RESEARCH REPORT

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Potential Challenges and Research Needs in Reaching 100% Zero Emission Vehicle Sales - A Focus on Plug-In Electric Vehicles

Scott Hardman, PhD, Professional Researcher[1]
Amrita Chakraborty, Graduate Student Researcher[1]
Kelly Hoogland, Graduate Student Researcher[1]
Claire Sugihara, Graduate Student Researcher[1]

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[1] Institute of Transportation Studies, University of California, Davis

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Scott Hardman, Ph.D., https://orcid.org/0000-0002-0476-7909 Amrita Chakraborty, https://orcid.org/0000-0001-8048-7282 Kelly Hoogland, https://orcid.org/0000-0001-5791-0767 Claire Sugihara, https://orcid.org/0000-0001-7238-2974	UCD-ITS-RR-23-38

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16. Abstract
This project provides a literature review of research on zero emission vehicles (ZEVs) which includes fuel cell vehicles, battery electric vehicles, and plug-on hybrid electric vehicles, the latter are referred to as plug-in electric vehicles (PEV). In the review we focus on PEVs due to a lack of literature on fuel cell vehicles. We consider buyer and consumer perceptions of PEVs including perceived barriers to PEV adoption, consumer knowledge of PEVs, issues associated with incentives, and issues associated with infrastructure. The aim is to understand potential barriers to higher PEV sales and future research needs relating to PEV adoption. The PEV market shows many signs of becoming more robust. This includes PEV buyer demographics shifting toward the demographics of buyers of all types of new cars and improvements in PEV technology. Some challenges may remain, however. These include understanding the needs of households without home charging, engaging female car buyers in PEVs, engaging more of the general population in the PEV transition, substantially reducing PEV purchase prices, and incentive discontinuities potentially impacting adoption. Finally, disparities in rebate allocation, infrastructure deployment, and PEV sales indicate the transition is not yet equitable. This may require specific policy actions to address.

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Executive Summary

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In this report we review literature to identify potential barriers to higher sales of zero emission vehicles (ZEVs), specifically focusing on plug-in electric vehicles (PEVs). The focus is on PEVs since there is more literature on those ZEV types compared to fuel cell electric vehicles. In this review, PEVs are any vehicle that can be plugged-in, including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Topics we focus on include sociodemographic profiles of PEV buyers, consumer perceptions of PEVs, perceived barriers to PEV adoption, consumer knowledge of PEVs, incentive efficacy, and infrastructure challenges. We highlight opportunities to support PEV adoption that are supported by research and identify areas where further study is needed.

So far, PEV buyers have predominantly been high-income, highly educated, homeowning, male, middle-aged or older, and own multiple vehicles in their household. Over time, PEV buyers' income, level of education, age, and number of household vehicles are becoming more similar to the average for new car buyers (Lee, Hardman and Tal, 2019; Williams, 2022). However, there has been little change to PEV buyer gender and home ownership, with PEV buyers remaining mostly male and the majority owning their home. Studies typically report fewer renters purchasing PEVs due to a lack of access to home charging. Reasons why other genders are less likely to purchase PEVs are unclear and warrants further research. Monitoring PEV market changes over time will enable responsive policy action.

Progress has been made on increasing PEV range, reducing charging times, and expanding infrastructure access. These, along with purchase price, continue to be the most frequently reported barriers to PEV adoption (Muratori et al., 2021). Progress on PEV purchase price has been mixed. At the lower end of the market, PEVs are available from around $25,600. Yet, from 2019 to 2022, the average transaction price of PEVs increased and is diverging from the average transaction price of conventional vehicles (Osaka, 2022). Projections that PEVs will reach price parity (Slowik et al., 2022) are not supported by historical PEV price trends as the average PEV price has increased in the United States (US) at a higher rate than internal combustion engine vehicles (ICEVs) (Osaka, 2022).

While technological improvements to PEVs continue, consumer awareness, perceptions, and knowledge of PEVs are not improving in a commensurate way. Several longitudinal studies surveying car buying households (Kurani 2019, 2022a, 2022b) show little change in consumer knowledge, perception, or intention to purchase a PEV. Despite increases in range, reductions in charging time, and increased charging access, buyer perceptions of PEVs have not significantly improved. This may indicate a disconnect between actual PEV performance and consumer perceptions. Non-technical solutions may be required to better inform consumers. Research shows greater resistance to PEVs among new car buyers in California and the US (Kurani, 2022b), and low support for a ZEV sales regulation in Canada (Long et al., 2020). It could be argued that those who resist PEVs will have to buy a PEV regardless, because of sales regulations, but the reasons why they oppose PEV purchase should be researched so that they can be addressed.

Slower rates of adoption among some groups could limit progress towards greenhouse gas reduction goals. Ignoring those who are resistant to policy can pose risks because policies with substantial opposition can fail (McConnell, 2015). Additional measures may be needed to engage consumers on a larger scale than has been done previously. These may include supporting information campaigns focused on increasing education and awareness of PEVs, and conventional advertising of PEVs by automakers. Beyond receiving information and advertising, consumers may also benefit from hands-on experience operating PEVs. Interacting with PEVs has been found to reduce range anxiety and quality concerns (O'Neill et al., 2019; Wicki et al., 2022).

Most studies on the impact of incentives find a positive and significant relationship between the availability of incentives and PEV adoption or adoption intention (Hardman et al., 2017). The impact varies based on how incentives are distributed to buyers. Incentives delivered at the point-of-sale are more impactful and efficient than those delivered later (Roberson and Helveston, 2022). Incentives in many international PEV markets are delivered at the point-of-sale, however, in the US, many incentives are delivered after PEV adoption. This lowers consumer perception of incentive value, likely limiting effectiveness, especially for lower income buyers.

We identified only one study that considered changes to the impact of incentives over time. There was an increase in the number of consumers reporting they would not purchase a PEV without the federal tax credit from 2010 to 2017 (Jenn et al., 2020a). Incentive importance was correlated to income, among other variables. Buyers with a high income were less responsive to tax credits and rebates than lower income buyers. If the trend continues, lower income buyers, who are more dependent on incentives, may be less likely to purchase a PEV. Incentives may, therefore, continue to be an important tool in encouraging car buyers to purchase a PEV.

Incentive programs in the US address some aspects of equity but could be more progressively designed. If funding for incentives is limited, targeting them for consumers whose PEV purchases depend on incentives may be necessary. This includes (adapted from Hardman et al. 2021):

- increasing incentive amounts for lower-income buyers;
- implementing purchase price caps or income caps to exclude those who do not need incentives;
- allowing buyers to claim the incentive regardless of purchase location (e.g., not only at a dealership);
- allowing lower-income buyers to apply the credit to used PEVs;
- not tying incentive amounts to tax liability (as is the case for the US federal tax credit);
- applying incentives at the point-of-sale;
- providing assurances on incentive availability in the case of funding discontinuities (which have been a recurring issue with California programs); and
- increasing awareness of available incentives.

Changes to the US federal electric vehicle incentive due to the 2022 Inflation Reduction Act may address some issues and inefficiencies reported in the literature, however, the changes could also reduce the program's overall effectiveness because fewer purchased PEVs will be eligible for incentives. Beginning in 2024,

consumers eligible for a tax credit could receive it at the point-of-purchase by effectively transferring their 'future' tax credit from the federal government to the dealership as a discount on the purchase price. Income caps and vehicle price caps have already been implemented, limiting the number of incentives going to high income buyers. These changes may increase incentive efficiency by targeting those that need incentives the most. However, under the new system, many PEVs will not qualify for an incentive. Those that do qualify may only receive half of the full amount of $7,500 due to stipulations in vehicle component manufacturing locations. The incentive also remains as a tax credit, still tying the incentive amount received to taxes owed, potentially resulting in lower-income buyers not being able to receive a full incentive as they have a lower tax burden. Future research should investigate the impact of these changes on the federal PEV tax credit.

