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Cost-effectiveness of plug-in hybrid electric vehicle battery capacity and charging infrastructure investment for reducing US gasoline consumption

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HIGHLIGHTS

- ► We compare cost of PHEV batteries vs. charging infrastructure per gallon of gasoline saved.
- ► The lowest cost solution is to switch more drivers to low-capacity PHEVs and HEVs.
- ► If more gasoline savings is needed, batteries offer a better value than chargers.
- ► Extra batteries & chargers are both more costly per gal than oil premium estimates.
- ► Current subsidies are misaligned with fuel savings. We discuss alternatives.

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ABSTRACT

Federal electric vehicle (EV) policies in the United States currently include vehicle purchase subsidies linked to EV battery capacity and subsidies for installing charging stations. We assess the cost-effectiveness of increased battery capacity vs. nondomestic charging infrastructure installation for plug-in hybrid electric vehicles as alternate methods to reduce gasoline consumption for cars, trucks, and SUVs in the US. We find across a wide range of scenarios that the least-cost solution is for more drivers to switch to low-capacity plug-in hybrid electric vehicles (short electric range with gasoline backup for long trips) or gasoline-powered hybrid electric vehicles. If more gasoline savings are needed per vehicle, nondomestic charging infrastructure installation is substantially more expensive than increased battery capacity per gallon saved, and both approaches have higher costs than US oil premium estimates. Cost effectiveness of all subsidies are lower under a binding fuel economy standard. Comparison of results to the structure of current federal subsidies shows that policy is not aligned with fuel savings potential, and we discuss issues and alternatives.

1. Introduction

US interest in federal policy to reduce gasoline consumption in the transportation sector began in response to the Arab oil embargo of the 1970s. The 1975 Energy Policy Conservation Act created corporate average fuel economy (CAFE) standards to mandate increases in the efficiency of the vehicle fleet by setting efficiency standards for passenger cars starting in 1978 (Energy Policy and Conservation Act, 1975). Efficiency requirements initially increased annually until 1985, but standards for cars remained static until further legislation was passed. In 2007 the Energy Independence and Security Act set a target of 35 mpg for combined car/truck fuel economy by model year 2020 (which has since been moved to 2016 (EPA and NHTSA, 2011)), but it stipulated penalties only if manufacturers fell below 92% of the standard (Energy Independence and Security Act of 2007, 2007). The standard allows manufacturers to trade credits, and it was implemented using formulas tied to vehicle footprint, rather than direct averages of corporate fleets (Whitefoot and Skerlos, 2012). The act also provided loan guarantees for advanced battery research and grant programs for plug-in hybrid electric vehicles (PHEVs, which use a mix of electricity and gasoline) and battery electric vehicles (BEVs, which use electricity only and have no gasoline backup) to help make them economically feasible as mass market vehicles.

At the end of 2010 General Motors introduced a PHEV called the Volt, Nissan introduced a BEV called the Leaf, and other automakers have also begun to offer PHEV and BEV models—collectively referred to here as electric vehicles (EVs). These types of vehicles use grid electricity to displace gasoline.

In August 2012 the National Highway Traffic Safety Administration (NHTSA) finalized rules pushing CAFE standards higher to

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40.3 mpg by 2021 and 48.7 mpg by 2025 (EPA and NHTSA, 2012). In addition to CAFE standards the Environmental Protection Agency (EPA) released greenhouse gas (GHG) standards of 163 g/mile by 2025 that will match (these values correspond with 54.5 mpg, but the EPA expects other improvements such as a decrease in coolant leakage to reduce GHG emissions) (EPA and NHTSA, 2012). The EPA standards include a number of incentives to encourage the use of "game changing" technologies (EPA and NHTSA, 2012). These incentives begin with "off cycle" credits for model year (MY) 2012–2016 vehicles that implement specific technologies. Alternative fuel vehicles such as PHEVs are permitted a multiplier for model years 2017–2021 in the GHG calculations (EPA and NHTSA, 2012). The rule also treats emissions from electric travel as 0 g/mile in model year 2022–2025.[1] Thereafter upstream fuel emissions will be taken into account (EPA and NHTSA, 2012).

While BEVs may seem to be the most complete solution to displacing gasoline with electricity, there are significant drawbacks. Among them are range and refueling constraints. High rate charging for the Nissan Leaf allows the battery to be charged to 80% in 30 min at a specialized high-voltage charging station (Witkin, 2012). Despite being many times faster than a typical home charger, this rate is still slow compared to refilling a gas tank and requires new infrastructure. On a long trip, this would mean stopping every 60 miles for approximately 30 min and would require changes in infrastructure (such as new transmission, sub-transmission, and distribution lines) (Lemoine et al., 2008; Hadley and Tsevetkova, 2008; Peterson et al., 2011; Lemoine et al., 2008). While BEVs may function well for some applications, they are not an adequate replacement for most primary vehicles unless a secondary vehicle is available to be used for longer trips. We focus on PHEVs because they can more easily replace current vehicles and can benefit from availability of public charge points without being dependent on them.

PHEVs act like gasoline-powered hybrid electric vehicles (HEV), such as the Toyota Prius, by using a battery as a buffer to store braking energy and improve engine efficiency. But PHEVs have the additional ability to store electricity from the grid onboard and use it to displace gasoline while driving. PHEV drivers will not need to change their habits. Long trips can still be taken using gasoline, while short trips can be powered mostly or entirely using electricity. These advantages do not come without a penalty. PHEVs require both an internal combustion engine (ICE) and a substantial battery pack. Because of this, a PHEV designed for 40 miles of electric range will weigh and cost more than a BEV with similar range or a conventional vehicle with similar performance and interior space.

To help overcome obstacles to EV adoption, policymakers have provided purchase incentives based on battery size and incentives for installation of charging infrastructure. The American Recovery and Reinvestment Act of 2009 provides a tax credit of $2500 per plug-in hybrid electric vehicle sold (requires at least 4 kWh battery capacity) and an additional $417 for each additional kWh of battery capacity in excess of 4 kWh (capped at $7500 for vehicles with a gross vehicle weight less than 14,000 lb) (The American Recovery and Reinvestment Act of 2009, 2009). This subsidy for a specific manufacturer's vehicles declines to 50% then 25% in a phaseout period, which begins in the second calendar quarter after that manufacturer has sold 200,000 vehicles and lasts four calendar quarters (The American Recovery and Reinvestment Act of 2009, 2009).

The US Department of Energy (DOE) also granted $37 million for installing 4600 charge points in specific markets around the nation (over $8000 per charge point) (Dogget, 2011) and granted $99.8 million to fund the EVProject, which is installing 14,000 level 2 (208–240 V) chargers and a variety of other infrastructure and monitoring equipment (Advanced Vehicle Testing Activity, 2011). While BEVs require a large number of charge points in order to act as primary vehicles, PHEVs can benefit from a smaller number: charge points could help small-battery PHEVs displace a greater amount of gasoline.

