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Demand-side challenges and research needs on the road to 100% zero-emissions vehicle sales

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ABSTRACT

Most net-zero emissions targets require electrification of the entire light-duty vehicle fleet, and before that the electrification of all new vehicle sales. In this paper, we review literature on demand-side issues related to achieving 100% zero-emissions vehicle (ZEV) sales, focusing on plug-in electric vehicles (PEVs). We discuss potential demand-side challenges to increasing PEV sales and related research gaps, including consumer factors (perceptions, knowledge, and consumer characterises), demand-focused policy (incentives), infrastructure, and energy prices. While global PEV sales have substantially increased in recent years, several challenges remain: some demographic groups are currently underrepresented among PEV buyers (e.g. renters, lower income buyers), some car drivers are resistant to PEVs, incentives are influential but have predominantly benefited higher-income new-car buyers and are being phased out, infrastructure is not sufficiently developed or equally distributed, infrastructure is not user friendly, and some households lack charging access. Some issues we identify may be related to the early stage of the PEV market, though will need to be addressed to reach higher PEV sales and PEV fleet shares. Finally, we outline areas where more research is needed to understand and guide the PEV transition.

1. INTRODUCTION

More than 30 countries and several subnational regions have introduced, or indicated their intent to introduce, regulations requiring 100% zero emission vehicle (ZEV) sales by between 2025 and 2040 (*1–3*). Many of these targets are tied to greenhouse gas emissions reductions targets, including 2050 net zero emission targets and the need to constrain global warming to 1.5 °C as determined in the Paris Climate Accords (*4*). Most markets currently have low ZEV sales and even lower shares of ZEVs on the road. In 2023, 18% of global vehicle sales were ZEVs. The largest auto market, China, reached 30% and the second largest, USA, reached 10%, with some Nordic nations achieving sales of as high as 90% (*5*). Of course, the stock of ZEVs lags this, at around 7.6% in China, 2.1% in USA, and 29% in Norway (*6*). In short, most regions pursuing 100% light-duty ZEV sales and eventually 100% ZEV stock still need dramatic changes in their vehicle fleet.

Our aim with this paper is to identify potential challenges to higher ZEV sales and outline future research needs to help understand, and guide, the ZEV transition. Most existing studies do not consider challenges to reaching 100% sales. Therefore, we review studies related to ZEV demand to identify potential challenges to higher ZEV sales by highlighting areas where progress is lacking, or issues exist. Then, we identify areas where more research is needed based on the currently published literature. Some identified challenges and research questions may relate to the early stage of the ZEV market and could be resolved as the transition takes its natural course. However, if they are not resolved the issues may impact market growth.

We selected topics to include in this review in three workshops held with the authors and based on reviewing literature on factors related to ZEV demand to identify areas to include. Based on this, the authors proposed these topics as key issues and research areas related to ZEV demand and consumer adoption of ZEVs. The review is a narrative review, we did not develop a systematic review protocol, instead our goal was to identify and review key studies related to the topics we identify. We focus on plug-in electric vehicles (PEVs), including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Among PEVs, only BEVs are fully zero-emission from a tailpipe perspective, though numerous policies globally include PHEVs as part of their definitions of ZEVs (*7*). Therefore, we include evidence from studies on PHEVs. We also do not consider fuel cell electric vehicles (FCEVs) due to the nascent status of the FCEV market.

We focus exclusively on demand-side or consumer factors, including characteristics of current adopters, consumer perceptions of PEVs, PEV use, incentives, and infrastructure issues that broadly relate to consumers. We do not discuss technical issues (technology development, electricity demand, etc.) or supply-side issues (manufacturing, supply chain issues, etc.). Supply-side issues are the topic of another review by Jenn et al (*8*). Since most research on PEV adoption focuses on new PEV purchases, we primarily review literature on new vehicle adoption, although literature on used PEV adoption is included where available. We consider studies in all regions and draw from studies with a broad range of quantitative and qualitative methods. Finally, we only focus on PEVs but note that other sustainable transportation options are can and are needed to contribute to meeting net zero targets, including active transportation, micromobility, transit, and reductions in car centric transportation (*9*). We organize the literature review along different themes, including:

- Consumer perceptions and preferences: This includes perceptions related to technological, financial, and social factors and attitudes, perceptions, and purchase intentions towards PEVs and their attributes.

- Consumer characteristics: PEV adopter demographic profiles and lifestyles, attitudes, norms, and whether PEV buyers are changing over time.
- PEV use: This includes how PEVs are being used by households, focusing on annual miles or kilometres driven.
- Consumer engagement: This includes literature on consumer awareness and knowledge of PEVs and how car buyers may learn about PEVs.
- Contextual factors: including incentives, infrastructure, and energy prices, and their impact on PEV sales.

The paper discusses findings from the literature in each of these in the above order. Following that we discuss potential challenges to higher ZEV sales and future research needs. In many areas we review there is a large and growing body of PEV research, using a wide variety of methods across different regions. One major distinction between studies is that some focus on understanding ZEV adopters (owners) versus potential future adopters. Both perspectives offer useful information and will be needed to guide the PEV transition. PEV adopter research provides more concrete evidence on consumer characteristics and behaviour but is limited in most markets to the earliest buyers and doesn't necessarily provide evidence regarding future buyers. Forward-looking consumer research typically relies on stated response methods such as choice experiments and helps to anticipate future adoption and behaviour.