Research on the availability of charging infrastructure shows that access to home charging has so far been the most influential charging location in the decision to purchase a PEV, home is the most frequently used charging location, and availability of home charging is important in the decision to continue owning a PEV (Hardman et al., 2018a; Hardman and Tal, 2021). A higher portion of future buyers of new and used PEVs are likely to reside in homes without home charging, including rented homes and apartments or condos. To best support policy development, research will need to consider several questions:

- how households without home charging could be served by workplace, at or near home (not in a private driveway), or public charging;
- whether access to workplace or public charging will encourage PEV adoption;
- how to increase home charging access for households that cannot afford home charger installation; and
- how to install charging that serves multi-unit housing residents.

Research on the impact of public charging on PEV sales is mixed. Some findings suggest that infrastructure availability can cause sales (Mersky et al., 2016; Narassimhan and Johnson, 2018), whereas other studies show that the former merely correlates with but does not cause sales (Hoogland et al., 2022; White et al., 2022). Understanding whether infrastructure influences sales, or vice versa, is important for several reasons. If sales influence infrastructure development, the charging network could be unevenly developed, mostly serving existing PEV owners rather than future PEV buyers. Policymakers need to understand this relationship because infrastructure is sometimes considered a tool to increase PEV sales. Research, however, shows no relationship between the density of chargers in an area and the tendency of people in local car-owning households to report having seen the infrastructure (Hoogland et al., 2022). More actions may be needed to engage consumers with the PEV transition.

Research shows that disadvantaged communities, underserved communities, and communities of color have fewer public charging stations and fewer home types associated with home-charging access (C. W. Hsu and Fingerman, 2021). Policymakers, charging providers, and researchers will need to focus specifically on the needs of these communities to understand what types of charging may best serve them. Without consideration of how to provide access to charging, there is a risk of perpetuating under investment in transportation access in communities that have historically been underserved. This inhibits the ability of these communities to access

the health (lower emissions, lower noise) and economic (lower operating costs) benefits of PEVs. The US Justice40 Initiative directs 40% of federal investments in PEV charging to disadvantaged communities (The White House, 2022). This may help increase the distribution of PEV charging in underserved communities. However, even if charging is equally distributed, this may not serve the needs of PEV buyers in the same way across communities. Policymakers and other stakeholders should engage communities in planning processes through engagement, community led analysis, community organization, and participation in budgetary processes (Karner et al., 2020).

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Introduction

More than 30 countries, as well as several regions (e.g., California, British Columbia), have indicated their intent to reach 100% zero emission vehicle (ZEV)[1] sales by between 2025 and 2040. Most governments declaring their intention to reach 100% ZEV sales currently have ZEV shares of new vehicle sales, and even lower shares of ZEVs of vehicles on the road. In 2021, 2.5% of global vehicle sales were electric, most large auto markets are at less than 10-20% ZEV sales, with some Nordic nations achieving sales of between 30% and 90% in 2021. This means most regions (except for Norway) are heading toward uncharted territory.

Most existing studies do not consider the challenges of attaining 100% ZEV or PEV sales. Therefore, our aim is to identify potential barriers to higher ZEV sales (focusing on PEVs), highlight areas where progress is needed, and determine where more research may be needed. In this report we review literature on plug-in electric vehicle (PEV) adoption (rather than ZEVs which would also include fuel cell electric vehicles) and potential adopter profiles, perceived barriers to PEV adoption, and issues associated with PEV incentives and infrastructure. Most of this literature is on plug-in electric vehicles (PEVs), including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). For this reason, we focus on PEVs, and not on fuel cell electric vehicles. We discuss potential barriers to reaching 100% PEV sales and future research needs to help understand this transition using insights from the literature. We discuss characteristics of current adopters, perceptions of PEVs, incentives, and infrastructure as issues that broadly relate to consumers.

Not all households need to purchase a PEV to reach 100% PEV sales, because not all households purchase new vehicles. Consequentially, most research on PEV adoption focuses on new PEV purchases. Therefore, we mainly review literature on new vehicle adoption and include literature on used PEV adoption where available. We consider studies in all regions and do not select studies with specific methods. Our review is a narrative; we do not systematically identify all studies on PEV adoption. Our goal is to use this literature to identify potential challenges in reaching 100% ZEV sales and future research needs (see discussion). Similar to Wicki and others (2022), we consider challenges along different determinants. We consider the following:

- Sociodemographic and lifestyle determinants, including who is currently buying PEVs, their demographic profile and lifestyle, attitudes, or norms, whether EV buyers are new car buyers, and whether PEV buyers are changing over time.
- Perception and knowledge determinants, including attitudes, perceptions, and purchase intentions towards PEVs and their attributes (e.g., range). This also includes knowledge of PEVs and how car buyers may learn about PEVs.
- Contextual determinants, including incentives and infrastructure. For incentives, we consider how they have so far impacted PEV sales, how their removal could impact car buyers, and whether incentives address inequities in the PEV market. For infrastructure, we consider the relationship between

[1] ZEVs include battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEV), collectivity referred to as plug-in electric vehicles (PEVs), and fuel cell electric vehicles (FCEVs). The latter are not considered in this study.

infrastructure and PEV sales, the distribution of infrastructure, refueling behavior of PEV buyers, and differences in infrastructure access.

Literature Review

Sociodemographic and Lifestyle Determinants

Sociodemographic Profile of Electric Vehicle Buyers

Prior to the market introduction of PEVs, researchers used stated preference studies to characterize potential early PEV buyers. These stated preference studies found that PEV buyers are likely to be male, highly educated, have a higher than average household income, reside in a multi-vehicle household, and be young or middle-aged (Carley et al., 2013; Hackbarth and Madlener, 2013; Hidrue et al., 2011; Plötz et al., 2014). More recently, papers that profile PEV buyers, generally show that their demographics are similar to those predicted by stated preference studies. Studies with data on PEV buyers find they are generally higher income, highly educated, own multiple vehicles, and are more likely to be male (Axsen et al., 2016; Fevang et al., 2021; Lee et al., 2019). Rather than being younger to middle aged, PEV adopters are generally middle- to later-aged. Research also suggests PEV buyers are clustered in specific regions due to network effects (Chakraborty et al., 2022). A study by Canepa et al. (2019) also found used PEV buyers were not similar to the general population, with used PEV buyers being more likely to own their home, live in a detached house, have a higher level of education, and have a higher household income. A more recent study found that used PEVs are more geographically dispersed than new PEVs, though they were still more likely to be in areas with higher numbers of new PEVs. Zip codes with a higher share of used PEVs had higher median incomes compared to zip codes with low shares of used PEVs (Tal et al., 2020).

These characteristics mean that PEV buyers are dissimilar to conventional car buyers. The demographics of PEV buyers have been changing over time. However, the changes have been small, so far (Lee et al., 2019). While PEV buyer demographics are not similar to all households, research on California rebate recipients is beginning to show some convergence with PEV rebate recipients and new car buyer demographics (Williams, 2022), though this could be a result of income and vehicle purchase price rebate eligibility criteria. New car buyers, like new PEV buyers, are generally higher income, older, more likely to have a college degree, own their home, and identify as white/Caucasian compared to the general US population. Gender among new car buyers in the US population is roughly 50% male, whereas rebate recipients are 71% male. The percent of new car buyers that own their home is higher than in the general population (63% vs. 54%), and the percent pf PEV buyers than own their home is even higher (84%) (Williams, 2022). Gender and home ownership may be the biggest difference between new car buyers and PEV buyers, and neither attribute has changed substantially since the PEV transition began.