We examine the strategies of subsidizing EV battery capacity and charging infrastructure installation by assessing cost-effectiveness of each approach for reducing US gasoline consumption under a range of scenarios.

2. Methodology

To estimate costs and gasoline savings of each approach, we first calculate gasoline and electricity use by PHEVs of varying battery capacity under a range of charging scenarios. Second, we estimate the necessary charging infrastructure to enable each charging scenario. Finally we use estimates of cost and gasoline displacement to compare across options. We discuss each in turn.

2.1. Fuel use model

This work uses two main data sources. The first is the National Household Travel Survey 2009 (NHTS) which includes travel information from diaries of over 150,000 households (National Household Travel Survey, 2010). The NHTS day trip file lists trips taken by each household on a randomly-assigned day. The second data source is the Department of Energy's Greenhouse Gasses, Regulated Emissions, and Energy Use in Transportation (GREET) model, version1.8d (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, 2010). The GREET model assesses energy use in transportation and includes simulations for passenger cars, SUVs, and light trucks with over 80 fuel systems and technologies. We use GREET 1.8d estimates of year 2015 vehicle efficiency in charge depleting (CD) and charge sustaining mode (CS). Combining these efficiency numbers with vehicle travel patterns from the NHTS day trip file allows the prediction of estimated gasoline and electricity consumption from a set of PHEVs, with designs that span battery capacity values producing all-electric range (AER) values from 5 to 60 miles. Base case assumptions are described below and summarized in Table S.39 of the supporting information.

The GREET model assumes that PHEVs with AER less than or equal to 25 miles utilize a split powertrain and blended control strategy, while PHEVs with AER in excess of 25 miles utilize a serial hybrid design, which is far less efficient in charge sustaining mode (the Chevy Volt with AER of 35 does not use a serial design (Markus, 2010)). This assumption causes the model to predict lower efficiency for vehicles with AER over 25 miles (as shown later in Fig. 3). To avoid the serial powertrain assumption, we consider only AER of 25 miles or less. Our results shown later suggest that AER values above 30 miles are not competitive with the shorter AER ranges on a cost per gallon saved metric regardless of powertrain assumption across all sensitivity scenarios.

The NHTS data were processed following (Peterson et al., 2011) with several modifications described below (Fig. 1). The daily vehicle travel data were extracted and weighted according to the vehicle weights assigned in the sample. To estimate the timing of fuel savings, vehicles are partitioned by age and vehicle class because their travel varies significantly along both dimensions (Figs. 2–3). They are further partitioned into trips taken on

[1] This incentive is for PHEVs, BEVs, or fuel cell vehicles and covers the first 200,000 vehicles for all manufacturers and 600,000 vehicles for those that sell 300,000 such vehicles in the 2019–2021 timeframe (EPA and NHTSA, 2012).

weekdays and weekends and then the results are weighted by the number of weekend (104) and weekdays (261) in the year (see Eq. (1)). The trip chain and the resulting total distance traveled in CD and CS mode for each vehicle under each charging strategy scenario is averaged over the vehicles within each class and age and within each weekend or weekday group in the NHTS data set. This approach represents the driving patterns of an aggregate US vehicle for each class and age, and we do not examine heterogeneity for different vehicles that have different driving patterns within each class-age group (Raykin et al., 2012; Shiau et al., 2009; Neubauer et al., 2012; Traut et al., 2012). Changes in efficiency and AER as vehicles age were ignored. In practice, PHEV battery capacity will decline with age, which would shorten AER; however, vehicles are typically designed to use only a portion of the battery's available energy, in part to delay reduction in AER perceived by the consumer. Whether PHEVs will encounter more or less engine wear than conventional vehicles (CVs) depends on how PHEVs use their engines. If the engine speed is partially decoupled from the wheel speed using the electric motor to compensate, this could prolong engine life by enabling the engine to run mostly at steady state, but if the engine starts and stops often and revs to follow vehicle power demand then engine wear could increase. We consider cars, SUVs, and trucks (vans were ignored because data were unavailable for efficiency and cost, but they make up the smallest portion of the classes mentioned here). The energy consumption of each vehicle in the sample is calculated assuming vehicles began each day fully charged and charge completely after the last trip of the day. Several charging scenarios were included to determine how much additional gasoline could be displaced with electricity by also charging vehicles at work or also at every location where the vehicle parked for at least 30 min. Table 4 describes these charging scenarios.

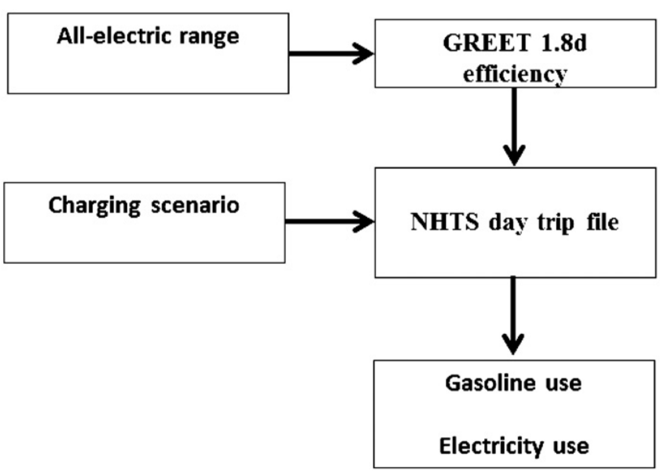

Fig. 1. Basic fuel use model overview.

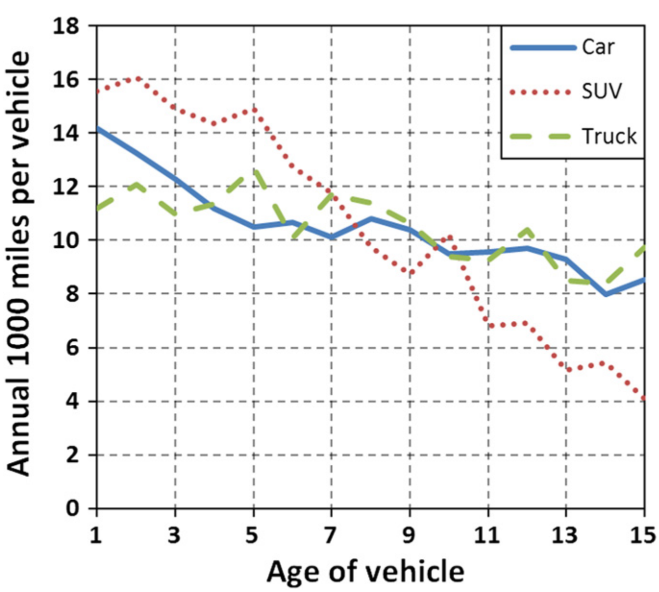

Fig. 2. Change in annual VMT with vehicle age as found from NHTS data.