2. CONSUMER PERCEPTIONS AND PREFERENCES

In this section we review research on consumer perceptions of PEV related attributes including technical and financial attributes. We include this area of research since negative perceptions of PEV attributes may be a barrier to continual market growth.

2.1. Perceptions of technical attributes

The limited driving range of BEVs has been one of the most commonly mentioned barriers to adoption (*10*), with some studies (published between 2012 and 2015, when the average BEV range was less than 200 km) finding range to be the most substantial barrier (*11–13*). Consumers have perceived BEV ranges as insufficient compared to the range of ICEVs to meet demand for general travel (*14–16*), longer trips (*17*, *18*), and for drivers with higher than usual travel demands (*10*, *11*). Whether range continues to be a barrier may depend on if consumer perceptions keep up with range improvements. Many of the studies that reported range as a barrier to PEV adoption were published before recent improvements in driving range[1]. However, even recent studies suggest range may still be an issue. As Herberz et al. (*20*) show, range is a psychological barrier rather than technical barrier that can be partially addressed by providing information on the compatibility of BEV range with travel demand. Drivers may also be

[1] In 2022, the sales weighted average BEV range was approximately 350km (217 miles) in the US and 300km (186 miles) in European countries, compared to less than 200 km (125 miles) in all regions 10 years ago (*19*).

concerned about the impact of ancillary load (e.g., heating and cooling), driving style, weather, towing, and battery degradation on range (*14*, *21*), and also if they only have one vehicle in their household (*10*).

Wicki et al. (*10*) identified long charging times as one of the top three concerns reported in the literature. Several studies conducted in North America, Europe, and Asia find charging is the most substantial barrier for PEV purchase (*12*, *13*, *21*–*25*). Lack of access to charging stations while at home is a commonly reported barrier, particularly for consumers without access to a private garage or dedicated parking space (*26*, *27*). Several studies find home charging is the most influential in the decision to purchase a PEV (*17*, *28*–*30*). Kurani (*31*) found that in 2021 car owners perceived there are not enough places to charge a PEV in California despite growth in EVSE deployment. In addition to a perceived lack of charging, consumers can be deterred from purchasing PEVs due to the complexity of charging infrastructure, including the large variety of user interfaces, payment and interoperability issues (*27*, *32*–*34*), and difficulty locating public charging stations (*14*, *17*). Research is also beginning to highlight issues with public infrastructure reliability (*35*), which could impact the experiences of PEV buyers and perceptions of perspective PEV buyers which could in turn impact demand.

While some studies found acceleration, smoothness, and decreased noise as benefits of BEVs, other studies found that BEVs were viewed less favourably in terms of performance (*10*, *14*, *16*). This discrepancy may be at least partially attributable to a lack of knowledge and experience with PEVs, as numerous studies find perceptions of PEV driving performance are positively correlated with experience (*28*, *36*, *37*). Safety concerns are also prevalent in older studies, including the 2012 studies by Egbue and Long (*38*) and Graham-Rowe et al. (*39*) and in more recent studies on emerging PEV markets (*14*). Negative perceptions of safety include concerns over the safety of the battery as well as the vehicle itself (*40*). Consumers also report the lack of diversity in vehicle types, drivetrain options (e.g., four-wheel or all-wheel drive), body types (e.g., sedans, hatchbacks, pickup trucks) (*14*), and the limited number models to choose from as barriers to purchase (*11*). While the number of PEV models in the U.S., Europe, and Asia is increasing, some models are in low supply, and less mature PEV markets face limited vehicle choices (*41*). Other issues include a lack of brand choice, a lack of used PEVs, and supply shortages or long waiting periods for vehicles (*14*, *42*, *43*).

Finally some consumers also report avoiding PEV purchases because they did not like how the vehicles looked or because they lacked joy (*14*, *17*). Some consumers are also skeptical that PEVs can provide social and environmental benefits (*14*, *17*, *21*) and have concerns on whether environmental harms from battery manufacturing might mitigate emissions savings (*14*, *15*, *17*, *21*). Perhaps because of some of these perceptions, Kurnai (*44*) reports that 17% of California drivers indicate they would never consider purchasing a PEV.

2.2. Perceptions of financial attributes

Purchase price is frequently mentioned as a barrier to PEV adoption (*10*, *15*, *41*, *45*), and two studies from 2016 and 2017 found this to be the largest barrier (*22*, *25*). While lower operating costs can result in cost savings over the lifetime of the vehicle, that is not always the case in instances of lower gasoline and higher electricity prices (*46*, *47*). Consumers may also ignore any potential savings and focus on upfront costs (*18*, *41*), doubt longer term savings (*10*), lack the expertise needed to calculate the total cost of ownership savings (*16*), or be unaware of vehicle economy or fuel expenditures (*48*). Some consumers also perceive PEVs as more expensive to maintain and repair than ICEVs (*10*, *14*), sometimes due to concerns about battery degradation and the potential need to replace the battery (*11*).