PEV adopters are still a minority of vehicle owners in all regions. In Norway, the leading PEV market, only 23% of all vehicles on the road are electric. In California, only 3% of vehicles on the road are electric. The current understanding of PEV buyers still represents understanding the earliest adopters of PEVs. More research may need to consider mainstream buyers (Axsen et al. 2016) and identify differences in their perceptions and

motivations relative to early PEV buyers. Studies should also consider why some people are reluctant to adopt PEVs and reasons why others currently indicate they would not purchase a PEV. Adoption of PEVs by these households will be essential in reaching 100% PEV sales.

Lifestyles, Attitudes, and Norms of PEV Buyers

PEV adoption is related to consumer beliefs, attitudes, and norms (Haustein and Jensen, 2018). Having positive attitudes toward pro-environmental behavior is significantly related to PEV acceptance in 33 of 38 studies reviewed by Wicki et al. (2022), while interest in technology was identified as significant in 7 of 12 studies that included technology as a measure. Additionally, studies found that concerns about foreign oil (Carley et al., 2013; Hardman and Tal, 2018) and local air pollution (Hardman and Tal, 2018) are correlated with PEV adoption. Compared to PEV adopters, buyers of conventional vehicles have fewer norms and attitudes related to their decision to own a vehicle (Haustein and Jensen, 2018). This may mean conventional vehicle buyers will not be motivated to purchase PEVs unless attitudes correlated with PEV adoption become more widespread, PEVs are perceived as having other meanings, or PEVs are perceived as a mainstream choice.

Existing studies test a limited set of variables related to attitudes, beliefs, and norms when studying the correlation with PEV interest. For example, Hardman and Tal (2018) only include three measures: local air pollution, greenhouse gas emissions, and oil dependency. White and Sintov (2017) include five: environmentalism, social innovator, environmental behavior, climate change, and car identity. Haustein and Jensen (2018) consider six attitudes and norms formed from a list of 21 attritional statements on car ownership, mobility, PEVs, and environmental issues. The choice to include these variables may be because PEV interest is correlated with beliefs and attitudes that early adopters have.

As the market for PEVs progresses, more consumers will adopt them, different models will become available, and automakers will develop marketing strategies. With these changes, PEVs could elicit different meanings and symbolism for different consumers. This may result in additional attitudes, beliefs, and norms becoming associated with PEV adoption. Most studies, therefore, while including the key variables associated with PEV interest, may omit variables that could elicit PEV interest among future buyers of PEVs. With rapid changes in the market and goals in reaching 100% ZEV sales, it will become more important to consider including variables that have not, so far, been correlated with PEV adoption. For example, in the US, outdoor lifestyles are featured in conventional vehicle marketing (Berk, 2021). If PEVs are framed in this way, outdoor lifestyles could become correlated with PEV adoption.

Technological, Economic, and Social Determinants

This section focusses on barriers to PEV adoption as perceived by consumers. Studies on factors affecting PEV adoption commonly categorize barriers as technological, economic, or social (Adhikari et al., 2020; Axsen et al., 2017; O'Neill et al., 2019; Tarei et al., 2021). We follow this grouping in exploring barriers to PEV purchase below.

Technological determinants

Range

The limited driving range of BEVs is one of the most commonly mentioned barriers to adoption in the literature (Wicki et al., 2022). Some studies found range to be the most important barrier to PEV adoption (Adhikari et al., 2020; Franke et al., 2012; Schneidereit et al., 2015). Consumers reported BEV range was insufficient in comparison to that of internal combustion engine vehicles (ICEV) and compared to the range needed or desired in daily use (Krishna, 2021; Kurani et al., 2018; Rezvani et al., 2015). They also reported that BEV range was insufficient for longer trips (Axsen et al., 2017; Hardman et al., 2017). In particular, drivers with higher travel distances placed a greater importance on range (Adhikari et al., 2020; Wicki et al., 2022). Drivers were also concerned with range as it related to the potential impacts of ancillary load (e.g., heating, cooling), driving style, weather, towing, and battery degradation (Krishna, 2021; Tarei et al., 2021). People living in rural areas may have a higher sensitivity to range limitations as they drive longer average distances to work and other destinations (Krishna, 2021). Households with more vehicles reported less range anxiety than those with fewer vehicles (Wicki et al., 2022). This is likely because drivers can use other vehicles in the household for longer trips. Range concerns mean some consumers favor PHEVs because they can use the ICEV when needed (Carley et al., 2013; Tarei et al., 2021).

Charging

Range anxiety can be exacerbated by the longer time required for charging PEVs in comparison to fueling ICEVs (Krishna, 2021; Rezvani et al., 2015). Wicki et al. (2022) identified long charging times as one of the top three concerns reported in the literature. Studies conducted in North America, Europe, and Asia found charging is the most substantial barrier for PEV purchase (Adepetu and Keshav, 2017; Franke et al., 2012; Jabbari et al., 2017; Schneidereit et al., 2015; She et al., 2017; Tarei et al., 2021; Vassileva and Campillo, 2017).

Lack of access to charging stations while at home is a commonly reported barrier, particularly for consumers without a private garage or dedicated parking space. Wicki et al. (2022) found that increasing the availability of home charging stations has a positive effect on BEV adoption, and several studies found home charging availability is the most influential in the decision to purchase a PEV (Bailey et al., 2015; Dunckley and Tal, 2016; Skippon and Garwood, 2011). Axsen et al. (2017) found that consumers viewed home charging as convenient, and public charging as inconvenient. Compared with new car buyers, used PEV buyers are more likely to perceive there are not enough places to charge a PEV, and are less likely to have access to charging at home (Kurani, 2022a). Studies report that consumers find it difficult to locate convenient charging stations away from home. This can make it difficult to incorporate PEVs into one's lifestyle, particularly for people without access to home charging (Axsen et al., 2017; Krishna, 2021).

In additional to a perceived lack of charging availability, consumers report being deterred from purchasing PEVs due to the complexity of charging station infrastructure. For example, PEV drivers may face limited charging station locations, stations with various charging speeds, and stations operated by different charging providers which may require unique membership cards (Hardman et al., 2018). Interoperability, where drivers can access any station via one payment or access method, has been found to positively impact the favorability

of PEVs (Hardman et al., 2018). A Norwegian study found that drivers saw a single access method as the easiest solution and this option was preferred by 61% of PEV owners (Lorentzen et al., 2017).

In addition to interoperability, information on how payments work for each station need to be made clear to users (Hardman et al., 2018). Stations often have multiple components that determine price (e.g., charging speed, price, energy consumed, connection fee), which is not the case for ICEVs. This is seen as confusing and can lead consumers to not adopt PEVs. LaMonaca et al. (2022) recommend greater transparency so that customers are fully informed on the comparative price of charging between various operators and home charging.

Performance

Reported PEV driving performance concerns include power, top speed, noise, and responsiveness (Adhikari et al., 2020; Krishna, 2021; Rezvani et al., 2015). While some studies found that acceleration, smoothness, and decreased noise of BEVs were a benefit, other studies found that BEVs were viewed less favorably in terms of performance (Krishna, 2021; Rezvani et al., 2015; Wicki et al., 2022). This discrepancy may be at least partially attributable to drivers' lack of education and experience with PEVs, as numerous studies found perceptions of PEVs are positively correlated with experience (Jensen et al., 2013; Roberson and Helveston, 2020; Skippon and Garwood, 2011).

Safety

Safety concerns were found to be prevalent throughout older studies, and in studies on emerging PEV markets (Egbue and Long, 2012; Graham-Rowe et al., 2012; Krishna, 2021). Recent research shows similar results with PEV drivers reporting their vehicle posed a medium level of risk (Pardo-Ferreira et al., 2020). Negative perceptions of safety relate to the battery as well as the vehicle itself (Schuitema et al., 2013). Consumers expressed concerns around the lack of noise generated by vehicles, which they viewed as being unsafe for both pedestrians and vehicle occupant(s) (Krishna, 2021). The combination of faster speeds and lower ambient noise leads to further safety risks for pedestrians, who may not hear a vehicle approaching (Tarei et al., 2021). Recent (2018 in the US, and 2019 in the EU) regulations mandate PEVs to omit synthetic noise, which may ameliorate this issue.

