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Evaluating Electric Vehicle Policy Effectiveness and Equity

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Abstract

In this article, I review the academic literature on the economics of plug-in electric vehicles (PEVs), with a focus on PEV policy, benefits, and equity. PEVs are one of the most promising technologies for decarbonizing the transportation sector. As such, many government policies exist to promote their adoption. Understanding the effectiveness and equity of existing policies, what the realized environmental benefits are, and how these benefits compare to costs is crucial to improving future PEV policy. This review suggests that consumer PEV subsidies are not cost-effective and are often expensive relative to estimated environmental benefits. Furthermore, higher-income households who make up a larger share of the PEV market receive both a disproportionate amount of government subsidies as well as PEV benefits. There is considerable room for policy improvement.

1. INTRODUCTION

Plug-in electric vehicles (PEVs) are one of the most promising technologies for decarbonizing the transportation sector. Governments around the world have implemented various policies to incentivize PEV adoption over the last decade to reduce not only greenhouse gas (GHG) emissions but also local air pollution. Though early market adoption was low, with PEVs accounting for less than 0.5% of new vehicle sales in the United States in 2012, adoption has accelerated in recent years (see **Figure 1**); PEVs accounted for about 2% of the market in 2018–2019. This has likely been due to a combination of factors: policy incentives, improvements in the technology, the introduction of new models, and increased knowledge and popularity of these vehicles. Although average driving costs of PEVs are less than half of the costs of typical gasoline vehicles (Sivak & Schoettle 2018), the purchase price of PEVs is likely to remain higher than that of conventional vehicles for at least the next decade (Chakraborty et al. 2021a).

PEVs include both battery electric vehicles (BEVs), which have only electric motors and run exclusively on electricity, and plug-in hybrid electric vehicles (PHEVs), which have both an electric motor and an internal combustion engine. PHEVs tend to have shorter all-electric ranges than BEVs, be less expensive given their smaller batteries, and perform similar to regular hybrid vehicles when driven in gasoline mode. To narrow the scope of this review, here I focus on the private, light duty PEV market in the United States.

In this article, I review the academic literature on the economics of electric vehicles, with a focus on PEV policy, benefits, and equity. Understanding the effectiveness and equity of existing

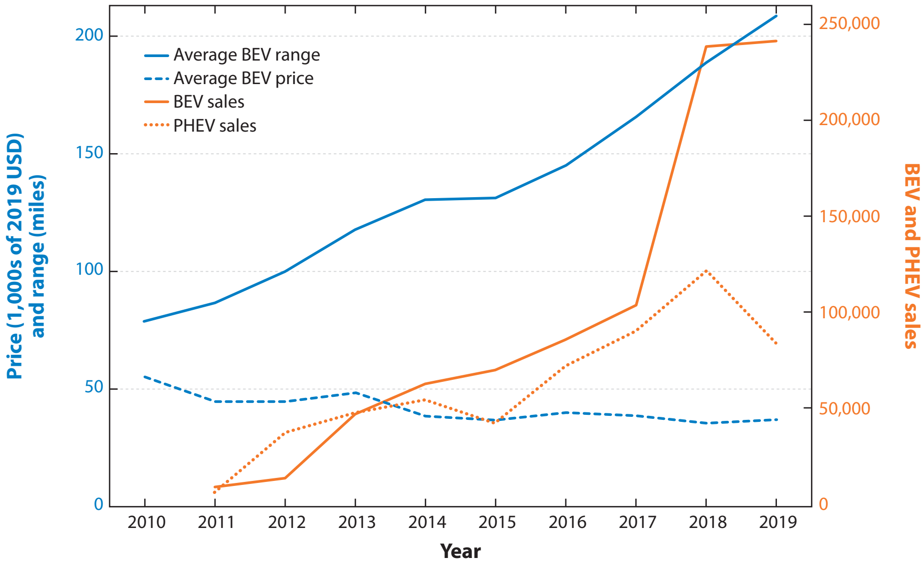

Figure 1

US PEV sales and average BEV price and range, 2010–2019. US BEV and PHEV sales data come from the Transportation Research Center at Argonne National Laboratory (**http://www.anl.gov/es/light-duty-electric-drive-vehicles-monthly-sales-updates**). BEVs and PHEVs do not include neighborhood electric vehicles, low-speed electric vehicles, or two-wheeled electric vehicles. Only full-sized vehicles sold in the United States and capable of 60 mph are included. BEV average price and range data come from the International Energy Agency (**https://www.iea.org/data-and-statistics/charts/average-price-and-driving-range-of-bevs-2010-2019**). Abbreviations: BEV, battery electric vehicle; PEV, plug-in electric vehicle; PHEV, plug-in hybrid electric vehicle.

policies, what the realized environmental benefits are, and how these benefits compare to costs is crucial to improving PEV policy going forward.

This review proceeds as follows. First, in Section 2, I discuss the barriers to PEV adoption before reviewing the empirical evidence on both the effectiveness and equity of adoption policies in Section 3. I then discuss the state of knowledge of the environmental benefits of PEVs in Section 4, including important assumptions, caveats, and unknowns. After a brief overview of the used PEV market in Section 5, I conclude in Section 6.

2. BARRIERS TO ADOPTION

Although electric vehicle technology has existed for more than 100 years, the modern PEV market dates back to the introduction of the Tesla Roadster in 2009, the Nissan LEAF in 2010, and the Chevrolet Volt (the first commercially available PHEV) in 2010 (US Dep. Energy 2014). Prior to the modern PEV market, stated preference studies on consumer preferences and early market adopters suggested that the range between refueling was a top consumer concern (e.g., Bunch et al. 1993, Brownstone & Train 1998, Brownstone et al. 2000). Early research also suggested that PHEVs, which are less subject to range anxiety, would have wider appeal (e.g., Axsen & Kurani 2009, 2013; Sheldon et al. 2017). Notably, in part due to considerable demand for Teslas, BEV market share has been and remains higher than PHEV market share (see **Figure 1**). Safety is generally an omitted attribute in PEV stated preference studies, with most choice experiments telling respondents that except for the varying attributes, they should assume everything else is identical about the PEVs. However, in a survey of over 500 car buyers, less than 1% of respondents identified safety as the most important PEV concern, versus 33% and 27% who identified battery range and cost, respectively (Egbue & Long 2012). Charging infrastructure and reliability were two intermediate concerns.