3. CONSUMER CHARACTERISTICS

Here we summarize trends in PEV consumer characteristics, we include this area of research as studies show PEV buyers are different in many areas compared to conventional vehicle buyers. For the PEV market to reach higher levels of adoption PEV buyers should have similar characteristics as new car buyers, and for higher levels of fleet adoption similar characteristics as all drivers.

3.1.Sociodemographic & household characteristics of ZEV consumers

In many cases new technology adopters differ from the general population, and so far, this is the case for PEV adopters. Stated preference studies in the US and EU often find PEV buyers are likely to be highly educated, have a higher than average household income, own multiple vehicles, are younger or middle aged, and live in a detached house or single family home (*26*, *36*, *49*–*52*). Studies with samples of early adopters generally show PEV buyers are similar to what stated preference studies predicted. PEV buyers are generally higher income, highly educated, own multiple vehicles, and are more likely to be male in some markets (*53*–*56*). Rather than being younger to middle aged, PEV adopters are middle to later aged. Some longitudinal or cross-sectional studies show demographics are changing over time, the reported changes have been small so far and are mostly relate to changes in PEV buyer income, education, or buyer age. Notably there has been little change to PEV buyer gender (buyers are mostly male) in some markets (e.g. USA and Germany) and home ownership (buyers mostly own their home) (*55*–*58*). Research also suggests PEV buyers are often clustered in specific regions characterized by higher income households and a high proportion of houses that are detached or single family homes (*59*–*61*).

Research on used PEV buyers is in a nascent stage but is beginning to show used PEV buyers are also different from the general used car buying population. Used PEV buyers are more likely to own their home, live in a detached house, have a higher level of education, and have a higher household income (*62*), though used PEV owners may be more geographically dispersed than new PEV owners (*63*).

The characteristics of new and used PEV buyers mean that both those interested in buying PEVs and those adopting them are currently and historically dissimilar to conventional car owners (a much more diverse population) though they are becoming more similar to *new* car buyers who have higher incomes, are older, are more likely to have a college degree, own their home, and identify as white (*56*, *57*, *64*). This means PEV owners also share many characteristics with early adopters of new technologies in general (*65*).

3.2.Lifestyles, attitudes, and norms of PEV buyers

Studies have also investigated how PEV adoption is related to beliefs, attitudes, and norms (*66*), sometimes using frameworks such as the theory of planned behaviour (*67*), theory of reasoned action (*68*), value-belief-norm theory (*69*), and other theories. Studies that consider attitudes generally consider respondents evaluations and perceptions related to specific issues, often technology, the environment, or transportation issues. Studies that consider norms typically consider aspects like subjective norms which pertain to participants perceptions of societal expectations on certain behaviours. Beliefs are often related to aspects that precede consumer attitudes and norms and relate to consumer thoughts on various issues.

Attitudes, beliefs, or norms related to PEV adoption typically include factors related to the environment or technology. Having positive attitudes toward pro-environmental behaviour is significantly related to PEV acceptance in 33 of the 38 studies reviewed by Wicki et al. (*10*). Studies also find concern on dependence on foreign oil (*50*, *70*) and local air pollution (*70*) are correlated with PEV adoption. Wicki et al. (*10*) also found interest in technology was significantly related to PEV adoption in 7 of 12 studies that included technology as a measure. While interest in technology is related to PEV adoption some consumers are resistant to new technology in general (*65*), and the same resistance has been found for PEVs (*21*). Some consumers view PEVs as unproven technology (*14*, *39*). While the data from these studies was collected in earlier years, a study with 2021 data found that some California car owners still perceived PEVs as being unproven technology not ready for mass markets (*44*).

4. PEV USE

Here we consider PEV use, focusing on the annual miles or kilometres PEVs are driven. We include this in the review since studies show differences in PEV use compared to conventional vehicles. How PEVs are used may relate to demand, for example, if PEVs are driven less than conventional vehicles this could point to a lack of demand among higher mileage users. Additionally, to reach higher PEV sales the vehicles may need to be like-for-like replacements for conventional vehicles.

Several studies have explored PEV use, often focusing on annual vehicle miles or kilometers travelled. Large sample size studies (on the order of 100,000 vehicles) using vehicle odometer readings (*71*) and estimated VMT from home charging data (*72*) have concluded that PEVs are driven significantly less than conventional vehicles, approximately 7,000 to 8,000 miles per year compared to 11,000 to 12,000 for conventional vehicles. Older survey-based studies have drawn the same conclusions (*73*). However, these differences may reflect the demographics of early adopters, most of whom own multiple vehicles, have different demographic attributes, and may have different driving needs, or they may be due to other factors such as higher leasing rates (leases have annual mileage caps) or limited driving range and/or charging infrastructure. Higher-range BEVs and BEVs with dedicated charging infrastructure (e.g. Teslas) have been found to have higher mileage than other PEV (*71*). Some recent survey based studies (*74*, *75*) and studies using vehicle loggers (*76*) have found PEVs are driven at similar rates as conventional vehicles, although these studies have smaller sample sizes (on the order of 1,000).