Perceptions of Technology

Some consumers are known to resist new technology (Rogers, 2003). This phenomenon has been found to affect the PEV market, with some people perceiving their novelty as a barrier to adoption (Tarei et al., 2021) and indicating they would not purchase a PEV (Kurani, 2022a). Several studies report consumers view PEVs as a developing technology that has not yet achieved its full potential (Graham-Rowe et al., 2012; Krishna, 2021). The adoption of PEVs has been found to be related to buyers' interest in new technology (Egbue and Long, 2012; Hardman and Tal, 2016; Schuitema et al., 2013), and those who are not interested in new technology have been found to be less interested in PEVs (Axsen et al., 2012). There is moderate agreement among car owning households that BEVs are "ready for mass markets," with a slight increase in agreement from 2019 to

2021, higher agreement among new car buyers, and higher agreement by respondents in California compared to other states (Kurani 2022b).

Model Availability

Consumers reported that the lack of diversity in vehicle types is a barrier to PEV purchase (Adhikari et al., 2020; Kurani et al., 2018). This includes offerings not being available with certain drivetrains (e.g., four-wheel or all-wheel drive) and body types (e.g., sedans, hatchbacks, pickup trucks) (Krishna, 2021). The limited number of available options decreases the chance that a PEV will appeal to a wide range of customers (Adhikari et al., 2020). Hoen and Koetse (2014) found a positive association between the number of models available and the preferences for PEVs. The number of PEV models in the US is limited compared to that of ICEV models, however, less mature PEV markets face even fewer vehicle choices (O'Neill et al., 2019). Other model availability issues include a lack of brand choice, a lack of used PEVs, and long waiting periods for vehicles (Krishna, 2021; Tal et al., 2017; Thomas Turrentine et al., 2018).

Economic determinants

Purchase and Operating Cost

Purchase price was frequently mentioned as a barrier to PEV adoption (Kurani et al., 2018) with some studies finding this to be the most substantial barrier (Adepetu and Keshav, 2017; Vassileva and Campillo, 2017). While lower operating costs can result in cost savings over the lifetime of a vehicle, higher initial costs can cause consumers to doubt long-term savings (Wicki et al., 2022). Consumers may also ignore the potential operational cost savings and focus only on upfront costs, increasing the impact of the purchase price barrier (Hardman et al., 2017; O'Neill et al., 2019). Other studies found that consumers lack the expertise needed to calculate total cost-of-ownership savings of PEVs (Rezvani et al., 2015), and earlier work shows that consumers are often unaware of vehicle economy or fuel expenditures (Turrentine and Kurani, 2007).

Higher upfront costs can create a challenge for consumers who need to finance their purchase but do not have enough credit to support the higher price (Adhikari et al., 2020). This barrier is likely to be particularly problematic for individuals who primarily purchase used vehicles, as they are generally more price-sensitive (Hoen and Koetse, 2014). De Rubens et al. (2018) found that, in many of the Nordic countries, the high purchase cost of PEVs in comparison to ICEVs inhibited their sale even when incentives were factored in. The higher purchase price barrier demonstrates the need for incentives that directly reduce the purchase price of PEVs (Hardman et al., 2017; Rezvani et al., 2015).

Some perceive PEVs as more expensive to maintain and repair than ICEVs (Krishna, 2021). Consumers reported believing batteries have an expected life of 8 to 10 years, which may require them to replace the battery during the vehicle's lifetime (Wicki et al., 2022). Accelerated degradation due to extreme weather, driving conditions, or charging were seen as potentially accelerating degradation, causing the battery to need to be replaced sooner (Adhikari et al., 2020). While studies generally found PEVs to have lower operating costs compared to ICEVs, the perception that they may have higher operating costs acts as a barrier for consumers (Wicki et al., 2022).

Social Determinants

Unclear Environmental Benefits

Some consumers may be skeptical that PEVs can provide the social and environmental benefits that they claim, thus creating a lack of trust in the technology (Axsen et al., 2017; Krishna, 2021; Tarei et al., 2021). Some consumers report their desire to contribute to social benefits, but are unsure whether PEVs would help them achieve their goal(s) (Kurani et al., 2018; Wicki et al., 2022). Some drivers report being unaware of the environmental harms caused by ICEVs, so are therefore unaware of the emissions reduction benefits of PEVs. (Adhikari et al., 2020).

Consumers question whether battery manufacturing and disposal processes mitigate their benefits (Axsen et al., 2017; Krishna, 2021; Kurani et al., 2018; Tarei et al., 2021). Batteries for PEVs are sometimes seen as toxic and difficult to recycle, resulting in a perception that there is shift in environmental impacts rather than an overall reduction (Axsen et al., 2017). Other consumers are concerned about the potential for illegal and unethical mining processes associated with sourcing battery materials (Krishna, 2021).

PEV Desirability and Consumer Perceptions

Purchase of most products is influenced by social, functional, emotional, symbolic, economic, and other considerations (Sheth et al., 1991). Vehicle purchases are no different. The perceived desirability of PEV adoption is an important factor in purchase decisions and PEV market success. Emotional motivations play a critical role in vehicle purchase decisions with a positive correlation between PEV adoption and having personal communications with PEV owners (Axsen and Kurani, 2012a; Krishna, 2021).

Some consumers reported avoiding PEV purchases because they did not like how the vehicles looked or drove, and felt that they lacked joy (Axsen et al., 2017; Krishna, 2021). Perhaps because of some of these perceptions, Kurnai (2022b) reports that 17% of California drivers indicated they would never purchase a PEV, an increase from prior years. Long et al. (2020) reported that support for a moderate ZEV sales mandate varies by region in Canada, ranging from 39% to 61%.

Consumer Knowledge

A lack of consumer knowledge, awareness, and familiarity affects attitudes and willingness to adopt PEVs (Axsen et al., 2017; Hardman et al., 2017; Rezvani et al., 2015; Tarei et al., 2021; Wicki et al., 2022). While the lack of knowledge prevents consumers from adopting PEVs, it does not necessarily mean that they are unwilling to adopt a PEV (Tom Turrentine et al., 2018). Research shows that PEV market share is correlated with measures of PEV awareness (Vergis and Chen, 2015), that consumer knowledge of PEVs is generally poor (Krause et al., 2013), that few buyers have seriously considered purchasing a PEV (Kurani, 2019), and that charging stations were viewed as mysterious (Kurani et al., 2018).

Research has found little change in awareness, knowledge, or consideration over time. Long et al. (2019) surveyed Canadian consumers in 2013 and 2017 and found no increase in reported familiarity with BEVs or PHEVs and no increase in the percent of respondents who know how a PHEV or BEV was refueled between the

two surveys. Kurnai (2022a) surveyed US and California households from 2014 to 2021. From 2014 to 2021, there was a small increase in households considering a PEV, but also an increase in households that would never purchase a PEV. The survey also found that fewer buyers were aware of PEV incentives, and that buyers had worse perceptions of PEVs, in 2021 than in 2014. Less than half of respondents reported being aware of federal incentives or California rebates available for PEVs. Kurnai concluded there was little evidence for a growing consumer base interested in PEVs.