Further stated preference studies around the early years of the modern PEV market found that while range anxiety and charging availability continued to be important considerations for potential adopters, knowledge barriers and up-front cost were also likely to be major factors. Egbue & Long (2012) found that uncertainty and unfamiliarity with the technology were major concerns to a technologically minded target group, while Krause et al. (2013) found a majority of respondents had misperceptions about basic PEV characteristics and no awareness of PEV policies. Hidrue et al. (2011) estimated a maximum willingness to pay for a BEV of $16,000, at a time when the cheapest model available, the Nissan LEAF, cost around $25,000 after factoring the maximum federal income tax credit (Squatriglia 2010).

Evidence on likely and actual purchasers supports the notion that up-front cost is the biggest barrier to PEV adoption. Research suggests that better-educated and higher-income consumers are more likely to purchase PEVs (Tal & Nicholas 2016, Sheldon et al. 2017, Jia & Chen 2021). The revealed preference data utilized by Sheldon & Dua (2019a) show that 73.4% of BEVs and 60.1% of PHEVs from a nationally representative sample of model year (MY) 2015 new vehicle sales were purchased by households with incomes of $100,000 or more. Furthermore, 85.2% of BEVs and 77.6% of PHEVs were purchased by individuals with at least a college degree. A recent survey of over 11,000 PEV owners in California revealed that 49% are higher-income families, though this fraction has decreased over time from 55.6% in 2012 to 40.4% in 2017 (Lee et al. 2019). This may in turn be due to the price of lower-end PEVs declining over this time period (see **Figure 1**). Although concerns over resale value may exacerbate those over up-front cost, this issue has yet to be explored in the literature.

The high up-front cost of PEVs is partially offset by fuel cost savings and, indeed, stated preference studies have shown that potential adopters value these cost savings (e.g., Bunch et al. 1993, Brownstone & Train 1998, Sheldon et al. 2017). However, in practice, consumers may have difficulties estimating their savings. Indeed, a new study shows that gasoline prices are four to six times more impactful than electricity prices in terms of vehicle adoption decisions (Bushnell et al. 2021). The authors cite confusion over what marginal electricity price a consumer faces and translating that to per mile fuel cost as reasons for this difference.

Meanwhile, range concerns may have been alleviated over time as technological improvements have substantially increased range over the last decade, with average BEV range increasing from 79 miles in 2010 to 209 miles in 2019, according to the International Energy Agency (**https://www.iea.org/data-and-statistics/charts/average-price-and-driving-range-of-bevs-2010-2019**). The US Federal Highway Administration's 2017 National Household Travel Survey (NHTS) data show that the average one-way commute in the United States is approximately 13 miles, suggesting that the typical BEV range more than covers the average round trip commute (US Dep. Transp. Fed. Highw. Admin. 2017b).

3. PROMOTING PLUG-IN ELECTRIC VEHICLE ADOPTION

3.1. Financial Incentives

A variety of policies have been implemented at the national, state, and local levels to incentivize the adoption of PEVs. The most common consumer incentives at the federal and state levels are financial incentives that reduce the cost of purchasing a PEV, thereby addressing one of the major barriers to adoption. The federal government introduced an income tax credit for PEV purchases starting in 2010. The credit ranges from $2,500 to $7,500 depending on battery size, such that the credit generally increases with electric range. The first 200,000 qualifying PEVs sold per manufacturer are eligible for the credit, after which tax credits for that manufacturer's PEVs start to phase out. Tesla and General Motors (maker of the Chevrolet Volt) are the only two automakers to have reached this limit, with phaseouts starting in the first and second quarters of 2019, respectively, and tax credits eliminated as of the first and second quarters of 2020, respectively (**https://www.irs.gov/businesses/irc-30d-new-qualified-plug-in-electric-drive-motor-vehicle-credit**).

Since 2010 nearly 20 states have or have had at some point a financial incentive for PEV purchases. These vary in amount from $500 up to nearly $10,000 for some segments of the California market. Many are a function of battery capacity or range, some differ for BEVs versus PHEVs, and most take the form of either a tax credit or rebate. Numerous studies have assessed the effectiveness of financial purchase incentives, though the majority of these rely on country-level cross-sectional or panel data and aggregate national PEV market shares, with some using only a representative PEV. As the econometric models tend to be identified mostly off of country-level variation, estimated effects are average effects across countries, despite the fact that consumer responsiveness likely varies across countries. Some of these studies perform simple correlational analyses, whereas many use regression analysis. However, most do not account for policy endogeneity, e.g., the fact that countries with more generous incentives may also have a more environmentally conscious electorate. See Hardman et al. (2017) for a review of such studies.

Sierzchula et al. (2014) wrote one of the best-cited papers on this topic. The authors use regression analysis on a panel of 30 countries to evaluate the impact of financial incentives and population-adjusted number of charging stations on PEV market share in 2012. They find that, all else equal, a $1,000 increase in financial incentives leads to a 0.06 percentage point increase in PEV market share. They also find that, all else equal, an additional charging station (per 100,000 residents) leads to a 0.12 percentage point increase in PEV market share.

A smaller literature exists that uses higher-resolution revealed preference data (including monthly, state-level and annual, individual-level) or stated preference data to investigate the effectiveness of the federal income tax credit and/or state-level subsidies. Tal & Nicholas (2016) use stated preference data on PEV owners in 11 states to estimate the effectiveness of the federal tax credit. In their survey, respondents are asked which vehicle they would have chosen to buy had the tax credit not been available, out of a choice set that includes their actual purchase, four other vehicles preferred by the respondent based on prior questions, or no vehicle. Based on this question, they find that 28.5% of PEV sales could be attributed to the federal tax credit, though this percentage was lower for some models (15% for the Prius Plug-in and 14% for the Tesla Model S) and higher for others (40% for the Chevrolet Volt and nearly 50% for the Nissan LEAF). Since the $7,500 tax credit increased Tesla Model S adoptions by only 14%, this translates into a cost per additional PEV sold of $7,500/0.14 = ~$53,000. In other words, for each consumer induced by the $7,500 to purchase the Tesla, six more $7,500 tax credits were given to consumers who would have bought the Tesla regardless of the subsidy. The authors similarly calculate the cost per additional Nissan LEAF sold of $14,700.