In places with a more developed PEV market and infrastructure, such as Norway, there is growing evidence that PEVs are being driven further than gasoline vehicles (*77*) or a similar amount (*78*, *79*). This could mean early observed VMT differences will be short-lived as more diverse buyers adopt PEVs and more PEV options become available in the future. This is important as PEV adoption by higher-mileage drivers has larger net environmental benefits .

5. CONSUMER ENGAGEMENT

Here we review literature on consumer awareness, experience, and knowledge of PEVs, which we broadly refer to as engagement. Research shows PEV sales are correlated with measures of PEV awareness (*81*, *82*) and there is positive a correlation between PEV adoption and having personal communications with PEV owners (*14*, *83*, *84*). The latter is one potential explanation for PEV buyers being clustered in specific regions, due to social network effects, where PEV adoption increases because more people observe PEVs or engage with other PEV owners (*59*). However, among the general population, studies show a lack of consumer knowledge, awareness, and familiarity of PEVs (*44*, *85*), which affects attitudes and willingness to adopt PEVs (*10*, *16–18*, *21*). Research has also found little change in awareness, knowledge, and consideration over time, with Kurani (*31*) finding few changes between 2014 and 2021 and Long et al. (*86*) finding little change between 2013 and 2017. Whether awareness or knowledge have changed after those years is not yet clear.

While technological progress continues, less progress has been made on improving consumer awareness, perceptions, and knowledge of PEVs. Several cross sectional studies in North America (*31*, *44*, *86*, *87*) show little change in consumer knowledge, perceptions, and consideration to purchase a PEV. This may indicate there is a disconnect between the technical improvements of PEVs and perceptions of PEVs, although it is unclear whether this is because of a lag in buyers' perceptions about PEV advancements or because they still perceive them to be unsuitable even with these advancements. Research also shows increased resistance to PEVs among new car buyers (*44*), low support for ZEV sales regulations (*88*), and lessening support for PEV incentives over time (*89*).

Studies have also identified some dealerships and salespeople as a barrier to PEV adoption (*14*, *15*, *41*, *45*, *90–92*). Studies have found car sellers were uninformed, misinformed, and unmotivated to learn about PEV technology, charging, and incentives, leading to poor customer experiences. Dealers have also been found to directly misinform customers about PEV range, incentives, and charging experiences as well as be dismissive of PEV technology, leave them out of conversations, steer customers away from them, and portray them as an inferior technology (*45*, *92*). These barriers may be a result of a lack of knowledge about PEVs, expected difficulties in selling them to customers (*41*, *45*), and the potential for PEVs to contribute less to post-sale service revenue given their lower maintenance requirements compared to conventional vehicles (*21*, *92*).

6. CONTEXTUAL FACTORS

In this section we review literature on contextual issues including studies on PEV incentives, infrastructure, and energy pricing. We consider these three areas since they, in addition to the other areas reviewed above, are often related to PEV sales or adoption.

6.1. Incentives

Most leading PEV markets provide financial purchase incentives for PEVs in the form of grants, rebates, vehicle tax discounts or waivers, or income tax credits (*93*). These lower the cost of PEVs for consumers, though 100% of the incentive value is not necessarily received by consumers, as automakers may also adjust vehicle prices based on the availability of incentives. Research from North America (*54*, *82*, *94–96*), Europe (*97*, *98*), and Asia (*99*) shows incentives are positively related to PEV sales, adoption decisions, and preferences for PEVs. Other incentives are also positively related to PEV sales, these include policies that discourage conventional vehicles and provide exemptions for PEVs. This includes PEVs receiving waivers to licensing restrictions in Chinese cities (*100–103*) and exemptions for PEVs to access special lanes or central areas of cities (e.g. carpool lanes, bus lanes, congestion charge zones, low emissions zones) (*33*, *104*, *105*). The only studies we identified that considered changes to incentives impacts over time found incentives increased in importance during the periods studied (*54*, *96*).

Studies show higher income buyers and buyers of longer range and more expensive PEVs are less dependent on incentives (*54*, *58*, *96*, *106*, *107*) while lower and middle income buyers are more sensitive to incentives (*95*, *96*, *107–111*). Nonetheless, higher income households and households in higher income and non-disadvantaged areas receive a disproportionate number of PEV incentives (*111*, *112*), though a large portion of this may be attributable to new-car buying rather than specific to EVs and rebates (*57*). Changes to incentive designs and targeting incentives to lower income buyers are improving incentive distribution, and incentive recipients are becoming more similar to new car buyers in some cases (*57*). Some programs are designed specifically for lower income buyers, and research shows these may be more cost effective than incentives that are not targeted (*58*, *113*). Incentive impacts also differ based on when they are received by buyers, with incentives delivered at the point of purchase being more impactful than post purchase rebates or income tax credits (*114*). Incentives received at the point of purchase may also better serve lower income buyers as they directly reduce purchase price (*115*). Research has also found low awareness of incentives in the general population (*44*, *85*, *106*, *116*) and that awareness correlates with incentive impact (*82*). Finally some tax credit designs are not equitably designed, the US federal tax credit in particular is tied to household income so can mean lower income buyers receive a smaller credit (*115*), though buyers can now transfer the credit to a dealer to receive the full amount.