Finally, interviews with experts in Norway, Denmark, Sweden, Iceland, and Finland by Noel et al. (2020) found that 42% of those interviewed identified knowledge as a barrier to EV adoption, making this the fourth most mentioned barrier after range, price, and charging. In Norway, knowledge was the third most mentioned barrier identified by 30% of experts after range and infrastructure. Misperceptions of PEVs can create a bias against PEVs, so ensuring that drivers have correct information is an essential step in improving perceptions (Adhikari et al., 2020; Wicki et al., 2022).

Dealer Knowledge

Studies have identified car dealerships and salespeople as a barrier to PEV adoption (Cahill et al., 2014; De Rubens et al., 2018; Krishna, 2021; Kurani et al., 2018; Matthews et al., 2017; O'Neill et al., 2019; Tom Turrentine et al., 2018). Dealers have been found to be uninformed, misinformed, and/or unmotivated to learn about PEV technology, charging, and incentives, leading to poor customer experiences. They have been found to directly misinform customers about PEV range, incentives, and charging experiences, be dismissive of PEV technology, leave PEVs out of conversations, steer customers away from PEVs, and frequently portray them as an inferior technology (De Rubens et al., 2018; Tom Turrentine et al., 2018). In a study of 82 dealerships across five countries, De Rubens et al. (2018) found that two-thirds of the salespeople were dismissive of PEVs and intentionally directed customers away from them.

Salespersons' lack of knowledge about PEVs and expected difficulties in selling them to customers could explain why dealers are less motivated to promote them, compared to ICEVs. In a dealership study conducted by De Rubens et al. (2018), 71% of dealers had little or no knowledge of PEVs. One salesperson reported manufacturers only train select dealerships on selling PEVs. Salespeople also reported preferences for selling vehicles that are easier to sell, such as those with lower prices. PEVs often take two to four times longer per customer to sell than an ICEV due to the many questions customers ask. This requires salespeople to become experts and take on the role of a consultant, which they felt was a waste of time, in the event that their efforts did not lead to a sale (O'Neill et al., 2019).

Over time, PEVs likely contribute less to dealer service revenue given they do not require the same level of maintenance as conventional vehicles (Tarei et al., 2021; Tom Turrentine et al., 2018). Selling PEVs also increases the upfront investment required to train salespeople and install infrastructure. These factors impact dealer revenue and decrease their willingness to sell PEVs. In interviews with car dealers in Ireland, O'Neill et al. (2019) found that dealers felt that their role was to "give customers what they want," and that being asked to promote PEVs was "a step too far."

Incentives

Impact of Incentives on PEV Adoption and Sales

Most leading markets provide incentives for PEVs (Kong et al., 2021). In the US, incentives such as the federal tax credit and state and local incentives have stimulated PEV adoption (Breetz and Salon, 2018; Jenn et al., 2020, 2018). Jenn et al. (2018) estimated that, for every $1,000 of incentives, PEV sales increased by 2.6%, and that as much as 30% of PEV sales were an outcome of the federal tax credit. Similar observations by Clinton and Steinberg (2019) suggest an increase of BEV registrations by 8% for every $1,000 of incentives offered. Research from Europe also shows that incentives impact PEV sales. Münzel et al. (2019) observed that an incentive of €1,000 (about $1,120 in 2019 dollars) would increase PEV sales shares on average by about five to seven percent.

In China, the largest PEV market, high rates of PEV sales are explained by incentives, population density, and fuel price. The exemption from needing to enter a lottery to obtain a vehicle license proved to be the most effective incentive for private car buyers (Liu et al., 2021). Waivers for licensing and purchasing restrictions were also influential for BEV adoption in Beijing and Shanghai (Wang et al., 2017).

Some markets incentivize PEV adoption through "feebate" policies where a fee is applied to conventional vehicles and rebates are given to PEVs. Feebates operate in Sweden and France. Research shows that these incentives can increase PEV sales and be revenue-neutral (Wappelhorst, 2022, 2020; Wappelhorst and Tietge, 2018). The only longitudinal study on incentive impact we could identify found that, from 2010 to 2017, the probability of PEV buyers purchasing a PEV without the federal tax credit decreased over time (Jenn et al., 2020). This may mean incentives are more important for later adopters of PEVs compared to early buyers.

Differences in Incentive Impact

Research has identified differences in incentive impact based on incentive type, vehicle model and plug-in type, and PEV buyer demographics. In the US, the federal tax credit is less efficient than some state rebates because of the delay buyers experience prior to receiving the federal tax credit. The study by DeShazo et al. (2017) included a choice experiment sample size of 1,261 new car buyers in California. They estimate the California clean vehicle rebate increases PEV sales by at least 7%, and that the policy at the time had a large number of free riders. The authors identify differences in response to rebates by BEV or PHEV, vehicle purchase price, and income. The authors find that increasing price caps of $60,000 would improve incentive efficiency. They also find that providing higher rebates to lower income buyers would increase the number of PEVs sold relative to program expenditure.

Narassimhan and Johnson (2018) found that rebates influenced PEV adoption more than tax credits because rebates were received closer to the time of purchase. A choice-based study by Roberson and Helveston (2022) in the US found that participants preferred immediate incentives over post-purchase incentives. The authors find income tax deductions, income tax credits, and sales tax exemptions were valued $580, $1,450, and $2,630 less than an immediate incentive, respectively.

Studies have detected differences in incentive impact by vehicle type. Narassimhan and Johnson (2018) found no significant impact of incentives on the adoption of Tesla PEVs, which have a higher price-point, and observed a significant relationship between incentives and the adoption of Nissan Leaf BEVs, which are more affordable. Jenn et al. (2020) found buyers of Tesla BEVs were less likely to report that their purchase was dependent on the federal tax credit than buyers of other PEV types. Lower-income buyers' purchases were more sensitive to incentives than those of higher income buyers. Muehlegger and Rapson (2022) find that demand for lower and middle income vehicles is elastic with a 10% reduction in PEV price associated with a 21% increase in demand, suggesting incentives offered to lower and middle income households through in California are influential. In interviews with Tesla adopters, Hardman and Tal (Hardman and Tal, 2016) gathered that Tesla purchases were motivated by interest in performance vehicles, technology, and environmental benefits rather than purchase incentives. Incentives are less important for PHEVs with shorter electric driving ranges. Financial incentives were most important for BEVs with the longest driving ranges, like the Chevrolet Bolt (Hardman and Tal, 2016).

Correlation of Incentive Awareness to Incentive Impact

Studies show PEV sales differ based on awareness of PEV incentives (Jenn et al., 2018), with consumers often unaware of local, state, or national incentives (Hardman et al., 2020; Krause et al., 2013; Kurani, 2022b). Even recent studies in California show low awareness of incentives (Hardman et al., 2020; Kurani, 2022b). In a 2021 survey of Californian car-owning households, Kurani (2022b) found that less than half of respondents were aware of federal incentives and around 33% were aware of California incentives. Most respondents supported offering incentives, while around 20% did not support offering incentives for PEVs. Narassimhan and Johnson (2018) found that a lack of awareness about incentives and high upfront costs hindered adoption of PEVs. In their study of the California Enhanced Fleet Modernization Program (EFMP) Plus-Up pilot, Pierce and DeShazo (2019) found that program administrators reported low awareness among their target audience, which slowed PEV adoption initially. With better outreach programs, demand for incentives among the lower- and moderate-income population surpassed the supply, and demand remained high over time.