DeShazo et al. (2017) use stated preference data from a choice experiment embedded in a survey of a representative sample of new vehicle buyers in California. Respondents make several choices among BEVs, PHEVs, and traditional internal combustion engine vehicles with varying attributes, where the choice sets are based on respondents' preferred makes and body types. Using these data, the authors calibrate a vehicle choice model and use it to predict BEV and PHEV market share under various rebate scenarios. They find that the California state rebate at the time ($2,500 for BEVs and $1,500 for PHEVs) induced less than 10% of PEV purchases (i.e., the vast majority of PEV buyers would have purchased the PEV even without the rebate). Assuming the rebate is applied to all qualifying purchases, the policy cost of an additional PEV purchase was around $30,000. The authors explain that PEV subsidy cost-effectiveness depends on both ex ante preferences for PEVs, which determines the number of inframarginal buyers, and the consumer's marginal utility of income, which determines her responsiveness to the rebate. Cost-effectiveness is maximized when targeting consumer segments or vehicle types with low ex ante preferences, as fewer subsidy dollars will be wasted on free-riders, and when targeting consumer segments with greater price elasticity of demand, such as lower-income households, for whom the subsidy is more impactful. On these grounds the authors ultimately recommend higher rebates for BEVs, vehicle price caps, and larger rebates to lower-income consumers, measures that could lower the cost per additional vehicle by over one-third.

An evaluation of the combined effect of the federal income tax credit and charging infrastructure investment using quarterly PEV sales data from over 350 metro areas from 2011 to 2013 implied that 40% of PEV sales during that time could be attributed to the federal tax credit, though 40% of that was, in turn, explained by feedback loops from charging infrastructure (Li et al. 2017). Jenn et al. (2018) perform regression analysis on a monthly, state-level data set of new vehicle sales and various PEV incentives from 2010 to 2015. The results suggest that a $10,000 subsidy would increase PEV sales by 26%.

Sheldon & Dua (2019a) estimate a vehicle choice model using individual-level sales data from MY 2015, incorporating both federal- and state-level subsidies and performing counterfactual simulations under various subsidy scenarios. Choice models are estimated separately by income-education groups to account for heterogeneous preferences and price sensitivity. The authors find the federal income tax credit excluding state subsidies to be responsible for 17% of PEV sales and including state subsidies to account for 22% of PEV sales. This translates to a cost per additional PEV of roughly $35,000. Similar to DeShazo et al. (2017), the authors find that this cost could be reduced to as low as around $15,000 by increasing (decreasing) subsidies for lower- (higher-) income households. Using additional counterfactual simulations and incorporating consumer-level fleet and demographic information, the authors find that assigning subsidies by income and vehicle disposal, geography, or vehicle miles traveled (VMT) could further reduce gasoline consumption. Specifically, gasoline consumption would be minimized by targeting (*a*) consumers who would trade in a larger, less-fuel-efficient vehicle, (*b*) consumers with higher monthly VMT, or (*c*) those who live in rural and farming communities who tend to drive larger vehicles and have higher monthly VMT.

Using a differences-in-differences identification strategy combined with household-level vehicle purchase data from 2014 to 2015, Sheldon & Dua (2019a) evaluate the effectiveness of California's Replace Your Ride program that provides additional incentives to lower-income households, with maximum total state subsidies toward PEV purchases of $9,500. The authors estimate that at least 49% of BEVs and 39% of PHEVs sold during the postpolicy time period under evaluation were a result of the policy, resulting in a cost per additional BEV and PHEV of $17,600 and just under $22,000, respectively. Thus, the authors find empirical evidence consistent with the claims of policy simulations by DeShazo et al. (2017) and Sheldon & Dua (2019a) that targeting lower-income consumers would improve policy cost-effectiveness.

Jenn et al. (2020) perform latent class cluster analysis on three waves of PEV owner surveys spanning 2010–2017, where owners are assigned group membership based on their responses to a question about the importance of various purchase incentives. Next, they estimate a multinomial logit model to estimate how socio-demographics and household fleet impact group membership. They find that the proportion of PEV buyers who require incentives grew in the latest survey wave (2016–2017) relative to the prior waves, from 17.6% to 22.2% to 23.6% to 27.2%, with federal and state financial incentives being the most important, followed by high occupancy vehicle (HOV) lane access. However, they also find that the proportion of buyers who do not find such incentives important decreased from 38.5% to 16% over the same time period (with remaining buyers finding incentives somewhat important), with relatively more Tesla owners belonging to this group. More than 60% of respondents claim they would have made their PEV purchase even absent the federal income tax credit, for additionality of 40%. Higher-income respondents were less likely to find incentives important and less likely to change their purchase behavior if the federal tax credit were unavailable.

Table 1 summarizes the above studies' findings in terms of effectiveness and cost-effectiveness (if available) of federal and state PEV subsidies. Effectiveness is measured by additionality, or the percent of PEV purchases the authors find were induced by the subsidy. Cost-effectiveness is measured by cost per additional PEV, accounting for nonmarginal purchases (i.e., free-ridership). Additionality estimates for the federal tax credit (either excluding or including state subsidies) range from 14% to 50%, with a mean of around 30%. In other words, empirical evidence suggests that roughly two out of every three PEVs purchased would have been purchased regardless of the federal tax credit. The only additionality estimate for a state-only policy is 6% for California (DeShazo et al. 2017), which may in part be lower due to the lower amount of the subsidy (note that cost-effectiveness is similar to other studies). Because subsidy polices cannot distinguish marginal versus inframarginal buyers, all buyers are eligible for the subsidies. This translates into poor cost-effectiveness, with the cost per additional PEV at $30,000–35,000, greater than the purchase price of some PEV models. There does not appear to be a systematic difference in estimates based on revealed preference versus stated preference data, nor does there appear to be a clear trend in these metrics over time.