6.2.Infrastructure

In section 2.1 we discussed perceptions of infrastructure, and here we consider research on charging infrastructure impacts on PEV demand. First, several studies show that home charging infrastructure is influential in the decision to purchase or consider a PEV (*26*, *33*, *117*) and is correlated with the decision to continue owning a PEV (*118*). After home, some studies find workplace charging is often the next most influential location of PEV charging (*119–121*). The impact of public charging on PEV sales, PEV purchase, or preferences is not yet clear; the relationship may be only correlational (*122*, *123*), some studies show a causal relationship (*100*, *106*, *124*), others find no relationship (*29*, *125*), and some contest that infrastructure causes PEV sales and suggest the impact of infrastructure on sales is mediated by other factors, for example attitudes or norms and prior interest in PEVs (*126–128*).

Even if it is not clear how infrastructure impacts sales, both slow and fast charging is still needed for drivers to use a PEV. To reach 100% PEV fleet penetration, charging must be accessible essentially everywhere in some form to facilitate all travel, including long-distance travel. However, this is not currently the case with infrastructure not equally or equitably distributed. Those living in multifamily building (apartments, condos, etc.) are less likely to have access to charging while at home (*129–132*). Additionally, studies from the US and UK show lower income and Black and Hispanic communities have lower access to public and private infrastructure (*62*, *133–135*) than higher income or non-minority communities.

6.3.Energy Prices

The final area of research we consider are studies that consider the relationship between energy prices (i.e. liquid fuel/gasoline and electricity prices) and PEV sales. PEV demand may be influenced by both liquid fuel and electricity prices, with lower electricity prices and higher fuel prices potentially positively impacting PEV sales. Studies in several regions have found fuel prices, often in combination with other incentives, taxes for conventional vehicles, or demographics correlate with PEV demand (*106*, *125*, *136–138*). Changes in liquid fuel prices may have a larger impact on PEV demand than changes in electricity prices, potentially because of a lack of awareness about electricity prices as well as regional and temporal variation in electricity prices (*139*). A potential explanation offered by Bushnell et al. (*139*) is that fuel expenditure is also generally higher than electricity expenditure over a vehicle's lifetime and home charging cost is obscured in household electricity bills.

Finally some research is beginning to show a relationship between PEV ownership and residential solar photovoltaic ownership (*140*). Potentially due to this providing lower cost electricity, at least during sunny periods, which leads to lower operating costs for PEVs (*141*). An additional synergetic integration of the charging process into the electricity system, where low electricity prices are used for charging the car – or even allow a feeding-back of electricity to the grid, the so called vehicle-to-grid (V2G) – could also lead to decreasing electricity costs for flexible PEV users (*142*, *143*). How the availability of V2G may impact demand for PEVs is not currently clear.

7. DISCUSSION OF CHALLENGES AND RESEARCH NEEDS

Here we discuss emergent challenges in reaching higher ZEV sales based on our evaluation of the literature. We also outline areas where more research may be needed to better understand and address some trends we identify (see Table 1).

7.1.Consumer perceptions and preferences

While progress been made on technical aspects of PEVs, including increasing range, reducing charging times, and expanding infrastructure access (*144*) consumer perceptions may not have improved at the same rate. This may mean perceptions will not always align with technical advances in PEV technology, and overcoming perceived barriers will require approaches beyond technical improvements. Further because PEV range, refuelling time, and infrastructure availability are still behind that of conventional vehicles, some buyers may resist PEVs until they are more directly comparable to conventional vehicles or until buyers understand more about PEVs and how they fit their mobility needs (*145*). Research will need to consider if and when perceptions of PEV attributes match improvements in the technical attributes of PEV models and when PEVs are broadly perceived as viable alternatives for conventional vehicles for most vehicle buyers.

Progress on PEV purchase price has been mixed. At the lower end of the market, PEVs with long driving ranges are becoming more available at more affordable prices, but the average cost of PEVs has increased and is diverging from the price of conventional vehicles in the US (*146*). Reductions in PEV cost due to reduced battery costs and increased economies of scale have translated into longer driving ranges instead of lower prices, and projections that PEVs will reach price parity (*147*) are not supported by historical PEV price trends (*146*, *148*). This could be due to automaker decisions on the variety of PEV models they supply, often focusing on larger or more expensive models in some markets. Regardless, until lower cost models are available, research may need to consider how this impacts demand for PEVs, how price changes impact adoption, and if (or how) consumers evaluate higher purchase prices compared to conventional vehicles and how they consider potential operating cost savings.

7.2. Consumer characteristics

PEV buyer average income, level of education, age, and number of household vehicles are progressing closer to the average of new car buyers (*57*), although it is unclear how incentive discontinuities may impact this (which we discussed in section 6.1). The little change to PEV buyer gender and home ownership may indicate some buyers face barriers in choosing a PEV. Lacking dedicated home charging is typically reported as the explanation for fewer renters purchasing PEVs, but why other genders are not purchasing PEVs in higher numbers in some markets (notably the United States and Germany) remains unclear and warrants more research. Most PEV adoption has also been among multi-vehicle households. Research shows single vehicle households are more concerned about PEV range (*10*). Whether the concerns of single vehicle households will change overtime is not clear and requires further research.