Incentive Equity Issues

Research shows higher income buyers in Norway and the US are less sensitive to incentives (Jenn et al., 2020; Zhang et al., 2016). Conversely, incentives are more important for lower-income buyers. Several incentive programs in North America are distributed to consumers post PEV-purchase, which does not reduce the upfront cost of PEVs. The federal tax credit is additionally tied to income, with lower-income buyers receiving smaller incentives (Hardman et al., 2021). Most other PEV markets provide incentives at the point-of-sale and do not tie incentive amounts to buyers' tax liability (Kong et al., 2021). Point-of-sale incentives may make PEVs more affordable to a larger consumer base and are more efficient. Research suggests that PEV incentives are not reaching the consumers who would benefit the most. In evaluating rebate allocation, Gou and Kontou (2021) found that most rebates in California are distributed to people in higher income and non-disadvantaged census tracts, with a change over time to a more equal distribution. Guo and Kontou (2021) found that the effect of income caps increased the share of rebates per capita in both lower- and middle-income communities

and disadvantaged communities. They also found that providing higher rebates for low/mid-income households increased rebate allocation in the bottom 25% of disadvantaged communities from less than 7% to more than 11% of rebate funds.

Sheldon and Dua (2019) explored the Replace Your Ride Program, which provided larger point-of-sale rebates for lower-income car buyers, and found that it was more cost-effective than the statewide Clean Vehicle Rebate Project (CVRP) program and the US federal tax credit in 2015. Ju et al. (2020) examined rebate allocation among disadvantaged and non-disadvantaged communities under the CVRP and EFMP, and whether CVRP enrollment changed after the introduction of income caps and an income-tiered rebate amount. They found that disadvantaged communities, on average, receive 77% fewer CVRP rebates. Income caps and income-tiered structures reduced the gap, but CVRP rebate allocation rates still displayed a negative correlation with higher levels of disadvantage. EFMP rebate allocation was positively correlated to higher levels of allocation to disadvantaged communities due to the additional vehicle eligibility criteria, stricter income caps, income-tiered rebate amounts, and different rebate amounts (Ju et al., 2020).

Other parts of the US, such as Massachusetts, offer higher subsidies for relatively inexpensive PEVs, making the vehicles affordable to consumers from lower-income communities (Linn, 2022). It was observed that, because lower-income households are more price sensitive, subsidies targeting them were more effective in increasing sales of PEVs compared to uniform subsidies. The same study indicated that income-based subsidies are more progressive than other subsidies because, by design, they are claimed by the lower-income groups and also because of their interactions with ZEV standards. Providing subsidies while simultaneously taxing gasoline-powered vehicles was found to be more effective than providing subsidies alone (Linn, 2022).

Infrastructure

Impact of Charging on PEV Sales and Infrastructure Use

In a review of consumer preferences for charging infrastructure, Hardman et al. (2018) concluded that public charging availability was less influential than home and workplace charging availability in increasing consumers' PEV purchase interest. Nicholas et al. (2017) found that more than half of PEV owners charged only at home, while just 14% charged solely from workplace or fast charging opportunities. Lin et al. (2011) similarly found that widespread access to at-home charging has a greater impact on PEV sales than does access to public and workplace charging. Gnann et al. (2019) modeled the diffusion of the PEV market and charging infrastructure in Germany. They concluded that home and work charging are more important than public slow PEV charging infrastructure for early PEV market penetration, because many households have access to home charging infrastructure. The paper did not consider the fast public charging. Similarly, research by Funke et al. (2019a) indicates that more home charging access reduces the need for public charging. Hardman and Tal (2021) examined PEV discontinuance in California and found that the perceived inconvenience of charging and not having access to Level 2 charging at home were associated factors.

Research therefore suggests that consumers' homes have, so far, been the most influential charging location affecting the decisions to buy a PEV and to continue owning one. In the US, up to 72% of residents of single family homes report being able to charge at home, compared to only 20% of residents of apartments (Ge et al., 2021). In total, around half of new car buyers could charge a PEV at home (Axsen and Kurani, 2012b). This may mean that home charging in a garage or private driveway will only allow a portion of households to access home charging.

After home, the workplace is often identified as the next-most influential location for PEV charging (Gnann et al., 2019; Hardman et al., 2018; Lee et al., 2020). Lee et al. (2020) investigated how PEV drivers use combinations of home, workplace, and public charging. They found that 86% of PEV drivers report using home charging with 53% using only home charging. Additionally, 31% of respondents use workplace charging with 8% using only workplace charging, and 23% reported using public with 3% using only public charging.

Researchers have reached different conclusions on the role of public charging infrastructure in increasing PEV sales. One set of studies found that public infrastructure resulted in higher PEV sales, while another set of studies, detailed below, found only a correlation with PEVs and the presence of public charging.

Cass and Grundoff (2017) concluded that the diffusion of a visible network of charging infrastructure is necessary for non-adopters to overcome range anxiety. Similarly, Greene et al. (2020) reported that public charging infrastructure provides benefits to both current and prospective PEV adopters. Narassimhan and Johnson (Narassimhan and Johnson, 2018) performed regression analysis on US PEV purchase data from 2008 to 2016, and reported that PEV charging infrastructure availability significantly influenced per capita PEV purchases. Sierzchula et al. (2014) performed regression analysis of PEV sales data from 30 different countries and found that the availability of public charging infrastructure was the best predictor of PEV sales. Mersky et al. (2016) also concluded that public charging availability was the best predictor of PEV sales in Norway.

In contrast, other studies have found a weak or non-existent relationship between public charging and PEV sales. White et al. (2022) suggest that there are intermediate variables between PEV charging infrastructure and sales. Their work found that greater perceived subjective norms in support of BEVs explained much of the association between charging facility density and adoption intent. Nazari et al. (2019) reported that the number of public PEV charging stations was only statistically significant for households choosing PHEVs, but not BEVs. Miele et al. (2020) reported that the PEV market in Canada may not substantially benefit from increased public charging infrastructure. Lastly, using a survey of California car owning households, Hoogland et al. (2022) found no relationship between the density of charging infrastructure and whether respondents see infrastructure or have considered purchasing a PEV. They found that prior interest and engagement in PEVs explained higher levels of PEV purchase consideration.

The potential difference in results could be due to the methods used. Chakraborty et al. (2019) caution against the inference of causality from correlation between PEV charging infrastructure and sales. In a study of factors influencing PEV adoption in California they found that, while there was a positive correlation between Level 2

public charging and BEV sales, no causal claims could be drawn from the results. They highlighted that reduced-form models are not adequate for establishing causality.

Differences in Access to Charging

Davis (2019) explored PEV ownership in the US and found that, even after controlling for income, homeowners are three times more likely to own a PEV than renters. Authors concluded that renters may have less access to a reliable parking spot and less incentive to invest in home charging equipment. Those living in multifamily buildings, such as apartments or condominiums, are less likely to have access to charging while at home (Ge et al., 2021; Lopez-Behar et al., 2019; Pierce et al., 2020). Additionally, in a study of PEV adoption in disadvantaged communities in California, Canepa et al. (2019) concluded that the lack of access to public or private charging infrastructure located near multi-unit dwellings is a barrier to widespread PEV adoption in these regions. Hsu and Fingerman (2021) found public charging access is lower in Black- and Hispanic-majority communities and in areas with below-median household incomes.

Even if public charging is more equitably distributed in the future, charging costs in public locations can exceed the cost to charge at home, which may mean PEVs deliver less financial benefit to those without home charging access (Hardman et al., 2021). In a study examining charging behavior of California PEV owners, Lee et al. (2020) showed that at-home is the most frequently used charging location for PEV owners. They concluded that, for market shares to continue to grow, policymakers should support the development of home charging for residents of multi-unit dwellings. For the PEV market to include more renters living in apartments, more efforts may be needed to increase lower-cost charging access for consumers without access to at-home charging.

Future Infrastructure Needs

Researchers have modeled PEV charging infrastructure development needs. Their efforts are primarily motivated by literature which finds PEV charging infrastructure to be a key enabler of widespread PEV deployment. Metais et al. (2022) reviewed the literature on PEV infrastructure planning and found that studies generally have two goals: (1) cost minimization for a given level of service or (2) service maximization for a given cost. The authors also identified three primary barriers to PEV charging deployment, which are: technical, economic, and user acceptance.