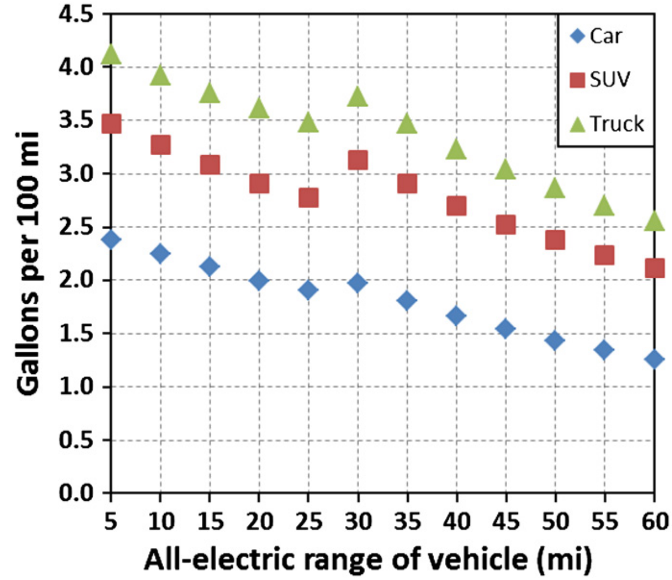

Fig. 3. Gasoline consumption over a 12 year life for vehicles of various AER using GREET 1.8d 2015 efficiency estimates. AER corresponds to GREET AER. Gasoline use includes both CD and CS travel. The increase at AER of 30 is due to the assumption in GREET that PHEVs with AER above 25 have a series drivetrain rather than a split drivetrain.

Specifically, the total electricity use f^{ELEC} and gasoline use f^{GAS} are calculated for each vehicle class c, vehicle age a (years), vehicle AER β (miles), and charging scenario γ. For each case, we compute average distances traveled in CD and CS modes separately for weekday (WD) vs. weekend (WE) data, and we use these averages to compute annual and total distances, as shown in Eq. (1), where L is the vehicle life (12 years base case), j indexes the vehicle driving profiles taken from the NHTS day trip file, $J_{a,c,\mathrm{WE}}$ is the set of NHTS vehicle profiles of age a and class c surveyed on a weekend, $J_{a,c,\mathrm{WD}}$ refers to those surveyed on a weekday, $|J_{a,c,\mathrm{WE}}|$ is the number of NHTS vehicles of age a and class c surveyed on a weekend, $|J_{a,c,\mathrm{WD}}|$ is the number of vehicles of age a and class c surveyed on a weekday, and $\eta^{\mathrm{CD\text{-}E}}$, $\eta^{\mathrm{CD\text{-}G}}$, and $\eta^{\mathrm{CS\text{-}G}}$ are the vehicle's electrical efficiency in CD mode (mi/kWh), gasoline efficiency in CD mode (mi/gal, for blended operation), and gasoline efficiency in CS mode (mi/gal) as estimated by GREET (shown in tables Tables 1–3 below). These GREET values are estimates for efficiency of future vehicles as indicated by year. Note that the PHEVs run blended operation in CD mode, meaning that they consume both gasoline and electricity.

$$f_{ca}^{\mathrm{ELEC}}(\beta,\gamma) = 104\frac{\sum_{j\in J_{a,c,\mathrm{WE}}} d_j^{\mathrm{CD}}(\beta,\gamma)}{|J_{a,c,\mathrm{WE}}|\eta_c^{\mathrm{CD-E}}} + 261\frac{\sum_{j\in J_{a,c,\mathrm{WD}}} d_j^{\mathrm{CD}}(\beta,\gamma)}{|J_{a,c,\mathrm{WD}}|\eta_c^{\mathrm{CD-E}}}$$

$$f_{ca}^{\mathrm{GAS}}(\beta,\gamma) = 104\left(\frac{\sum_{j\in J_{a,c,\mathrm{WE}}} d_j^{\mathrm{CD}}(\beta,\gamma)}{|J_{a,c,\mathrm{WE}}|\eta_c^{\mathrm{CD-G}}} + \frac{\sum_{j\in J_{a,c,\mathrm{WE}}} d_j^{\mathrm{CS}}(\beta,\gamma)}{|J_{a,c,\mathrm{WE}}|\eta_c^{\mathrm{CS-G}}}\right)$$

Table 1
$\eta^{CD\text{-}E}$ in mi/kWh for 2015 vehicles from GREET 1.8d.

	PHEV5	PHEV10	PHEV15	PHEV20	PHEV25
Car	5.2	5.2	5.3	5.3	5.3
SUV	4.5	4.5	4.5	4.5	4.5
Truck	4.9	4.9	4.9	4.8	4.8

Table 2
$\eta^{CD\text{-}G}$ in mi/gallon for 2015 vehicles from GREET 1.8d (blended operation).

	PHEV5	PHEV10	PHEV15	PHEV20	PHEV25
Car	74	74	78	82	82
SUV	54	54	56	58	58
Truck	41	41	42	42	42

Table 3
$\eta^{CS\text{-}G}$ in mi/gallon for 2015 vehicles from GREET 1.8d.

	CV	HEV	PHEV5	PHEV10	PHEV15	PHEV20	PHEV25
Car	27	38	43	43	43	42	42
SUV	20	28	28	28	28	28	28
Truck	18	24	25	25	25	25	25

Table 4
Charging scenarios.

Charging scenario	Brief description
HomeEve	Vehicle charges after arriving home on last trip of the day
HomeAll	Vehicle charges anytime it is parked at home for at least 30 min
WorkHomeEve	Vehicle charges when it first arrives at work and is parked for at least 30 min and at home after last trip of the day
WorkHomeAll	Vehicle charges anytime it is parked at either home or work for at least 30 min
AllStops	Vehicle charges anytime it is parked anywhere for at least 30 min

$$+261\left(\frac{\sum_{j\epsilon J_{a,c,\mathrm{WD}}} d_j^{\mathrm{CD}}(\beta,\gamma)}{|J_{a,c,\mathrm{WD}}|\eta_c^{\mathrm{CD-G}}}+\frac{\sum_{j\epsilon J_{a,c,\mathrm{WD}}} d_j^{\mathrm{CS}}(\beta,\gamma)}{|J_{a,c,\mathrm{WD}}|\eta_c^{\mathrm{CS-G}}}\right)$$

$$f_c^{\mathrm{ELEC}}(\beta,\gamma,L)=\sum_{a=1}^{L} f_{ca}^{\mathrm{ELEC}}(\beta,\gamma)$$

$$f_c^{\mathrm{GAS}}(\beta,\gamma,L)=\sum_{a=1}^{L} f_{ca}^{\mathrm{GAS}}(\beta,\gamma) \quad (1)$$

The functions d_j^{CD} and d_j^{CS} use the NHTS data to compute the distance that a vehicle with AER of β under charging scenario γ traveling on vehicle day trip profile j would travel in CD mode and CS mode, respectively. We examine $\beta\in\{5,10,15,20,25\}$ miles and $\gamma\in\{$*HomeEve*, *HomeAll*, *WorkHomeEve*, *WorkHomeAll*, *AllStops*$\}$, where the charging scenarios are described in Table 4.