The existing literature on PEV financial incentive effectiveness stops short of a true benefit-cost or welfare analysis, which would factor in opportunity cost of public funds and compare policy

Table 1 Summary of PEV financial incentive effectiveness and cost-effectiveness results in the United States

Reference	Stated or revealed preference data	Geographic region	Year(s)	Policy	Subsidy amount	Additionality	Cost per additional PEV
Tal & Nicholas 2016	SP	11 states	2010–2014	Federal income tax credit	\$2,500 to \$7,500 depending on battery capacity	14–50% depending on model; an average of 28.5%	\$14–53,000 depending on model
DeShazo et al. 2017	SP	California	2013	California PEV rebate	\$2,500 for BEVs, \$1,500 for PHEVs	6%	\$30,000
Li et al. 2017	RP	353 metro areas	2011–2013	Federal income tax credit	\$2,500 to \$7,500 depending on battery capacity	40% (40% of which was due to charging infrastructure feedback loops)	NA
Jenn et al. 2018	RP	All states	2010–2015	Federal and state subsidies (tax credit and/or rebate)	\$10,000	26%	NA
Sheldon & Dua 2019b	RP	All states	2015	Federal income tax credit and state subsidies	\$2,500 to \$7,500 depending on battery capacity for federal credit; \$500 to \$7,500 for state subsidies	17% for federal policy; 22% for federal and state combined	\$35,000
Jenn et al. 2020	SP	California	2010–2017	Federal income tax credit	\$2,500 to \$7,500 depending on battery capacity	40%	NA
Sheldon & Dua 2019a	RP	California	2014–2015	California's Replace your Ride Program for lower- and middle-income households	Up to \$9,500 depending on income	39–49%	\$17,600–\$22,000

Abbreviations: BEV, battery electric vehicle; NA, not applicable; PEV, plug-in electric vehicle; PHEV, plug-in hybrid electric vehicle; SP, stated preference; RP, revealed preference.

costs to benefits. While such second best policies are clearly not efficient, whether or not a cost per additional PEV of $30,000 is expensive depends on the size of the externalities involved. PEV benefits include a reduction in negative externalities in the form of air pollution. Furthermore, subsidizing the early market may be justified on grounds of knowledge spillovers on both the consumer and producer sides as well as increased energy security. A small but growing literature seeks to quantify the pollution reduction benefits of PEVs (see Section 4.1), which appear to be much lower than the estimated policy cost per additional PEV. However, other benefits (e.g., the extent of knowledge spillovers in PEV production and consumption such as learning by doing and neighborhood/peer effects, improvements in energy security) have yet to be quantified.

3.2. Public Charging Infrastructure

After up-front cost and knowledge barriers, range anxiety and charging availability appear to be the other major barriers to PEV adoption. Existence of away-from-home charging infrastructure may alleviate these concerns. Although numerous studies have documented the positive relationship between PEV adoption and public and workplace chargers, identifying a causal relationship between charging stations and PEV adoption has proven difficult, as locations with greater PEV market penetration tend to install more charging infrastructure (Hardman 2019). This is often referred to as a chicken-and-egg problem.

The majority of PEV charging takes place at home, with most drivers charging exclusively at home; the next most popular location is the workplace followed by public DC fast charging stations (Smart & Salisbury 2015, Dunckley & Tal 2016, CARB 2017, Hardman et al. 2018). Sheldon et al. (2019) confirm this in a discrete choice experiment of potential PEV adopters in California, finding the highest willingness to pay for workplace charging out of nine alternative away-from-home locations. They also find that willingness to pay for public charging tends to cover the actual variable cost plus some fixed costs of the charging infrastructure. Using regression analysis of vehicle purchase data from 2008 to 2016, Narassimhan & Johnson (2018) find that the positive correlation between PEV purchases and public charging availability increases with electric range of PHEVs but decreases with increased BEV range. This in turn suggests that public charging may be more useful to shorter-range PEVs, while drivers of longer-range PEVs are better able to make it through the day without recharging and instead charge exclusively at home.

Li et al. (2017) offer one of the only causal analyses of the impact of charging infrastructure on PEV adoption and the first to empirically characterize the chicken-and-egg nature of the two technologies. The authors combine quarterly PEV sales and charging station deployment data for 353 metro areas from 2011 to 2013 with a model that incorporates network effects in terms of positive feedback loops. Specifically, they estimate both a PEV demand equation that depends on charging infrastructure and a charging infrastructure equation that depends on the PEV stock. To address endogeneity due to unobserved factors simultaneously impacting both stock and inflows of charging stations and PEVs, the authors use an instrumental variables approach. They instrument for charging station stock with an interaction between a national deployment shock and local market conditions, and they instrument for PEV stock with current and historic gasoline prices. In addition to the previously mentioned finding of the effectiveness of the federal income tax credit (to which they attribute 40% of PEV sales during the time period, 40% of which are in turn attributable to indirect network effects), they conclude that spending the federal tax credit budget instead on subsidizing charging infrastructure could have been twice as effective in terms of increasing PEV adoption.

That most PEV drivers charge exclusively at home begs the question: Do consumers actually use away-from-home charging infrastructure, or does its existence simply allay anxiety about finding oneself away-from-home with not enough charge? A study conducted by Smart & Salisbury (2015) using 2011–2013 data found that for 2,400 public Level 2 charging stations nationwide, the median usage was 1.4 charges per week, and that three-quarters of these sites averaged fewer than five chargers per week. However, they did find very high usage at a small number of charging stations located mostly in shopping malls and parking areas that serve multiple venues. Usage was higher for DC fast chargers at a median of 7.2 charges per week, with a quarter of the stations averaging over 15 per week. The most heavily used stations were located near interstate highway exits but were used at least as much by locals as by longer-distance travelers.

Other surveys and anecdotal evidence suggest that many drivers overuse some public chargers, possibly to take advantage of the benefit of a convenient parking spot. A 2017 City of Sacramento survey of PEV users of large city parking facilities found that 42% of users were never or seldom able to access an EV charging station when they need it (**https://www.cityofsacramento.org/-/media/Corporate/Files/Public-Works/Electric-Vehicles/4-1_EV-Blueprint_Final-Public-and-Workplace-EVSE-Utilization.pdf?la=en**). This confirmed an earlier study on California that found that 38% of PEV drivers were unable to charge at their workplace at least once a week (Nicholas & Tal 2013).

In a more recent, larger-scale national analysis of charging data from 12,720 PEV charging stations from 2011 to 2015, Asensio et al. (2020) use machine learning methods to classify PEV users' text reviews of the charging stations to evaluate consumer experiences and perceptions. They find that privately owned charging stations do not outperform publicly owned or managed ones and that paid charging stations receive more negative reviews than free stations. The authors find that consumer sentiments are the most negative in dense urban centers, as opposed to smaller urban or rural areas. Many negative reviews point to congestion and lack of available stations, with complaints that charging spots are taken by cars that have finished charging or even by non-PEVs (known as getting ICE'd by an internal combustion engine vehicle).

A recent literature survey of charging infrastructure studies from across the world, including the United States, concludes that public charging infrastructure is only needed in some densely populated areas (Funke et al. 2019). This is consistent with the above findings that many charging stations are underutilized while a small number of stations are in high demand and experience congestion, particularly in dense urban cores. To combat congestion issues, Winn (2016) recommends graduated hourly rates to limit over-usage of charging stations, as well as charging station pricing at workplaces based on a parking model.