As for attitudes, beliefs, and norms of PEV buyers, existing studies test a limited set of these when studying the correlation with PEV interest, including anywhere from three (local air pollution, greenhouse gas emissions, and oil dependency) (*70*) to six measures formed from a list of 21 statements (on car ownership, mobility, PEVs, and environmental issues) (*66*). The choice to include these variables may be because PEV interest is correlated with a few beliefs and attitudes early adopters have (e.g. pro environmental, pro technology). Since not all consumers are motivated for environmental or technology related reasons (*149*), growing the PEV market may require PEVs to take on other meanings. For the market to have more diversity among PEV owners, different vehicle models and marketing strategies may be needed so that PEVs appeal to more consumers. Most studies, while including the key variables associated with PEV interest so far, may omit variables that could elicit PEV interest among future buyers. For example, in the United States, outdoor lifestyles are featured in many conventional vehicle marketing campaigns, and especially for trucks and SUVs (*150*); if PEVs are framed in this way, outdoor lifestyle could become correlated with PEV adoption or adoption intent. Research should continue to identify who PEVs appeal to and how to ensure PEVs appeal to consumers with differing attitudes, beliefs, and norms.

7.3.PEV use

Some research shows PEVs are on average being driven fewer miles than conventional vehicles (*71*), while other studies show PEVs are driven a similar amount (*74, 75*). PEVs being driven less could be due to PEV buyers having more vehicles in their households than conventional vehicle owners, meaning fewer miles or kilometres are driven in their PEV. The differences could also be due to PEVs being leased at higher rates than conventional vehicles and buyers reducing miles to remain under lease mileage limits. The discrepancy could also be due to PEV buyers having different demographics to the car driving population. The discrepancy could also be due to shorter driving ranges of PEVs and because infrastructure is still being developed. If PEVs are driven more miles than conventional vehicles this could be due to PEVs having lower operating costs or multi vehicle households preferentially driving a PEV rather than an ICEV due to these costs. Either way more research is needed to understand any differences in PEV use, determine whether PEVs will be adopted by households who drive more miles annually, and understand if PEVs may lead to more or less miles driven.

7.4.Consumer engagement

Research shows the general population is not substantially engaged with the PEV transition; this may partly explain why perceptions lag technical improvements. Regardless more may need to be done to engage consumers and car salespeople on a larger scale than has been done so far. This may include automakers providing more information and using more conventional advertising to promote PEVs. Beyond purely information and advertising, consumers may also benefit from hands-on experience operating or even simply riding in PEVs, which has been found to reduce concerns on issues including PEV range (*10*, *37*, *41*). Second research in the US, Canada, and Norway shows increased resistance to PEVs or PEV supporting policy (*31*, *88*, *89*). Support for PEVs has also become partisan in the United States, with Democratic voters more likely to adopt a PEV than Republican voters (*151*), potentially due to differences in perceptions of climate change by political affiliation and the connection between climate change and PEVs. It could be argued that those who resist PEVs will have to buy a PEV eventually because of sales regulations. However, the reasons for opposing a PEV should be researched so that they can be understood and addressed. Slower rates of adoption among those opposed to PEVs could limit progress to greenhouse gas reduction goals, and ignoring those who are resistant to policy can pose risks since policies with substantial opposition can fail (*152*).

7.5.Contextual factors

Most studies on the impact of incentives find a positive and significant relationship between the availability of incentives and PEV adoption or adoption intention (*18*), and a potentially increasing importance of them over time (*54*, *96*). The impact differs based on how incentives are distributed to buyers, incentives delivered at the point PEV acquisition being more impactful and efficient (*114*). This may not matter for many PEV markets since incentives are commonly delivered at the point of purchase. However, in the United States, many are still delivered post-purchase, which will likely limit their efficiency.

Many regions are beginning to phase out purchase incentives and lane access or parking incentives, partly due to increasing costs or concerns that such incentives lead to substitution from other transport modes. Considering that incentive effectiveness is correlated with certain demographics and incentives may increase in importance over time (*54*, *96*), discontinuities could negatively impact some buyers, such as lower and middle-income households. Though more research is needed to understand the change in incentive impacts over time and when they may be phased out. Some markets are incentivizing PEV adoption through revenue neutral policy such as feebates, where a fee is applied to conventional vehicles and rebates given to PEVs, with the latter being funded by the fees. Feebates are currently in operation in France and used to operate in Sweden (the fee in Sweden is still in place, rebates have been removed). These incentives may increase PEV sales and be more financially sustainable (*153–155*).

Finally, many incentive programs are not equitably designed, this may be partly because incentives were originally designed to help start the PEV market. However more recently stakeholders are considering how to most efficiently use incentives and how to create a more equitable PEV market. If funding for incentives is limited, it may be necessary to target incentives to those who need them most. As discussed in (*115*) incentives should include increased incentive allocation for lower income buyers, implement purchase price caps or income caps to exclude those who do not need incentives, allow buyers to claim the incentive regardless of purchase location (e.g., not only at a dealership), allow lower income buyers to apply the credit to used PEVs, not tie incentive amounts to tax liability (as is the case for the US federal tax credit in some cases), apply incentives at the point of PEV purchase, provide assurances on incentive availability in the case of funding discontinuities (which have been a recurring issue with California programs (*156*), increase awareness of available incentives, and support other ownership models for PEVs, including car sharing.