The procedure for computing d^{CD} and d^{CS} for each vehicle in the set of a given age, AER, charging scenario, class, and weekday or weekend starts by assuming each vehicle begins the day fully charged. The vehicle is tracked through all reported trips and it is assumed it operates first in CD mode, where it consumes both electricity and gasoline, switches to CS mode once the battery drops to its target state of charge (SOC) (40% of battery energy remaining according to GREET), and fully recharges after the last trip of the day. We use trip distances and times specified in the NHTS dataset and assume a constant efficiency per VMT from GREET ($\eta^{\mathrm{CD\text{-}E}}$, $\eta^{\mathrm{CD\text{-}G}}$, and $\eta^{\mathrm{CS\text{-}G}}$), ignoring differences in efficiency for different drive cycles (Patil et al., 2009). For each trip if a vehicle's battery is above the target SOC then the total battery energy required to complete a trip is calculated. If the battery has enough energy, the SOC is decremented by the energy requirements of the trip. If the SOC is too low to complete the trip in CD mode then the SOC is decremented to the target SOC and the portion of the trip not traveled in CD mode is traveled in CS mode. If the vehicle battery is at the target SOC at the beginning of a trip the entire trip is traveled in CS mode. When a vehicle parks, the time between trips is calculated. If it is greater than or equal to 30 min then the vehicle can charge if the designated charging scenario allows charging at the location where the vehicle is parked.

GREET also accounts for reduction in real-world efficiency compared to test cycle efficiency, where the AER is rated. This means that simulated AER may be shorter than rated AER (but this is primarily pronounced for the serial hybrid configuration that is not included in this analysis). Vehicles that are not driven on the survey day have a d^{CD} and d^{CS} of zero but are included so that the average total mileage found when simulating the trips (found by adding d^{CD} and d^{CS} of all vehicles in a set and dividing by the total number in that set) and fuel use estimates properly reflect all vehicles in NHTS for each class. The resulting daily consumption is multiplied by either 104 for weekends or 261 for weekdays and summed to convert to annual consumption for a given age, AER, and charging scenario. The NHTS file does not specify if travel was on a holiday, nor are vacation days specified, so such days are included in computing average weekday or weekend travel. Calculating fuel use by CVs and HEVs is accomplished in the same manner, but total mileage is used instead of tracking d^{CD} and d^{CS} separately, since these vehicles do not use multiple energy sources.

The results of total distance traveled annually by all vehicles in a set of given age and class divided by the number of vehicles (both those driven and not driven on the day surveyed) in that set is shown in Fig. 2. To simulate the life of a vehicle it was assumed that it was driven in a manner consistent with reported NHTS data for a vehicle of its age and class. Thus, for the base case of a 12 year vehicle lifetime we assume a car drives roughly 14,000 miles in the first year, 13,000 in the next year and so on for each year until it reaches year 12 (Fig. 2). Calculation of fuel consumption treats each vehicle age and class separately so any changes in travel patterns as vehicles age are accounted for. It was found that a significant reason that vehicle miles traveled (VMT) decline with age is that older vehicles are less likely to be driven on a given day. This can be seen when looking at figures Fig. S.25 and Fig. S.26 in supporting information. The total consumption numbers for each AER, vehicle class, and vehicle age are reported in the supporting information for the base case.

2.2. Infrastructure estimates

Because the amount of shared charging infrastructure required per PHEV to enable the *WorkHome* and the *AllStops* charging scenarios will vary with the number of PHEVs in operation, we estimate an optimistic infrastructure case that is favorable to charging points. The first assumption is that charging infrastructure is based on widespread PHEV adoption and charger installation; thus a new charge point would not need to be installed every time a person moves, changes jobs, goes on a different errand and so on. To make these optimistic estimates the number of vehicle charges for each vehicle and each charging strategy was tabulated when simulating NHTS trips (as described above). The total number of charges per vehicle driven in the *WorkHomeEve* charging case was compared to the *HomeEve* charging case to determine how many additional charges are needed when vehicles are parked at work. Similarly the total number of charges per vehicle in the *AllStops* charging case was compared to the *WorkHomeAll* case to determine the number of additional charges at locations other than home or work. Since every trip uses some energy, the number of charges does not change with AER. The average additional charges for each NHTS data point (vehicle class and age) were weighted by the number of vehicles of a given age and class in the sample to determine the number of additional charge points used to estimate charging infrastructure. The NHTS includes only data that generally describes the location, such as home, work, place of worship, shopping and so on. It is acknowledged that this lack of information could lead to errors in the estimated number of charge points needed. Over-counting could result when a vehicle parks at the same location twice in the day (if it is not work or home) or when the same charge point could serve more than one vehicle if they parked at different times in the day. Undercounting will occur because averaging does not account for peak demand: a vehicle surveyed on a given day might not travel to work (on a holiday for example), but the next day that same vehicle may travel to work and require a charger. We are likely substantially undercounting infrastructure needs to fully enable each charging scenario, and thus results are purposefully favorable toward infrastructure.

Table 5 summarizes our estimates. The weekday or weekend set of vehicles was used depending on which resulted in a greater demand for charge points, resulting in 1.3 chargers per vehicle to enable *WorkHome* charging and 1.9 chargers per vehicle to enable *AllStops* charging.

