18.61
Low	95% worst	95% worst	19.32	2.71	0.34	7.07	54.37	83.81	0.95	0.01	0.32	9.02	16.35	1.29	0.28	28.23
Low	95% worst	weighted avg	8.01	1.37	0.07	1.20	15.50	26.15	0.43	0.00	0.07	0.67	0.65	0.10	0.01	1.93
Medium	5% best	5% best	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Medium	5% best	50% median	39.04	3.18	0.07	0.68	2.30	45.27	1.94	0.00	0.11	1.01	0.97	0.15	0.02	4.18
Medium	5% best	95% worst	38.29	3.19	0.29	5.03	71.97	118.77	1.90	0.00	0.11	0.99	0.95	0.14	0.02	4.10
Medium	5% best	weighted avg	24.03	1.37	0.07	1.20	15.50	42.17	1.55	0.00	0.08	0.55	0.53	0.13	0.01	2.84
Medium	95% worst	5% best	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Medium	95% worst	50% median	39.73	2.05	0.02	0.30	2.55	44.65	1.97	0.01	0.22	6.22	11.28	0.89	0.20	20.78
Medium	95% worst	95% worst	42.47	2.22	0.30	5.70	66.13	116.81	2.11	0.01	0.24	6.65	12.05	0.95	0.21	22.21
Medium	95% worst	weighted avg	24.03	1.37	0.07	1.20	15.50	42.17	1.29	0.00	0.07	0.67	0.65	0.10	0.01	2.79
High	5% best	5% best	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
High	5% best	50% median	114.59	3.36	0.02	0.23	0.02	118.22	20.50	0.00	0.23	0.01	0.02	0.57	0.02	21.36
High	5% best	95% worst	121.91	2.45	0.30	4.07	84.68	213.41	6.09	0.00	0.10	0.95	0.91	0.14	0.02	8.21
High	5% best	weighted avg	80.10	1.37	0.07	1.20	15.50	98.24	5.16	0.00	0.08	0.55	0.53	0.13	0.01	6.45
High	95% worst	5% best	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
High	95% worst	50% median	120.07	8.14	0.06	1.41	0.38	130.07	21.54	0.03	1.38	0.03	0.15	0.76	0.16	24.06
High	95% worst	95% worst	138.46	2.02	0.40	5.60	66.29	212.76	6.90	0.01	0.23	6.54	11.85	0.94	0.21	26.67
High	95% worst	weighted avg	80.10	1.37	0.07	1.20	15.50	98.24	4.31	0.00	0.07	0.67	0.65	0.10	0.01	5.81

Table S16. Driving pollutant valuation ($\$_{2010}$/t)

Pollutant	Base case, weighted avg	Low damages, 5% best-rural	High damages, 95% worst-urban
VOC	7,159	364	16,110
NO_x	3,445	1,160	9,232
$PM_{2.5}$	75,850	3,729	171,208
SO_2	25,512	2,173	40,857
PM_{10}	11,644	786	25,812
CO	886	298	2,374

Table S17. Externality costs due to supply disruption ($\$_{2010}$/bbl) (69)

	Domestic			Imports			Avg		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
GDP loss	0.81	3.84	11.24	1.08	5.13	14.85	0.95	4.51	13.11
Transfers	−0.61	−0.88	−2.07	0.07	0.12	0.26	−0.96	−0.37	−0.16
Total	0.20	2.96	9.16	1.16	5.24	15.01	−0.01	4.15	12.96

Table S18. Externality allocation to refined petroleum products (1)