It is worth emphasizing the lack of causal analysis of PEV charging infrastructure, as well as the lack of studies using post-2015 data. As the PEV market has shifted away from early adopters in recent years, the role and importance of public charging may have changed. Nevertheless, it appears that more consideration ought to be given to placement and pricing of away-from-home charging stations.

3.3. Other Incentives

Free HOV lane access for PEVs on highways is positively correlated with PEV sales in California and the United States (see Hardman 2019 for details). Jin et al. (2014) employ a stepwise regression of state-level BEV sales on monetary and nonmonetary incentives, finding that complementary HOV lane access contributes the second most to BEV sales, only slightly behind subsidies. Using PEV registration data by census tract in California, Sheldon & DeShazo (2017) employ a generalized propensity score method to estimate the impact of incremental miles of nearby HOV lanes on PEV sales. Their analysis attributes over one-quarter of California PEV sales from 2010 to 2013 to the state's HOV lane policy that allowed PEVs to utilize the HOV lanes free of charge. A back of the envelope calculation by Jenn et al. (2018) based on the estimated effect of HOV lane density (interacted with the presence of an HOV PEV incentive) on registrations suggests that California's HOV policy accounts for approximately 46% of PEV sales.

Various additional consumer incentives exist at local levels in the United States, including free or subsidized public charging, subsidies for installation of home chargers, time-of-use electricity rates, and discounted, free, or preferential parking. Hardman et al. (2018) and Hardman (2019) review the literature on the effectiveness of such incentives, both within and outside the United States.

Although this review focuses on consumer adoption incentives, it is worth mentioning the major federal manufacturer incentive for PEV production. The US Corporate Average Fuel Economy (CAFE) and GHG emissions standards mandate that the sales-weighted average of vehicles sold by each manufacture comply with fuel efficiency and carbon dioxide (CO_2) emissions standards that become more stringent over time. PEV production has been incentivized in two different ways under the CAFE-GHG standards. First, all upstream emissions associated with miles driven on electricity are assumed to be zero through MY 2021 and for a portion of sales for MY 2022–2025. Second, since 2017, multipliers starting at 2 for BEVs and 1.6 for PHEVs (which will decline incrementally to 1 in MY 2022) have been applied to PEVs, allowing them to count as more than one vehicle in the sales-weighted averaging (Transp. Res. Board/Natl. Res. Counc. 2015). Few studies have examined the effectiveness of these standards in terms of PEV adoption, though Jenn et al. (2016) find that these CAFE-GHG PEV incentives effectively lower the stringency of the standards, increasing CO_2 emissions relative to a counterfactual fleet without the incentives. They estimate that each additional alternative fuel vehicle sold under the regulation (including PEVs) leads to up to 60 tons of additional CO_2 emissions.

3.4. Equity

Combining data from the 2017 NHTS and the Bureau of Labor Statistics' 2018 Consumer Expenditure Survey, Bauer et al. (2021) show that vehicle ownership costs, including fuel, maintenance, insurance, and purchase costs, account for a much larger share of lower-income households' budgets. These costs account for more than 50% of income in households with annual income less than $25,000, about 25% in those with incomes between $25,000 and $50,000, and less than 10% in those with incomes more than $150,000. Given that fuel costs alone comprise more than 10% of annual income for the lowest income bracket, these households are best positioned to benefit from fuel cost savings associated with PEVs. Furthermore, lower-income households tend to drive older, more polluting vehicles, contributing a relatively larger share toward pollution externalities and worsening local air quality. According to the 2017 NHTS (US Dep. Transp. Fed. Highw. Admin. 2017a), households with incomes less than $50,000 drive vehicles with an average MY of 2004 and average fuel economy of 20.34 miles per gallon (mpg), while those with incomes more than $100,000 drive vehicles with an average MY of 2008 and average fuel economy of 20.89 mpg.[1] These issues are a contributing factor to California's policy focus on lower- and moderate-income households, especially those who reside in poor air quality areas such as the San Joaquin Valley (Sheldon & Dua 2019a).

[1]These differences are statistically significant at the 1% level. For reference, this 0.55 mpg difference is more than double the increase in average US light duty vehicle fuel economy from 2015 to 2019, which was 0.2 mpg, according to the US Bureau of Transportation Statistics (**https://www.bts.gov/content/average-fuel-efficiency-us-light-duty-vehicles**).

Though lower-income households and communities stand to potentially benefit most from PEV adoption, in terms of fuel cost savings and improvements in local air quality, they account for a much lower share of PEV purchases. Households with annual incomes less than $100,000 account for 72% of all vehicle purchases (new and used combined) but only 44% of PEV purchases (Muehlegger & Rapson 2019). The federal PEV tax credit is increasingly criticized for benefitting mainly well-off consumers.[2] According to a 2019 Congressional Research Service report (Congr. Res. Serv. 2019), in 2016, 78% of the federal tax credits (and 83% of the total credit amount) were claimed by households with adjusted gross income of more than $100,000. Guo & Kontou (2021) find that the bottom 75% of census tracts based on medium income received 38% of California's Clean Vehicle Rebate Program subsidies over 2010–2018, while the top eight census tracts received 25% of the subsidies. While this is in part due to higher demand for PEVs by higher-income households, it may also be in part due to the regressive nature of the tax credit. Taxpayers only receive the full credit for which they qualify (e.g., $7,500) if they owe at least that amount in federal income tax. Any overage does not roll over to the following year.

Not only is the value of the tax credit implicitly constrained by income, but, given that the credit is received during the calendar year following the PEV purchase, the credit is realized between a couple of months and more than a year after the purchase. Because lower-income households are more likely to be capital constrained, financial incentives that are realized closer to the point of purchase are better able to overcome the up-front cost barrier. Indeed, related research has shown that sales tax waivers for hybrid vehicles were ten times as effective as income tax credits (Gallagher & Muehlegger 2011). Nevertheless, while the PEV adoption literature often acknowledges that the type of financial incentives likely matter, empirical models tend to simply combine all financial incentives into up-front cost (e.g., Sierzchula et al. 2014, DeShazo et al. 2017, Li et al. 2017, Jenn et al. 2018, Sheldon & Dua 2019a). No studies explicitly and empirically compare the effectiveness of different types of PEV financial incentives, nor the relative effectiveness of different types by consumer income.