2.3. Cost estimates

We estimate lifetime cost by combining available cost estimates for vehicles, fuel, and infrastructure. The costs of charging infrastructure are varied over a range shown in Table 6. These costs include installation and equipment costs and are lower in the base case than has been observed thus far for charging away from home (Dogget. 2011; Morrow et al., 2008), maintaining our optimistic stance on infrastructure. Installation costs can vary substantially. Plugging into an existing outlet requires no infrastructure investment, while installing a new circuit or a new electrical panel with potential carpentry and concrete work or installing a public charger that can accept payment and withstand exposure to the elements while dealing with potential vandalism is more expensive. Public charge points would consume some amount of electricity even when not charging and would need maintenance, but neither of these costs is included in the model. Although the recently announced DC quick charger from Nissan costs far less than in the past ($9900), it requires three phase AC input (Nishimoto, 2011). The actual installation costs of such units are likely to be substantial. Co-locating fast chargers to save on trenching and other installation costs would increase the likelihood of transformer upgrades and other costly changes to the distribution system. The base case charging rates are assumed to be 1.4 and (optimistically) 7.7 kW for home and nondomestic (work and public) charging, respectively. Higher rates have small effects on gasoline and electricity consumption. In particular, we find that under the *HomeAll* charging strategy, increasing home charge rates from 1.4 to 3.8 kW results in a maximum increase of 2.5% in CD miles (for AER of 15 miles). Increasing from 1.4 to 7.7 kW for home charging results in a maximum increase of 3% in CD miles traveled (for AER of 20 miles) (see supporting information). We ignore any additional charging efficiency losses associated with ohmic heating at higher charge rates.

Lifetime cost premium estimates for different options are found as follows. Vehicle costs are taken from the 2015 average case estimated by Argonne National Labs (ANL) in their 2011 report on potential of technologies in the light duty vehicle fleet to reduce petroleum consumption (US Department of Energy, 2011b). ANL estimates the manufacturing cost premium of several plug-in vehicles compared to a reference CV, and we multiply costs by 1.5 to account for markup in retail pricing (Plotkin and Singh, 2009). Any differences in vehicle maintenance costs are ignored, and we assume that the traction battery lasts the lifetime of the vehicle for PHEVs (alternative assumptions are examined in the supplemental material). Lifetime gasoline and electricity use is estimated from the fuel use model described previously. Fuel costs are taken from the EIA Annual Energy Outlook (2011) (AEO) that lists retail prices including taxes (Annual Energy Outlook, 2011). We adopt the AEO "traditional high oil price" case as our base case and include other cases in supporting information. Vehicle cost and fuel costs are taken starting in the year 2015. Fuel costs occur over time, so we compute the change in net present value (NPV) compared to a reference CV (lifetime cost premium) for each AER and vehicle class. Negative lifetime cost premium values indicate lifetime savings.

$$\text{Lifetime Cost Premium} = C^{\text{NPV}}_{\text{PHEV},\,c} - C^{\text{NPV}}_{\text{CV},\,c}$$

Table 6
Charging infrastructure cost estimates (Dogget, 2011).

	Low ($)	Base case ($)	High ($)
Home 1.4 kW	25	75	550
Home 7.7 kW	500	1125	4000
Away 1.4 kW	1050	3000	9000
Away 7.7 kW	2500	5000	15,000
Away 38.4 kW	11,000	20,000	50,000

Table 5
Optimistic estimates of charging infrastructure requirements for each charging scenario.

	Home charging only	**Home and work charging**		**All stops charging**	
		Weekday	Weekend	Weekday	Weekend
Number of nondomestic chargers required per vehicle for vehicles driven on the day surveyed (excluding one home charger)	0	0.47	0.12	1.13	1.5
Portion of vehicles driven on the day surveyed		67%	60%	67%	60%
Number of nondomestic chargers required per vehicle (excluding one home charger)[a]	0	0.3	0.07	0.76	0.9
Total number of chargers required per vehicle	1	1.3	1.1	1.8	1.9

[a] Assumes optimistically that vehicles not driven on the survey day do not need charge points other than home.

$$C^{NPV}_{PHEV,\,c} = D + \sum_{a=1}^{L} \frac{f_{PMT}(C_c - D, i, L) + p^{ELEC}_a f^{ELEC}_{ca}(\beta,\gamma) + p^{GAS}_a f^{GAS}_{ca}(\beta,\gamma)}{(1+r)^a} + C_{CH}$$

$$f_{PMT}(C_c - D, i, L) = \frac{(C_c - D)i}{1-(1+i)^L}$$

$$C^{NPV}_{CV,c} = \sum_{a=1}^{L} \left(\frac{\sum_{j\in J_{a,c}} d_j}{|J_{a,c}|\eta^{CV}_c}\right)\left(\frac{p^{GAS}_a}{(1+r)^a}\right) \tag{2}$$

where D is the vehicle down payment (100% of the cost of vehicle of class c in our base case); f_{PMT} is the annual vehicle loan payment; C_c is the additional cost of a plug-in vehicle of class c (including home charging infrastructure) over a CV of class c; i is the vehicle loan's interest rate; L is loan period in years; p^{ELEC}_a is the price of electricity a years after 2015; p^{GAS}_a is the price of gasoline a years after 2015; r is the discount rate; C_{CH} is the cost of charging infrastructure away from home (see Table 5 for summary); d_j is the total distance that NHTS vehicle profile j drove on the day surveyed; and η^{CV}_c is the efficiency of the conventional vehicle in miles per gallon.

We consider two main cases for discounting. In our base case we use a normative consumer discount rate of $r=5\%$. The second case attempts to reflect consumer behavior using a higher discount rate for vehicles and fuels to reflect observed consumer behavior. Consumers often exhibit surprisingly high implicit discount rates and sometimes gravitate toward purchasing whatever costs less at the point of purchase regardless of lifetime costs (Meier and Whittier, 1983). Studies conducted using surveys have estimated consumer discount rates for alternative vehicle purchases in the range of 20%–50% with the most likely value closer to 20% (Mau et al., 2008; Horne et al., 2005). One problem with such surveys is that most consumers are unlikely to understand a NPV calculation (Kurani and Turrentine, 2004). It has been posited that when making an actual purchase a consumer might seek out expert information regarding lifetime costs (Santini and Vyas, 2005). This idea is supported by findings suggesting that implicit consumer discount rates decline as purchase price increases. A study conducted looking at refrigerator purchases found that consumers exhibit implicit discount rates of about 45% (Meier and Whittier, 1983). There is a possibility that some of these refrigerators were purchased by landlords, or others that were not paying the utility costs and therefore had little incentive to purchase an efficient model (principal-agent problem). Other studies focusing on retirement plans instead of appliance purchases found lower discount rates ranging from 1%–26% which may be attributed to the greater value (perhaps supporting the idea that an individual thinks more carefully about a financial decision of larger amount) (Gilman, 1976; Matthew, 1984; Steven et al., 1982; Warner and Pleeter, 2001). These studies also found that in general those with higher incomes and education levels exhibited lower discount rates. It is possible that studies focusing on retirement decisions are biased toward higher income households who exhibit lower discount rates. The newer of these studies examined the military drawdown of the early 1990s and the decision service members faced about accepting either a lump sum payment or annuity. It found that discount rates varied considerably among service members depending on whether they were enlisted or officers (Warner and Pleeter, 2001). It was found that officers had a discount rate of 12% and enlisted members had a discount rate of 26%. In aggregate the discount rate was 18%. Given that surveys regarding purchase of alternative vehicle found a likely implied discount rate near 20% and that the actual decision regarding retirement resulted in an implied rate of 18%, we use $r=20\%$ to represent our consumer case.