LaMonaca et al. (2022) explored the role of public and private actors in the PEV charging market. They found a need for public funding to support the deployment of charging infrastructure to overcome high installation and maintenance costs. Research has also identified the importance of tailoring charging deployment strategies based on geographic considerations, such as housing and population densities (Hall and Lutsey, 2017). Funke et al. (2019) reviewed the literature to identify the framework conditions shaping public charging infrastructure demand. They found that slow charging infrastructure needs are dependent on the availability of other charging options, namely, home charging.

Funke et al. (2015) estimated the amount of slow public charging infrastructure needed in Germany with both a coverage-based and demand-based approach. In the early stages of the PEV market, the authors found that a demand-based approach yielded approximately 17,000 charging stations, compared with 50,000 stations for the maximum coverage approach.

Davis et al. (2022) estimated the charging infrastructure necessary for California to meet its 2045 vehicle electrification goals. The authors found that there will be a higher increase in demand for shared, rather than private charging infrastructure from the late 2020s until the early 2040s due to later adopters being less likely to have any capacity for home charging, and multi-PEV households not being able to meet their entire charging demand at home. Authors estimate that, in California, 1.5 million chargers will be needed to support the PEV fleet by the end of the 2020s and 6 million by the end of the 2030s. The rate of installation reportedly needs to increase 10 times, compared to current rates, to keep on-track with state targets.

Lastly, Nicholas et al. (2019) quantified the gap in charging infrastructure needed to support PEV market growth through 2025. The authors identified the largest gaps in charging infrastructure where PEV uptake is growing most rapidly, such as Californian cities, Boston, New York City, Portland, and Washington DC, each needing to average at least 20% annual growth in charging infrastructure from 2017 to 2025.

Discussion

Sociodemographic and Lifestyle Determinants

In the US, PEV buyers have, so far, predominantly been high income, highly educated, homeowning, male, middle- to later-aged people residing in multi-vehicle owning households. Since 2012, the average income, average level of education, age, and number of vehicles in households of PEV buyers are progressing closer to the average of new car buyers (Lee et al., 2019; Williams, 2022). Although it is unclear how incentive discontinuities may impact this, especially considering that lower income buyers are more responsive to incentives. This could have a negative impact on the PEV adoption rate in lower- and middle-income households, at least based on studies that found incentives to be more important for lower-income PEV buyers (Jenn et al., 2020).

There has been little change to PEV buyer gender and home ownership over time. Buyers of PEVs remain mostly male and the majority own their home. The explanation for fewer renters purchasing PEVs is typically reported as being a result of lack of home charging, which we discuss more in the section on charging below. Why other genders are not purchasing PEVs in higher numbers remains unclear and warrants dedicated research. Most PEV adoption has been among multi-vehicle households. Research shows single-vehicle households are more concerned about PEV range (Wicki et al., 2022). Whether the concerns of single vehicle households will change over time and PEV range increases is not clear and should be researched.

Technological, Economic, and Social Determinants

The most frequently reported barriers for PEV adoption are purchase price, range, charging time, and lack of infrastructure. Progress been made on increasing range, reducing charging times, and expanding infrastructure access (Muratori et al., 2021). Progress on PEV purchase price has been mixed. At the lower end of the market, PEVs with long driving ranges are available from around $25,600, but the average cost of PEVs has increased and is diverging from the price of conventional vehicles. Reductions in PEV sales prices due to reduced battery costs and increased economics of scale have yet to be passed on to consumers, and projections that PEVs will reach price parity (Slowik et al., 2022) are not supported by historical PEV price trends. In the US, PEV prices have only increased, and at a higher rate than ICEVs (Energy Agency, 2022; Osaka, 2022). Research may need to consider why PEV prices have not been falling in line with expectations, when PEV prices may more closely align with ICEVs, and how price changes may impact consumer adoption.

While technological progress continues, less progress has been made on improving consumer awareness, perceptions, and knowledge of PEVs. Several longitudinal studies surveying car buying households by Kurani (2022a, 2022b, 2019) show little change in consumer knowledge, perceptions, and/or consideration of purchasing a PEV. The most recent survey showed an increase in the percentage of respondents indicating that

they will never purchase a PEV. This means that, despite increases in range, reductions in charging time, and increased charging access, buyer perceptions of PEVs have not improved. This may indicate there is a disconnect between metrics of PEV performance or suitability and perceptions, whether this is because buyers' perceptions lag PEV advancements or because they still perceive PEVs to be unsuitable for their needs is an area for future research.

Research has shown increased resistance to PEVs among new car buyers (Kurani, 2022b), and research from Long et al. (2020) shows low support for a ZEV sales regulation in Canada. It could be argued that those who resist PEVs will eventually have to buy a PEV, regardless of their preferences, because of sales regulations. Nonetheless, the reasons why these buyers oppose PEV purchase should be researched so that their concerns can be understood and addressed. Slower rates of adoption among some groups could limit progress to greenhouse gas reduction goals. Ignoring those who are resistant to policy can pose risks, because policies with substantial opposition can fail (McConnell, 2015).

More may need to be done to engage consumers on a larger scale. This may include providing persuasive information and conventional advertising of PEVs by automakers. Beyond receiving information and advertising, consumers may also benefit from hands-on experience operating PEVs, which has been found to reduce concerns around PEV range and quality (O'Neill et al., 2019; Wicki et al., 2022).

Incentives

Most studies on the impact of incentives found a positive and significant relationship between the availability of incentives and PEV adoption or adoption intention (Hardman et al., 2017). The impact differs based on how incentives are distributed to buyers, with incentives delivered at the point PEV acquisition being more impactful and efficient (Roberson and Helveston, 2022). This may not matter for many PEV markets, because incentives are commonly delivered at the point-of-purchase. However, in the US, many incentives are delivered post-purchase, which will likely limit their effectiveness. Changes to the federal PEV tax credit through the inflation reduction act may allow buyers to receive an incentive at the point-of-sale in 2024 if buyers are able to transfer their tax credit to a vehicle seller.

The only study we identified that considered changes to incentives impacts over time found that incentives increased in importance during the study period (Jenn et al., 2020). If this trend continues, the market could be impacted by incentive removal or incentives only being available for certain PEVs. For example, lower-income buyers whose PEV purchase is more dependent on incentives may be less likely to purchase a PEV. Feebate incentive designs, such as those used in Sweden and France, may help reach higher percentage PEV sales by solving the issue of incentive funding and the potential higher importance of incentives for future buyers by creating a revenue-neutral incentive structure.

Incentive effectiveness is also impacted by low awareness of incentives. If policymakers plan to continue using incentives as a tool to increase PEV sales, efforts may be needed to promote the existence of incentives.

Finally, many US incentive programs are not equitably designed. If funding for incentives is limited, it may be necessary to target incentives to those whose PEV purchase is dependent on incentives. Incentive designs should include the following (adapted from Hardman et al. 2021):

- increased incentive allocation for lower and middle income buyers;
- purchase price caps or income caps to exclude those who do not need incentives;
- allowing buyers to claim the incentive regardless of purchase location (e.g., not only at a dealership);
- allowing lower-income buyers to apply the credit to used PEVs;
- not tying incentive amounts to tax liability (as is the case for the US federal tax credit);
- applying PEV incentives at the point-of-sale;
- providing assurances on incentive availability in the case of funding discontinuities (a recurring issue with California programs); and
- increasing consumer awareness of available incentives.

Changes to the US federal electric vehicle incentive in 2022 may resolve some of these issues as well as inefficiencies reported in the literature. However, the changes could also reduce overall effectiveness for several reasons. Delivering the incentive at point-of-sale (beginning in 2024) via transferring the credit to a dealer and implementing income and vehicle price caps may increase incentive efficiency. Allowing buyers of used PEVs to claim a credit may help used vehicle buyers purchase PEVs. However, many PEVs will not qualify for an incentive, and those that do may not receive the full amount of $7,500. The incentive also remains as a tax credit, which could mean the amount received will still be tied to income. The result may be that lower-income buyers are ineligible to receive a full incentive. Future research will need to investigate the impact of changes to federal tax credits received by PEV buyers.