Subsidized financing programs may be another mechanism to help lower-income households overcome the up-front cost barrier of purchasing a PEV. To the extent that these households have low or no credit scores, even with a large tax credit or rebate, the inability to procure reasonable financing may preclude a PEV purchase. However, little is known about the design or impact of favorable financing programs. A working paper by Sheldon et al. (2020) uses data collected from a choice experiment administered to lower- and moderate-income households in California. In addition to varying vehicle type and attributes, choice sets varied financing options such as the interest rate. The authors conclude that offering low, subsidized interest rate vehicle loans to such households could be substantially more cost-effective than offering larger rebates to such households. A relatively new program in California, the Clean Vehicle Assistance Program (**https://cleanvehiclegrants.org/financing/**), aims to ease credit constraints for lower-income households by partnering with a lender that offers special rates at no more than 8% to qualifying households who may qualify even with no credit score or a low credit score.

Another analysis of 2017 NHTS data shows that homeowners are much more likely to own PEVs than renters, even controlling for income (Davis 2019). One in 130 homeowners and 1 in 370 renters with annual incomes between $75,000 and $100,000 own PEVs. While the homeowner-renter gap in PEV ownership is likely driven by access to parking and outlets at home, the authors also point to the landlord-tenant problem. Specifically, renters have less incentive to invest in charging-related improvements (such as upgrading outlets and electric

[2] See, for example, Osaka (2021) and Penn & Chokshi (2021).

panels) to property they do not own. Landlords may also be reluctant to make the investments given that future tenants may not own PEVs.

Another recent study combines California public PEV charging station locations with American Community Survey census block-level data to assess equitability of access (Hsu & Fingerman 2021). The authors find that access to charging infrastructure is lower in Black and Hispanic majority communities as well as in lower-income areas. Furthermore, charging access disparities are larger in census blocks with a greater share of multiunit housing, where residential charging tends to be more difficult and public charging stations may be more important to PEV use and adoption.

4. BENEFITS OF PLUG-IN ELECTRIC VEHICLES

4.1. Local Pollution and Greenhouse Gas Reductions

Whereas gasoline vehicles emit local air pollutants, including carbon monoxide, nitrogen oxides, and hydrocarbons, at the location of combustion, any local air pollution associated with BEVs and PHEVs driven in electric mode arises from the electricity generation attributed to powering the PEV. Thus, local air pollution is shifted geographically, especially from urban areas with higher traffic density to the (often less urban) locations of power plants. PEVs may also be associated with reductions in local air pollution, depending on the power source. For example, coal plants emit sulfur dioxide, nitrogen oxides, and particulate matter, while nuclear and renewable power sources emit no local air pollutants. Similarly, reductions in GHGs depend on the PEV's source of electricity. For example, fossil fuel generation sources emit GHGs while solar power does not. However, because PEVs are often charged overnight, marginal emissions tend to increase generation by baseload sources, which are less likely to be solar power.

Several studies have attempted to quantify the magnitude of air pollution reductions from PEVs, and in some cases, shifts in local air pollutants. Graff Zivin et al. (2014) estimate marginal CO_2 emissions from PEVs by time of day and location. The authors focus only on fossil fuel generation in their analysis due to technical reasons and because renewable sources tend to be nonmarginal. The lowest marginal emissions occur in the western United States, while those in the upper Midwest are more than three times larger. Compared to gasoline vehicles, they find that PEVs driven in the western United States and Texas generate fewer CO_2 emissions than fuel-efficient hybrids, while those driven in the upper Midwest actually lead to an increase in CO_2 emissions relative to the average gasoline vehicle due to the more carbon-intensive electricity generation.

Archsmith et al. (2015) improve on Graff Zivin et al.'s (2014) analysis by considering life cycle emissions and temperature/climate effects on vehicle performance and by incorporating renewable generation. They find that, on average in the United States, replacing a midsize gasoline vehicle with a PEV leads to a small decrease in CO_2 emissions. They also find that in midwestern states, PEVs are associated with an increase in CO_2 emissions, which is exacerbated by cold temperatures that impair battery performance. They calculate that in clean generation regions, the net present value of CO_2 reductions is \$425 per PEV (compared to a \$3,200 benefit were PEVs to be associated with zero CO_2 emissions), assuming a \$38 social cost of carbon (SCC) in 2015 that increases over time and a 3% discount rate.

While prior studies focused on GHG benefits, Holland et al. (2016) also estimate changes in local air pollution due to PEV adoption by incorporating an integrated assessment model. The authors provide a theoretical framework to show that PEV subsidies should be set equal to the difference in lifetime damages between the PEV and a traditional gasoline vehicle and present their results in terms of such a subsidy. On average, assuming an SCC of \$41, they find an optimal

PEV subsidy in the United States of −$1,095, suggesting that PEVs lead to an increase in combined damages from both local and global emissions. However, this subsidy is large and positive in California ($2,785) and considerably lower in North Dakota (−$4,964) due to differential intensity of fossil fuel electricity generation. Furthermore, the authors find that 91% of local air pollution damages associated with PEVs is exported out of state, versus 19% for gasoline vehicles.

Overall, the empirical evidence suggests that PEVs have not delivered the large air quality and GHG improvements envisioned by many, at least not in many regions. Not only do some regions (especially the upper Midwest) have dirtier electricity on average, but there is often a mismatch between the time of day that PEVs cause increases in generation (often at night) and the time of day that the cleanest power sources come online. Note, however, that electricity generation has trended cleaner over the last decade. According to the US Energy Information Administration, 27.9% of the 317.6 gigawatts of coal-fired electric generation capacity in 2011 was retired by 2020 (**https://www.eia.gov/todayinenergy**). Meanwhile, there has been a steady increase in generation by relatively cleaner natural gas, as well as wind and solar (**https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php**). However, existing studies rely on older electricity generation data. Graff Zivin et al. (2014) utilize data from 2007 to 2009. Archsmith et al. (2015) utilize generation data from 2011 to 2012 to estimate marginal emissions, though life cycle emissions are based on various forecasts that incorporate a reduction in coal generation. Holland et al. (2016) use emissions and electricity load data from 2010 to 2012. Going forward, increases in renewable capacity as well as improvements in battery storage could enable more PEVs to charge using electricity from cleaner sources. Other important considerations not accounted for in the current PEV benefits literature, as discussed by Gillingham & Stock (2018), include learning by doing, economies of scale, and induced innovation, as well as increased energy security. Nevertheless, the estimated environmental benefits from PEVs are considerably lower than federal and many state subsidies.