Next, considering current research on PEVs and infrastructure it is not clear whether infrastructure correlates with PEV sales, whether sales are caused by infrastructure, or some combination of the two. 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 and mostly serve past and existing buyers while not supporting future buyers. Stakeholders also need to understand this relationship since infrastructure is sometimes considered a tool to increase PEV sales, but this may not be the case with other actions needed to encourage PEV adoption. It is also important to understand whether experiences and perceptions of infrastructure, including user interfaces, payment, interoperability, and reliability issues impact infrastructure's role in encouraging or facilitating PEV adoption.

Since home charging is influential in the decision to purchase a PEV, the most frequently used charging location, important in continuing PEV ownership (*33*, *118*), and because a higher portion of future new and used PEV buyers are likely to reside in homes without home charging (*157*), research should consider what forms of charging infrastructure can encourage households without home charging to purchase and use PEVs. This may include workplace, near home (not in a private driveway or garage), or public fast charging. Research should also explore how to increase home charging access for households who cannot afford home charger installation, for whom home charging is prohibitively expensive, how to install charging in multi-unit housing parking lots, and how renters can install home chargers.

Since research shows underserved or lower income communities have less access to charging (*133–135*), policymakers, charging providers, and researchers will need to focus specifically on these communities' needs to understand what types of charging may best serve them (e.g., helping make single-family residences charge-ready through electrical upgrades, supplying near-home charging for multi-family-housing residents, providing electric mobility hubs, etc.). Without consideration of how to provide access to charging, there is a risk of perpetuating underinvestment in transportation access in historically underserved communities. The US federal Justice40 initiative directs 40% of federal investments in PEV charging to disadvantaged communities (*158*). 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 different communities, especially because public charging costs are far higher than home charging costs (*159*). Policymakers, researchers and other stakeholders should investigate the needs of different communities, include communities in planning processes through engagement, community led analysis, community organization, and allowing communities to participate in budgetary processes (*160*).

Lastly energy prices (both gasoline and electricity) may impact PEV adoption, though more so gasoline than electricity prices based on current evidence. Some regions, for example the United States, have relatively cheaper gasoline compared to markets with a higher PEV market share (*161*). If buyers are motivated by operating cost savings and when more price sensitive consumers begin to consider PEVs, the relative gasoline versus electricity costs may not motivate consumers in regions without clear operating cost benefits to purchase a PEV. More research is needed to understand how buyers respond to gasoline and electricity costs.

7.6. Future research needs

Below we list the future research needs (see Table 1) discussed above and highlight some other general research needs. Although reporting and presentations including annual metrics are becoming more prevalent, we were only able to identify a small number of studies on PEV adoption that consider changes over time (*44*, *54*, *86*, *89*, *96*), there is a need for more longitudinal studies or multiple cross-sectional studies, including both studies on PEV adopters and studies of the general population using quantitative or qualitative methods. More studies like these may help understand the trajectory of the PEV market, help inform how policy can be continually revised, anticipate challenges to PEV adoption, and determine if the PEV market is headed towards its goals. Similarly, there is also a need for repeated studies of the same topics to understand whether identified challenges continue to be an issue. One example is the study by Forsythe et al. (*162*) which is a replication study of a 2012 survey (*163*) on car buyer preferences and PEVs survey fielded again in 2021. Another example is the repeated examination of rebate influence from 2013–2015 in California (*54*) that was repeated for 2016–2017 (*164*). This is important because most studies (with the potential exception of some recent papers on Norway) focus on the earliest adopters of PEVs meaning less is known about mainstream car buyers. Finally, there is a need to expand PEV research to more regions, a lot of current research focuses on developed PEV markets (e.g. China, USA, and Europe), as PEVs expand into new regions and markets more research will be needed on those regions. In addition, based on insights from the literature, Table 1 outlines specific questions that we identify as important to understanding challenges to reaching 100% ZEV sales.

Table 1: Demand related research questions, the rationale for these question, and source of literature for the rationale.