	Volumetric yield (gal output/bbl oil input)	Fraction of output			¢/gal output per $/bbl oil input		
		Mass, %	Energy, %	Volume, %	Mass	Energy	Volume
Liquefied refinery gases	1.764	2.66	2.58	3.94	1.51	1.46	2.23
Finished motor gasoline	19.404	39.83	41.26	43.34	2.05	2.13	2.23
Finished aviation gasoline	0.042	0.08	0.09	0.09	1.97	2.04	2.23
Kerosene-type jet fuel	3.906	8.63	8.97	8.72	2.21	2.30	2.23
Kerosene	0.042	0.10	0.10	0.09	2.27	2.30	2.23
Distillate fuel oil	11.256	26.42	26.54	25.14	2.35	2.36	2.23
Residual fuel oil	1.680	4.42	4.28	3.75	2.63	2.54	2.23
Naphtha for petrochemical feedstock use	0.462	0.98	0.98	1.03	2.13	2.12	2.23
Other oils for petrochemical feedstock use	0.420	0.89	0.89	0.94	2.13	2.12	2.23
Special naphthas	0.084	0.18	0.18	0.19	2.13	2.12	2.23
Lubricants	0.420	1.05	1.03	0.94	2.50	2.46	2.23
Waxes	0.042	0.09	0.09	0.09	2.22	2.24	2.23
Petroleum coke	2.226	7.07	5.43	4.97	3.18	2.44	2.23
Asphalt and road oil	1.008	2.91	2.71	2.25	2.89	2.69	2.23
Still gas	1.806	4.22	4.39	4.03	2.33	2.43	2.23
Miscellaneous products	0.210	0.46	0.49	0.47	2.18	2.35	2.23

Barrels, bbl.

1 US Energy Information Administration (2010) *Petroleum and Other Liquids: Refinery Yield.* (US Energy Information Admin, Washington, DC).

Table S19. Vehicle production and retail cost ($\$_{2010}$)

	Vehicle total cost					High voltage battery system cost				
	CV	HEV	PHEV20	PHEV60	BEV	CV	HEV	PHEV20	PHEV60	BEV
2015 literature review	15,346	17,912	18,865	22,973	35,771	0	1,379	1,755	5,820	21,302
2015 DOE goals	15,346	17,227	18,023	20,459	26,099	0	689	1,096	3,492	11,835
2015 literature review retail	23,019	26,868	28,298	34,459	52,450	0	2,068	2,632	8,730	31,953
2015 DOE goals retail	23,019	25,841	27,034	30,688	39,148	0	1,033	1,645	5,239	17,752
2030 literature review	15,346	18,184	18,882	21,619	28,165	0	956	1,170	3,873	13,479
2030 DOE goals	15,346	16,095	16,377	17,571	18,998	0	503	479	1,652	6,221
2030 literature review retail	23,020	27,276	28,323	32,429	42,247	0	1,434	1,755	5,809	20,218
2030 DOE goals retail	23,020	26,214	26,638	28,427	30,568	0	755	719	2,479	9,332

Table S20. Oil premium ($\$_{2010}$/gal)

	Low case	Base case	High case
Supply disruption	0.00	0.09	0.28
Monopsony premium	0.07	0.22	0.45
Military spending	0.00	0.03	0.16
Total	0.07	0.34	0.89

Table S21. Operating Costs

	Gasoline, $/gal	Electricity, $/kWh
Min 2008–2010	1.590	0.1015
Avg 2008–2010	2.751	0.1138
Max 2008–2010	4.054	0.1206

Table S22. Scheduled maintenance costs ($\$_{2010}$/gal per vehicle life)

	CV	HEV	PHEV	BEV
Lifetime oil change cost	1,486	1,413	926	0
Lifetime air filter replacement costs	117	154	77	0
Lifetime spark plug replacement costs	139	47	0	0
Lifetime timing chain adjustment costs	116	116	0	0
Lifetime front brake replacement costs	867	578	578	578
Additional scheduled maintenance costs	1,655	1,655	1,655	1,655
Total	4,380	3,962	3,235	2,232

Table S23. Charger costs (level 2) ($\$_{2010}$ per vehicle life)

	Equipment	Installation	Total
Low case	500	970	1,470
Base case	900	1,500	2,400
High case	2,500	4,000	6,500