4.2. Distribution of Air Quality Benefits

The broader PEV adoption has been shown to mostly benefit higher-income communities. Holland et al. (2019) build upon the methodology of Holland et al. (2016) by merging their spatial analysis with census block group data, finding that higher-income census blocks (with median income more than around $65,000) receive positive benefits from PEV adoption, and lower-income census blocks receive negative benefits. They also find that on average, census blocks with larger White and Black populations receive negative benefits, while those with larger Asian and Hispanic populations receive positive benefits.

4.3. Caveats

The environmental benefits of a PEV depend on the vehicle that the PEV is replacing. For example, a PEV that replaces a fuel-inefficient vehicle will result in greater benefits than a PEV that replaces a hybrid. The literature quantifying benefits relies on assumptions about counterfactual purchases. Graff Zivin et al. (2014) use two alternative counterfactual vehicles—a comparable economy car and a hybrid. In Archsmith et al.'s (2015) study the counterfactual is an average midsize vehicle, and in Holland et al.'s (2016) the counterfactual is the conventional vehicle most similar to each PEV in the analysis. Two more recent studies estimate vehicle choice models using US new vehicle sales data and use the calibrated models to predict counterfactual fleets assuming that PEVs are unavailable. Sheldon & Dua (2018) find that if PEVs were unavailable in 2015, more hybrid vehicles would be sold as well as more sport utility vehicles (SUVs) and pickups and fewer hatchbacks. Driven by the shift away from passenger cars toward light trucks, the net effect is an increase in gasoline consumption of 1.7% versus 1.1% using a conventional counterfactual (a vehicle with the average fuel economy of that vehicle size, e.g., compact or mid-size). In other words, the authors find that when accounting for more realistic substitution patterns, environmental benefits are somewhat larger than when using the conventional counterfactuals.

Xing et al. (2021) find that 12% of PEV buyers would otherwise buy a hybrid [versus ∼5% according to Sheldon & Dua (2018)]. The authors also find that PEVs replace relatively fuel-efficient cars with fuel economies 4.2 mpg on average greater than the fleet-wide average. This suggests that a conventional counterfactual approach overestimates the environmental benefits of PEVs by up to 39%.

There are a couple of possible reasons for the discrepancy between these two studies' findings. First, the data used by Xing et al. (2021) include survey responses indicating new car buyers' second choice vehicle, i.e., what they claim they would have purchased had their top pick not been available. This allows for better identification of preference heterogeneity. Second, Xing et al.'s data are from MY 2010–2014, whereas Sheldon & Dua's (2018) data are from MY 2015. Xing et al. may therefore pick up preferences of very early adopters, whereas Sheldon & Dua's (2018) results reflect a market with more PEV options that appeal to a larger segment of the new car buying population. Nevertheless, better understanding substitution patterns, particularly as the PEV market matures, will be a crucial factor in determining realized PEV benefits.

Another critical assumption underlying quantification of PEV benefits is their use patterns. Most of the literature quantifying environmental benefits assumes similar vehicle lifetime and VMT for PEVs as for conventional vehicles. Chakraborty et al. (2021b) use data from a multi-wave survey of PEV owners in California from 2015 to 2019 that include odometer readings from two different years to show that PEVs were driven approximately as much as, if not more than, conventional vehicles. Specifically, they found that on average, BEVs and PHEVs were driven 11,250 and 12,000 miles per year, respectively, with longer-range BEVs being driven 13,000 and shorter range ones being driven 10,250. This is in comparison to a statewide average of 10,790 miles per year for gasoline vehicles, according to the 2017 NHTS. However, the 2017 NHTS also documents an average annual VMT of only 7,040 for BEVs. Given that the respondent sample of Chakraborty et al. (2021b) consisted of less than one-fifth of the 25,000 PEV owners who participated in the first survey wave, it is possible that the sample was biased toward PEV enthusiasts, with heavier than average use patterns.

Burlig et al. (2021) avoid the sample selection problem by using electricity use data from 10% of residential meters in California's largest utility territory combined with EV registration records from 2014 to 2017. The authors estimate an event study and a differences-in-differences model to assess the change in PEV owners' household electricity use data after the PEV registration. They find that increases in electricity usage by these households is much lower than regulatory estimates, translating into approximately 1,700 electric miles per PHEV per year and 6,700 for BEVs. This suggests that, for the average PEV owner in California, PEVs are not nearly a perfect substitute for conventional vehicles. Indeed, a new working paper by Davis (2021) shows that 90% of PEV-owning households own at least one other vehicle and 66% have a nonelectric vehicle in which they drive more miles per year than their PEV. Although less is known about PEV VMT across the rest of the country, these usage patterns imply that environmental benefits may be considerably lower than previously estimated.

Given the different usage patterns of PEVs, there is a case to be made for policies targeting electric miles rather than PEV penetration. Indeed, Rajagopal & Phadke (2019) find an inverse relationship between PEV payback period and VMT, making the case that public policies to encourage PEV adoption should target high-use vehicles and applications. Some studies have also found that public charging infrastructure can increase electric VMT (Dong et al. 2014, Smart & Salisbury 2015).

Another PEV policy consideration is that as the PEV share increases, gasoline tax revenues decline. Using 2017 NHTS data, Davis & Sallee (2020) calculate the annual national loss in gasoline tax revenue due to PEVs to be $250 million. This has led many states in recent years to charge annual PEV fees, which are usually on the order of $50–200 (Hartman & Shields 2021). However, the theoretical analysis of Davis & Sallee (2020) does not offer a clear prediction of whether an optimal PEV mileage tax (more efficient than a fee) would be positive or negative, given competing externalities; i.e., although PEV drivers do not pay for congestion and accident externalities via the gasoline tax, they produce offsetting positive environmental benefits. The authors also point out that the regressive nature of the gasoline tax is exacerbated by PEVs, whose relatively higher-income drivers avoid the tax.

A last caveat about PEV benefits is that little research has been done on the interactions between PEV adoption policy and policies in other sectors with overlapping goals. Gillingham et al. (2021) provide a cautionary tale in the case of PEVs and carbon pricing. The authors use a dynamic simulation model to evaluate the impact of PEV adoption on GHG emissions from electricity generation under a range of carbon price scenarios. They find that PEV adoption policies would more effectively reduce GHG emissions with a high carbon price or no carbon price. However, they show that with a moderate carbon price, coal is more likely to be the marginal generation source such that an increase in electricity demand from PEV adoption is likely to be met by coal generation, and coal retirements are likely to slow, leading to relatively higher GHG emissions.