It has been reported that over 80% of new vehicles were purchased using a loan (between 1998 and 2003) and that the median loan had a period of 60 months and rate of 8.7% with down payment of 14% (Agarwal et al., 2008). Twenty percent of new vehicles are not purchased on a loan. Our consumer behavior case assumes an intermediate condition, where consumers take a 60 month loan at 8.7% with a 31% down payment. Table 7 summarizes the base case and consumer case.

Table 7
Summary of base case and consumer case.

	Base case (%)	Consumer case (%)
Discount rate	5	20
Down payment	100	31
Loan interest rate	–	8.7

3. Results

Fig. 4 summarizes results for the base case, and Fig. 5 shows results for the consumer behavior case. Each combination of

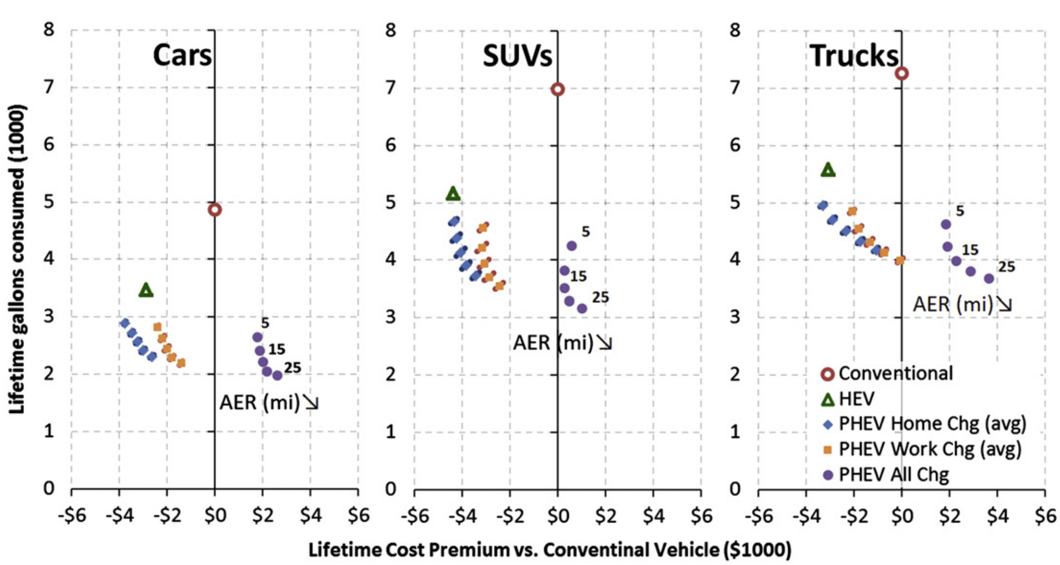

Fig. 4. Base case results. Lifetime gasoline consumption vs. NPV of vehicle, chargers, and fuel costs compared to CV given a 12 year vehicle life, AEO traditional high oil price, GREET 1.8d 2015 efficiency, 2015 average vehicle costs from ANL (2011) with 50% markup, and a 5% discount rate. Vehicles and chargers are purchased outright. PHEV AER values increase in 5 mile increments from 5 to 25 and are labeled on the *AllStops* charging scenario for clarity.

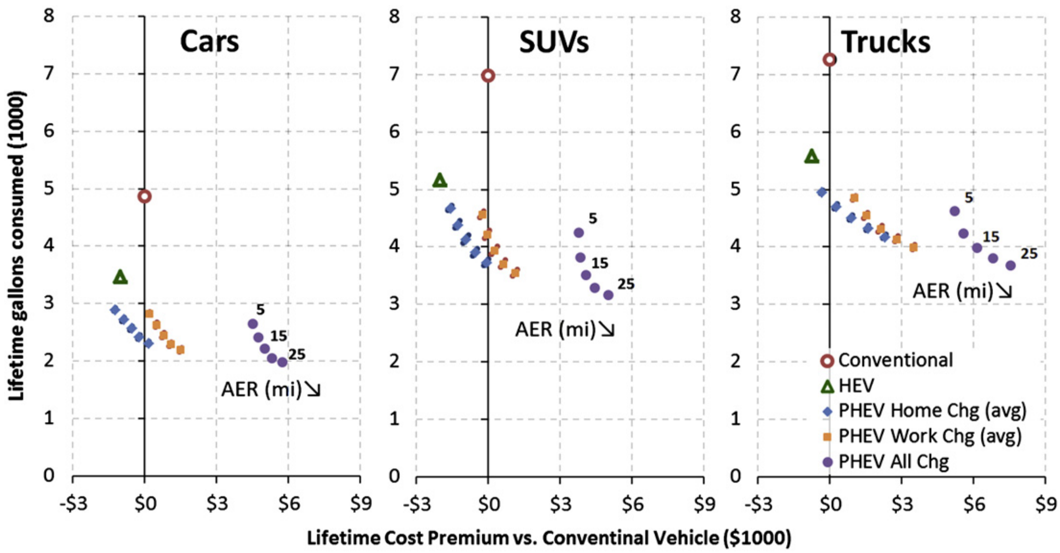

Fig. 5. Consumer behavior case. Discount rate at 20% for vehicle and fuel; 31% down payment; 8.7% loan interest rate. Other values the same as Fig. 4.

vehicle class, vehicle type (including CV, HEV, and PHEVs of varying AER), and charging scenario is plotted in two dimensions: lifetime cost premium (vs. the cost of the CV) and lifetime gasoline consumption. For clarity, PHEV AER is labeled only on the *AllStops* charging scenario, but in all cases increasing AER from 5 to 25 miles causes a decrease in gasoline consumption, so AER increases from top to bottom in all graphs. Also for clarity, the *HomeEve* and *HomeAll* charging scenarios are averaged to represent the home charging scenario (shown with diamonds), and error bars indicate variation under *HomeEve* and *HomeAll* scenarios. The *WorkHomeEve* and *WorkHomeAll* scenarios were averaged in the same way (shown with squares).

Given these two objectives, points on the lower left are preferred, and points toward the upper right are dominated. For example, in the case of cars, both the CV and HEV are dominated by the PHEV5 with home charging, since it offers more gasoline savings at lower lifetime cost. Generally, the PHEVs with home charging are Pareto optimal, and additional charging infrastructure provides slightly more gasoline savings at significantly higher cost.