Charging

Research on charging infrastructure shows that home charging availability is the most influential factor in the decision to purchase a PEV, the most frequently used charging mode, and is important in the decision to continue owning a PEV (Hardman et al., 2018; Hardman and Tal, 2021). A higher portion of future new and used PEV buyers are likely to reside in homes without home charging, including rented homes and apartments or condos. Research will need to consider how these households could be served by workplace, near home (not in a private driveway or garage), or public charging, and whether access to workplace or public charging will encourage PEV adoption. Research should also explore how to increase home charging access for households who cannot afford home charger installation and how to install charging in multi-unit housing parking lots.

Research on the impact of public charging is mixed. Some studies suggest infrastructure can cause sales (Mersky et al., 2016; Narassimhan and Johnson, 2018), whereas others show the relationship is correlational (Hoogland et al., 2022; White et al., 2022). Understanding whether infrastructure influences sales, or vice

versa, is important for several reasons. If PEV sales influence the density of charging infrastructure, the charging network could be unevenly developed. This would mostly serve past and existing buyers, while not supporting future buyers of PEVs. Policymakers also need to understand this relationship because infrastructure is sometimes considered to be a tool to increase PEV sales. This may not be the case with other actions needed to encourage PEV purchase. Research shows no relationship between charging infrastructure density and car owning households that report seeing charging infrastructure, nor a relationship between seeing charging infrastructure locations and PEV purchase consideration. Rather, consumers' prior engagement with, knowledge, and awareness of PEVs were associated with charging location awareness and purchase consideration (Hoogland et al., 2022). Therefore, more may need to be done to engage consumers with the PEV transition.

Research shows that disadvantaged communities, underserved communities, low income communities, and communities of color have fewer public charging stations and fewer home types associated with home charging access (Hsu and Fingerman, 2021). Policymakers, charging providers, and researchers will need to focus specifically on these communities' needs in order to understand which types of charging may best serve them. Without considering of how to provide access to charging, there is a risk of perpetuating under-investment in transportation access in communities that have historically been underserved. This inhibits access to health (lower emissions) and economic (lower operating costs) benefits of PEVs. The US federal Justice40 initiative directs 40% of federal investments in PEV charging to disadvantaged communities (The White House, 2022). While this may increase the distribution of PEV charging in underserved communities, equally distributed charging infrastructure may not serve the needs of PEV buyers in the same way across communities. Policymakers and other stakeholders should consider transportation justice approaches, not just equity and equality. Transportation justice will require engaging communities in planning processes, community-led analysis, community organization, and allowing communities to participate in budgetary processes (Karner et al., 2020).

Future Research Needs

Future research should include more longitudinal studies including cross sectional surveys and panel studies and should seek to answer key questions. We were only able to identify a small number of longitudinal studies on PEV adoption. These investigated the impact of incentives, whether incentives are equitably distributed, changes in PEV buyer demographics, and consumer perceptions of PEVs. More studies like this may help in understanding the trajectory of the PEV market and how policy can be revised to increase effectiveness. More longitudinal research will help determine progress in the PEV market and would likely indicate whether PEV market introduction is headed towards its goals.

There are numerous key questions that will be important to answer to inform efforts to increase PEV sales towards 100% of market share. The key questions listed below are based on trends and gaps identified in our literature review.

Sociodemographic and Lifestyle

- Why are fewer female car buyers purchasing PEVs? How can PEV adoption be increased among female car buyers?
- Why are fewer renters and those in apartments or condos purchasing PEVs? How can increased PEV adoption be facilitated among car owners in these house types?
- How will incentive discontinuities and changes to incentive eligibility criteria impact PEV buyer demographics?

Perception and Knowledge

- Why are buyers more resistant to PEVs? Why have some perceptions worsened over time even though sales have increased and PEV technology has improved?
- Why are some consumers opposed to PEVs and to purchasing a PEV, and can their perceptions be changed?
- If price is a barrier to adoption, will PEV price reductions impact this perception? When will PEV prices (for consumers) begin to fall?
- How can buyer knowledge and awareness of PEVs be improved?
- What is the impetus for seeking out information on PEVs, or having a conversation with a PEV owner, and how could this be further facilitated?
- Are dealers and car salespeople still a barrier to PEV purchases?

Incentives

- Are incentives continuing to increase in importance over time?
- How will changes to the federal tax credit impact incentive effectiveness?
- How should incentives be designed and administered to the lower-income buyers and households in disadvantages communities?
- How will incentive discontinuities impact PEV buyer demographics and PEV sales?

Charging infrastructure

- What infrastructure can best support PEV adoption and continued PEV ownership for those without home charging?
- Will home-based charging remain the most frequently used charging location at higher PEV penetration?
- What are the charging needs for underserved and disadvantaged communities? What charging will best support these communities' PEV charging needs?
- Are the charging needs and charging behavior of early adopters different than those of later adopters?

Conclusion

In this report, we considered potential barriers to reaching 100% ZEV sales, focusing only on PEVs, we lastly, we outlined future research needs. This information can help to support and guide this transition and to overcome potential barriers. Most studies do not consider 100% ZEV or PEV sales targets, and their purpose was not to understand potential barriers to 100% ZEV or PEV sales. Therefore, we used findings from prior studies in the literature to identify barriers to higher PEV sales and needs for future research.

We identified barriers related to potential PEV adopters' sociodemographic status and lifestyle, and their perception and knowledge of PEVs, PEV incentives, and charging infrastructure. Barriers related to sociodemographic and lifestyle factors include needing to engage female car buyers, renters, and/or apartment dwellers in PEVs, and understanding the needs of single vehicle households. Barriers related to perception and knowledge of PEVs include a lack of change in consumer awareness of PEVs over time and, in some cases, worsening perceptions of PEVs. Barriers for incentives include potential impacts to the PEV market from incentive discontinuities and current incentive designs not being optimal for low and middle income buyers and underserved communities. Barriers related to infrastructure include PEV charging needs in underserved communities, understanding the needs of those without home charging access, moving past considering infrastructure as an engagement strategy, and using engagement strategies to increase awareness of charging options.

Many regions are introducing 100% ZEV sales regulations or targets. It could be argued that, because automakers in some locations must sell only ZEVs by 2035, several issues discussed here are not relevant. For example, policymakers could leave automakers to solve issues of incentives, engagement, and infrastructure, and ignore consumer concerns and resistance to ZEVs and ZEV policy. However, firstly without widespread support, including from industry, policies can fail (McConnell, 2015), and historically ZEV sales regulations have been weakened (Axsen et al., 2022). Second automakers may not be motivated to create an inclusive and equitable transition to ZEVs or PEVs therefore policy may be needed to ensure the transition does not negatively impact or exclude underserved populations.

The PEV market is set to expand beyond motivated and interested early-adopters to consumers who do not support PEV policy and/or those that currently indicate they would never purchase a PEV (Kurani, 2022b; Long et al., 2020). For late-adopters, incentives, engagement strategies, and infrastructure may be needed to broaden support for PEV policy. Interventions by policymakers may also make it easier for automakers to sell PEVs, which may increase their support for policy and prevent them from seeking to change policy, as they have in the past (Wesseling et al., 2015, 2014). Policymakers may also need to intervene where automakers and infrastructure providers may not. For example, policy can serve a unique role in in making PEVs more accessible and ensuring that charging infrastructure is deployed in regions where automakers and infrastructure providers may not be motivated to install charging infrastructure.

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