5. THE USED PLUG-IN ELECTRIC VEHICLE MARKET

The used PEV market is still relatively nascent. Research on it is sparse and data are limited. In 2020, used light vehicle sales were nearly three times higher than new light vehicle sales (**https://www.statista.com/statistics/183713/value-of-us-passenger-cas-sales-and-leases-since-1990/**). As such, the used PEV market has important implications for fleet fuel efficiency, lifetime PEV environmental benefits, and equity.

The federal tax credit and most state incentives are restricted to new PEV purchases. The market price of used PEVs therefore depends on how well these vehicles hold their value. One recent study using Edmunds.com data from MY 2010 to 2016 found that PEVs generally do not hold their value as well as conventional vehicles or hybrids (Guo & Zhou 2019). Mass market BEVs held the least value, losing 15–25% more than mass conventional vehicles. Older luxury BEV models held less value, but by MY 2015 and 2016 they held more value than conventional vehicles. Differences were greater for earlier MY, suggesting concerns about battery deterioration as the vehicles age. Mass market PHEVs held value about as well as regular hybrids (which is slightly less than conventional combustion engine vehicles), and the Tesla Model S held value the best: more than 80% versus 45% for conventional vehicles for MY 2012. These results suggest that used high-end PEVs such as Teslas will continue to be expensive, while mass market BEVs will be relatively more affordable.

Nevertheless, a study of PEV owners in disadvantaged communities in California shows that both new and used PEV owners in these communities are not representative of their communities: They have higher incomes, more education, and are more likely to be homeowners (Canepa et al. 2019). Mean household income of used PEV buyers in disadvantaged communities was more than $182,000. Thus, initial evidence implies that although the price gap between new and used PEVs appears to narrow more than for conventional vehicles, the price still remains too high for lower-income households and/or demand for used PEVs is much stronger from higher-income households.

Many important questions about the used PEV market remain unanswered. Which used vehicles are replaced by used PEVs? What will used PEVs displace (i.e., what are the marginal vehicles scrapped and/or exported?)? What will average annual electric mileage and functional lifetime of used PEVs be, and how do they compare to conventional vehicles? Answers to these questions will have important consequences for total lifetime PEV pollution reductions.

6. CONCLUSIONS

Now that the modern PEV market has existed and related policies have been in effect for a full decade, research has shed much light on what drives PEV adoption, how effective policy has been, what the environmental benefits of PEVs are, and who has benefitted most from PEVs. Many gaps in our knowledge remain to be filled, and much can be done to improve effectiveness and equity of PEV policy.

A major concern in the very early market was the limited range of BEVs. This concern seems to have been somewhat allayed given the entrée of PHEVs in the market and the strong upward trend of BEV range, which more than covers the average commute. The primary barrier to adoption appears to be up-front cost.

Federal and state financial incentives help reduce the cost of purchasing a new PEV, and PEV owners generally cite these as the most important incentive in their car buying decision. Nevertheless, these subsidies appear expensive (with a policy cost per additional PEV purchase of around \$30,000) due to the free-rider problem (i.e., they are given to all consumers, including those who would purchase the PEV absent the incentive). For example, an average subsidy of \$5,000 only increases PEV adoption by 17% due to imperfect targeting. This leads to a policy cost of \$5,000/.17 = ∼\$30,000. In other words, for each consumer induced by the subsidy to purchase the PEV, the subsidy must also be given to five other consumers who would have purchased the PEV regardless. Meanwhile, though potential PEV consumers cite away-from-home charging as an important consideration, the vast majority of charging takes place at home, and there is very little empirical causal evidence on its effectiveness in terms of PEV adoption. Mixed evidence on usage suggests there are many inefficiencies in current siting and pricing of away-from-home PEV charging infrastructure. Future research could help determine optimal siting and pricing.

Lower-income households stand to benefit more from PEV adoption both in terms of improvements in local air quality and reduced operating costs. Not only would there be larger pollution reductions on average from switching, as this population tends to drive less-fuel-efficient vehicles, but lower-income households also frequently live in areas with worse air quality where the marginal benefit of a reduction in local air pollutants may be large. However, the large majority of PEV buyers are higher-income buyers. Indeed, higher-income households have been the primary beneficiaries of the federal tax credit, not only because they buy more PEVs, but also because they are generally able to claim a larger portion of the maximum credit. Capital constraints for lower-income consumers suggest financing programs could be helpful, but they are little explored. There is also a renter-homeowner gap, and less public charging infrastructure is located in disadvantaged communities. Preliminary evidence shows that even the used PEV market is dominated by higher-income households and that realized PEV benefits are disproportionately received by higher-income neighborhoods. Together, this implies an upward battle to get PEVs into more lower-income households.

Research has also shown that the environmental benefits of PEVs are much smaller than commonly believed and in some regions are nonexistent or negative. Benefits are generally smaller than federal and state subsidies, though dynamic considerations could increase the optimal subsidy above damages from air pollution. For example, more research quantifying knowledge spillovers and increases in energy security could better justify higher subsidy levels. Regular updates to estimates of environmental benefits would also be useful given the continual greening of the electricity grid. Furthermore, many behavioral and usage considerations are not well understood and could substantially impact realized benefits. Estimated environmental benefits make assumptions about vehicles replaced by PEVs and generally assume a high degree of substitutability between PEVs and conventional vehicles. Empirical evidence casts doubt on some of these assumptions, though research is limited and results are mixed, meriting more exploration. New research also shows that most PEV households have at least one additional vehicle and drive PEVs fewer miles than gasoline vehicles. This suggests that the estimated environmental benefits may actually be lower in reality. A better understanding of usage and full quantification of benefits, including for the used market, would allow for a more thorough welfare analysis of PEV policy.

Given our current state of knowledge, PEV subsidies are often expensive relative to their environmental benefits. Regardless of the level of future subsidies, policy design should consider how to minimize free-ridership, for example, by targeting subsidies strategically by income or vehicle replaced. More research is also needed on policy instruments that may better enable lower-income households to overcome the PEV cost barrier (e.g., rebates versus tax credits, financing programs). Given the lower mileage that PEVs appear to be driven, more research is warranted on targeting electric miles rather than PEV market penetration. Lastly, given the spatial heterogeneity of PEV benefits, policy makers should also consider geographic variation in PEV subsidies.

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