If the market were to adopt the alternative with lowest lifetime cost, it would be PHEV5 with home charging only for cars and trucks and HEV for SUVs. Purchase of additional AER or charging infrastructure represents a tradeoff of additional cost vs. additional fuel savings. For example, in the base case for cars, shown in Fig. 4, the PHEV10 is $275 more expensive than the PHEV5 over the vehicle's lifetime and saves 165 gallons of gasoline. This implies a value of $1.61 per gallon saved (if gasoline savings is the only benefit of interest). In contrast, paying for additional charging infrastructure requires $9.99 per gallon saved for workplace infrastructure and $19.50 per gallon saved for *AllStops* infrastructure.

For comparison, Michalek et al. (2011) summarize estimates of the US oil premium, including increases in supply disruption costs associated with increased US oil consumption of $0.10/gal ($0–$0.30/gal) (Brown, 2010), increases in payment of world oil prices due to additional US consumption of $0.24/gal ($0.08–$0.49/gal) (Leiby, 2007), and increases in military costs due to US oil consumption of $0.03/gal ($0–$0.17/gal) (Delucchi and Murphy, 2008), resulting in a total oil premium of $0.37/gal ($0.08–$0.96/gal) in 2015 dollars (using a projected GDP price deflator (US Department of Commerce, 2010)). This implies that public spending to increase vehicle AER would not pay back in oil premium costs, even in an optimistic scenario, and public spending to increase charging infrastructure is orders of magnitude more expensive than oil premium costs.

The consumer behavior case is shown in Fig. 5. Using a higher discount rate, similar results are found for relative benefits of increased AER and charging infrastructure, however not all PHEV options result in lifetime savings. In the case of trucks only HEV and PHEV5 decrease lifetime cost compared to CVs. HEVs are the lowest lifetime cost options for SUVs and trucks.

We summarize the results presented in Figs. 4 and 5 as follows. First, HEVs and PHEVs save gasoline over conventional vehicles in all cases. Second, HEVs and some PHEVs can save both gasoline and total lifetime costs over conventional vehicles both at normative and observed implicit discount rates. Third, the additional cost per gallon saved of alternatives other than the least-cost option in each case is higher than oil premium estimates, and charging infrastructure is orders of magnitude more expensive per gallon saved, even with our optimistic assumptions for charging infrastructure. These findings are robust across a wide range of sensitivity scenarios examined in the supplemental information.

4. Limitations and assumptions

Our base case and consumer behavior case analysis is based on several assumptions that should be understood to interpret results appropriately. Where possible, implications of assumptions are examined explicitly in the supplemental material, including sensitivity analysis on future fuel prices, vehicle retail cost and markup, discount rate, vehicle life, charging infrastructure costs, nondomestic charging infrastructure requirements, battery replacement, vehicle efficiency, charging rate, and vehicle loan down payment. Our key findings are robust to variation in these assumptions (see supplemental information). Individual driving behavior can vary from the aggregate survey data, and PHEVs will benefit some drivers more than others. Shiau et al. (2010) found that accounting for individual driving distances when allocating vehicles is of secondary importance for overall cost and emissions; however, variations in driving conditions (drive cycle, terrain, temperature, etc.) may have a significant effect on relative benefits (Karabasoglu and Michalek, in review). Additional limitations involve implications of having different buyers for vehicles vs. charging infrastructure, short vs. long term infrastructure requirements, non-cost reasons for vehicle adoption, social benefits of plug-in vehicles other than gasoline savings, and indirect effects. We describe each of these in turn.

First, we do not address how differences in who pays for vehicle, charger, and fuel costs will influence incentives or how infrastructure investment costs will be passed down to vehicle owners who purchase electricity. Not all vehicle owners have access to off street parking or a private garage. While vehicle owners who are home owners with a garage are likely to pay for home charge points themselves, landlords are less likely to invest in charging infrastructure for tenant use, and vehicle owners are unlikely to pay for infrastructure on property they do not own. The likely buyers of charge points are property owners where the charge point is installed, electric utilities, or charge point network operators. Our estimates of nondomestic infrastructure requirements are intended to be optimistic. However, if the typical life of charging infrastructure equipment is longer or shorter than the life of vehicles (considering design life as well as vandalism, accidents, maintenance, and obsolescence), it will affect the number of charge points needed per vehicle in the long run and thus costs. Investment in charging infrastructure does not necessarily imply use, and some infrastructure is likely to be underutilized due to poor site location, uncertainty, demographic changes, financial incentives, or inconvenience. These factors are expected to make charging infrastructure less competitive, strengthening our conclusions.

Secondly, we do not address other factors that affect vehicle adoption besides lifetime costs. For example, HEVs were not initially cost competitive with CVs, yet individuals adopted them for other reasons, including symbolism and image (Lave and MacLean, 2002; Heffner et al., 2007). We also assume a single owner purchases a vehicle and drives it until end of life with no salvage value. Given a consumer discount rate of 20%, a salvage value as high as $3000 in year 12 is worth only $335 at purchase, so we assume salvage value of the vehicle and batteries is negligible.

We consider only gasoline savings and no other benefits of plug-in vehicles. Other benefits include changes in negative externalities from life cycle air emissions, ground emissions, and noise as well as positive externalities associated with knowledge spillover in technology advancement (Michalek et al., 2011). Differences in these negative externalities among vehicles and charging scenarios is relatively small on average, and we expect that positive externalities associated with advancement of charger technology and large-battery plug-in vehicles would not substantially exceed those associated with small-battery plug-in vehicles, if at all.

Finally, we consider only direct effects and ignore indirect effects. One indirect effect of subsidizing EVs is to accelerate technology development, potentially leading to an earlier breakthrough of mass-marketed EVs and resulting gasoline savings. This effect is uncertain, but if current subsidies result in earlier mainstream adoption of fuel-efficient vehicles, cost effectiveness could be higher than reported here. However, other indirect effects could reduce or eliminate the net effectiveness of vehicle and charger subsidies. In particular, the Congressional Budget Office estimates that because CAFE standards are high enough to be binding for automakers, subsidies spent to encourage adoption of EVs will have practically zero effect on total gasoline consumption (CBO, 2012). The incentivized sale of gasoline-saving vehicles will simply allow automakers to sell more gas-guzzling vehicles under CAFE regulation, achieving the same net average fuel consumption to comply with the law. If this is the case, then the cost effectiveness of EV subsidies may be reduced to zero.