Table S24. Base case scenario

Factor		Scenario
Electricity	grid mix	weighted avg
	upstream location	5% best
Gasoline	refining location	weighted avg
	upstream location	weighted avg
	upstream counties	oil/gas counties
	oil source	9.4% oil sands GREET
Mfg.	assembly location	weighted avg
	upstream location	weighted avg auto mfg. counties
	electricity supply	US avg grid mix
Vehicle	data source	GREET1.8d (2010)
	tailpipe location	weighted avg
	NiMH battery life	12 y
	Li-ion battery life	12 y
Costs	vehicle price	ANL 2015 literature review (retail)
	gasoline price	avg 2008–2010 ($2.75/gal)
	electricity price	avg 2008–2010 ($0.114/kWh)
	charger cost	medium
Valuation	oil supply disruption	medium ($0.09/gal)
	oil monopsony	medium ($0.22/gal)
	oil military premium	medium ($0.03/gal)
	GHG valuation	medium ($42/t)

Table S25. Summary of base case air emission and oil premium costs ($\$_{2010}$ per vehicle lifetime)

	Air emissions							Oil premium			Total
	GHGs	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOC	Disruption	Monopsony	Military	
CV											
Vehicle production	316	18	30	60	162	264	79				928
Battery production	12	0	1	2	4	12	0				30
Gasoline production	290	2	51	16	56	137	45				597
Electricity production	0	0	0	0	0	0	0				0
Vehicle operation	1,408	292	22	31	106	0	102	335	829	120	3,246
Total	2,025	312	104	109	327	413	227	335	829	120	4,802
HEV											
Vehicle production	287	16	28	52	142	311	79				915
Battery production	30	0	2	4	9	77	0				122
Gasoline production	207	2	36	11	40	98	32				426
Electricity production	0	0	0	0	0	0	0				0
Vehicle operation	1,009	292	19	31	106	0	72	239	592	86	2,447
Total	1,533	310	85	99	296	486	183	239	592	86	3,910
PHEV20											
Vehicle production	291	16	28	53	144	315	79				925
Battery production	44	0	3	7	15	71	0				141
Gasoline production	168	1	30	9	33	79	26				346
Electricity production	149	0	8	4	10	91	0				263
Vehicle operation	819	209	13	29	91	0	52	194	481	70	1,958
Total	1,471	227	83	101	292	557	157	194	481	70	3,633
PHEV60											
Vehicle production	291	16	28	53	144	315	79				925
Battery production	151	0	11	24	51	244	1				482
Gasoline production	146	1	26	8	28	69	23				300
Electricity production	439	0	25	11	30	268	0				772
Vehicle operation	708	156	10	27	81	0	39	168	417	60	1,666
Total	1,734	174	99	123	333	896	141	168	417	60	4,146
BEV240											
Vehicle production	291	16	28	53	144	315	79				925
Battery production	532	2	44	101	213	1,012	3				1,906
Gasoline production	0	0	0	0	0	0	0				0
Electricity production	1,001	0	57	24	68	612	0				1,762
Vehicle operation	0	0	0	22	52	0	0	0	0	0	75
Total	1,824	18	129	200	476	1,939	82	0	0	0	4,667

Table S26. Lifetime ownership costs ($\$_{2010}$ per vehicle lifetime)

	CV	HEV	PHEV20	PHEV60	BEV
Base vehicle cost	23,019	24,800	25,666	25,729	20,497
Initial battery cost	0	2,068	2,632	8,730	31,953
Battery replacement cost	0	0	0	0	0
Gasoline cost	12,386	8,847	7,189	6,226	0
Electricity cost	0	0	788	2,314	5,282
Scheduled maint.	4,380	3,962	3,235	3,235	2,232
Charger/instl.	0	0	1,200	2,400	2,400
Net cost	39,786	39,677	40,709	48,635	62,364