5. Summary and conclusions

Using assumptions strongly favorable to charging infrastructure, we find that paying for charging infrastructure results in lower gasoline savings per dollar spent than paying for increased PHEV battery capacity, and both approaches are more costly per gallon saved than US oil premium estimates. Comparing the subsidy necessary to achieve lifetime cost parity with the least cost option for each vehicle class in the base case, we find that the maximum cost per gallon saved for increased AER is 5%–40% less than the minimum cost per gallon saved when installing charging infrastructure, depending on vehicle class. Looking forward as battery prices decrease and the AER resulting in maximum lifetime cost savings increases, the relative value of plugging in multiple times throughout the day will also decline. Nondomestic charging infrastructure is generally not necessary for operation of PHEVs, and substantial gasoline displacement can be achieved solely with home charging. In contrast, the limited range of BEVs make nondomestic charging infrastructure more critical if the vehicles are to be used as primary vehicles. But public investment in either large-battery vehicles or charging infrastructure generally produces fewer benefits per dollar spent than investment in small-battery PHEVs (Michalek et al., 2011), suggesting that subsidizing sales of BEVs and installation of charging infrastructure are not the most efficient use of limited public funds.

If the purpose of existing federal PHEV subsidies is to reduce gasoline consumption, this implies that the policy subsidizes 4 kWh battery PHEVs at ~$1.25 per gallon saved while subsidizing 16 kWh battery PHEVs at roughly $4.50 per gallon saved (Fig. 6), ignoring indirect effects. It is clear that federal subsidies are not currently aligned with the goal of decreased gasoline consumption in a consistent and efficient manner. Other relevant policy objectives, including reduction of emissions externalities, encouragement of technology development, and job creation do not show clear benefits of favoring large battery packs over small battery packs (Michalek et al., 2011).

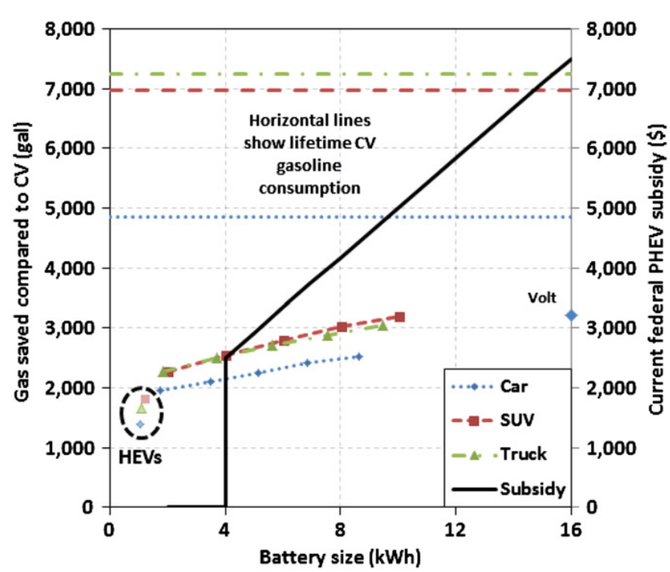

Fig. 6. Comparison of current federal subsidy to base case assumptions showing lifetime fuel savings (*HomeEve* charging scenario). An EPA estimate based on the Chevy Volt's reported efficiency is also included for comparison (Download Fuel Economy Data. US Environmental Protection Agency, 2011). The federal subsidy significantly favors larger battery packs to a stronger degree than their potential for additional gasoline savings.

Alternatives to the current federal subsidy structure include measures to redesign or replace the current policy. A policy redesign should consider the following issues:

- Current federal subsidies are tied to total battery capacity rather than usable battery capacity or AER, which incentivizes use of larger battery packs. The Chevy Volt, for example, uses only about 65% of its 16 kWh capacity in order to improve safety and battery life (Peterson et al., 2010; US Department of Energy, 2011a). Subsidizing usable capacity, rather than total capacity, would remove the disincentive for automakers to figure out how to use a larger portion of the battery (Shiau et al., 2010). Alternatively, subsidizing based on AER (as measured in a standardized test) would also encourage automakers to make vehicles more efficient, and removing the exclusion for lower-capacity lower-range vehicles would be more consistent with potential benefits.
- PHEVs have diminishing returns in gasoline savings as battery capacity increases. Subsidies intended to generate gasoline savings would be better if tied to estimated gasoline savings rather than battery capacity or AER, and subsidies that are tied to battery capacity or AER should avoid a fixed rate per kWh or per mile and instead reflect the structure of diminishing returns. However, methods for estimating gasoline savings may be controversial, and depending on what reference point is used, subsidies tied to gasoline savings could have unintended consequences, such as the potential for separate reference points in each vehicle class encouraging consumers to purchase larger vehicle classes.
- The current subsidy of \$2500 for 4 kWh (~\$1.25/gal saved) and \$7500 for 16 kWh (~\$4.50/gal saved) pays prices substantially higher than US oil premium estimates of \$0.37/gal (\$0.08–\$0.96/gal). Subsidies intended to generate gasoline savings would preferably be comparable to the social value of gasoline savings (and the value of other social benefits). To the extent that larger subsidies are able to kick-start adoption and sustainable market acceptance of plug-in technologies that would not otherwise be adopted, temporary larger subsidies may be warranted. But the magnitude or duration of this dynamic effect remains highly uncertain.
- More efficient policies generally target the policy goal, such as gasoline displacement, directly rather than a proxy, such as battery size. On economic efficiency grounds, subsidies are justified insofar as they correct for positive externalities, such as innovation knowledge spillover, and research funding is an alternative to subsidizing sales for achieving this effect. A more efficient way to address negative externalities is to apply Pigovian taxes, which would increase the price of gasoline and make plug-in vehicles more competitive in the marketplace while encouraging the most efficient responses to reducing externalities, including not only alternative powertrains but also efficiency improvements and incentives to drive less and purchase smaller vehicles (as well as to make changes in other sectors of the economy). Revenue from such taxes could be used to reduce taxes elsewhere on outcomes we prefer to encourage, like employment. We acknowledge the political challenge of increasing or creating a tax.
- Finally, considering the presence of binding CAFE standards, it remains in question whether EV subsidies will provide any net gasoline savings for the foreseeable future (CBO 2012).

Ignoring interactions with CAFE policy, HEVs and PHEVs with low AER and only home charging generally provide the largest direct gasoline savings per dollar spent, offering both lower costs and lower gasoline consumption than CVs, depending on the consumer's discount rate. It is therefore possible that incentivizing a larger number of consumers to purchase HEVs or low-AER PHEVs would save more gasoline under a fixed policy budget than incentivizing a relatively smaller number of consumers to purchase high-AER PHEVs (Michalek et al., 2011). However, given a fixed market of electrified vehicle adopters, if more gasoline savings is needed than what can be achieved with HEVs and low-AER PHEVs, additional savings can be achieved more efficiently by paying for additional AER than by paying for extra charging infrastructure.

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Appendix A. Supporting information

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