Theme	Research Question	Rationale	Source
Consumer characteristics	Why are fewer female car buyers purchasing PEVs in some markets? How can PEV adoption be increased among female car buyers?	Fewer females are purchasing PEVs in some markets, including the USA and Germany.	(*53–57*)
	Why are fewer renters & those in apartments or condos purchasing PEVs? How can increased PEV adoption be facilitated among car owners in these house types?	Fewer renters and apartment dwellers are purchasing PEVs in some markets.	(*57*, *64*)
	How will incentive discontinuities and changes to incentive eligibility criteria impact PEV buyer demographics?	The impact of incentives on PEV adoption is related to demographics (including income), removal of incentives could impact buyers whose adoption is dependent on incentives including middle- and lower-income buyers.	(*54*, *95*, *96*, *107–111*)
	How will the introduction of new models (e.g. PEV trucks, and more model choice) change PEV buyers demographics?	Consumers have reported a lack of model availability as a barrier to adoption, model availability is increasing including in the truck segment, demographics are typically correlated with vehicle choice.	(*11*, *14*)
	Will used PEVs lead to PEV market diffusion to new groups of buyers?	New PEV buyers and new vehicle buyers have different characteristics from the general population and used vehicle buyers. Current evidence shows used PEV buyers have so far been similar to new PEV buyers.	(*62*)
	What (if any) geo-spatial trends exist in PEV adoption patterns? Are PEVs being adopted in concentrated areas or are they becoming more evenly adopted? To what extent is this due to spatial trends in new-car buying?	PEV adoptions is clustered in specific regions and neighbourhoods, often with higher adoption in higher income areas.	(*59–61*)
	How can policymakers support ZEV adoption among low-income and minority buyers?	Low-income and minority households are not adopting new or used PEVs at the same rate as high-income households but will need to adopt PEVs when the fleet transitions to higher PEV shares.	
Consumer perceptions	Why are buyers resistant to PEVs and why have some perceptions not changed overtime when sales have increased and PEV technology has improved?	Consumer knowledge and awareness has not substantially improved when PEV technology, sales, and infrastructure has substantially improved.	(*31*, *44*, *86*, *87*)
	Why are some consumers opposed to PEVs in general, purchasing a PEV, and PEV related policies, and can or will their perceptions change?	Some consumers are opposed to PEVs, PEV supporting policy, and PEV incentives.	(*31*, *88*, *89*)
	If vehicle price is a barrier to PEV adoption, will lower PEV prices impact this perception? Will lower operating costs	Price is reportedly a barrier to PEV adoption, PEV prices are higher than conventional vehicles on average.	(*10*, *15*, *41*, *45*)

	offset higher upfront costs for buyers? Will incentives be needed to achieve widespread affordability?		
	Are all dealers and car salespeople a barrier to PEV purchase? If not, which are not serving as a barrier and which are serving to facilitate PEV adoption, how, and why?	Car dealers have been dismissive to PEV buyers and may be a barrier for PEV purchase.	(*45*, *92*)
PEV use	Are electric vehicles being used similarly as conventional vehicles? If not, what explains any differences?	Some studies show PEVs are driven less than conventional vehicles, whereas other studies show they are driven similarly.	(*71–75*)
Consumer Knowledge	How can buyers' knowledge and awareness of PEVs be improved?	Consumer knowledge and awareness has not substantially improved when PEV technology, sales, and infrastructure has improved.	(*31*, *44*, *86*, *87*)
	How can consumer awareness of PEVs be improved and how can resistance to PEVs be overcame among certain buyers?	Some buyers are resistant to PEVs and PEV supporting policy.	(*44*)
Incentives	Are incentives increasing in importance over time? At which point will they no longer be needed and how should they be phased out?	Incentives may be increasing in importance over time, are still important for some adopters, and related to PEV sales but are being discontinued in some markets.	(*54*, *96*)
	How will changes to incentive designs and their administration impact their effectiveness?	Incentive impacts differ based on when they are received by PEV buyers, changes to point of purchase incentives (e.g. in the US) may change their effectiveness.	(*114*)
	How should incentives be designed and administered such that they reach the lowest income buyers, households in disadvantaged communities, and to buyers whose PEV purchase is dependent on incentives?	Lower income PEV adopters purchase of PEVs is more dependent on incentives, but most incentives have been received by higher income new-car buyers, incentive designs are not optimal to support lower income buyers.	(*111*, *112*)
	How will incentive discontinuities impact PEV buyer demographics and PEV sales?	Incentives positively relate to PEV adoption, and the impact of incentives is related to demographics (including income). Incentives are being removed or reduced in many regions removal of incentives could impact buyers whose adoption is dependent on incentives	(*82*, *94–99*)
	What incentive designs can be most effective in increasing the share of PEV sales (feebates, tax schemes, grants, rebates, etc.) without unwanted substitution effects from other modes?	Incentive impacts differ based on when they are received by PEV buyers, changes to point of purchase incentives (e.g. in the US) may change their effectiveness.	(*114*)
	Are incentives needed for second hand/used PEV purchases?	Incentives are being offered for used PEVs, little evidence exists on the need for these or their impact on adoption decisions.	

Charging infrastructure	Does charging infrastructure correlate with or cause PEV sales and how can infrastructure be effective in promoting PEV sales?	Some research shows PEV charging can cause PEV sales, other studies show a correlational relationship, and others suggest other factors cause sales and infrastructure facilitates adoption.	(*29*, *122*, *123*, *125–128*, *165*)
	What mix of infrastructure can support PEV adoption among later adopters of PEVs? Are the changing needs and charging behaviour of early adopters different than those of later adopters?	Our understanding of infrastructure needs of PEV adopters is based on the earliest adopters of PEVs. The needs of later adopters may differ.	
	What mix of infrastructure can support PEV adoption and continued PEV ownership for those without access to home charging including households living in multi-unit dwellings?	Home charging has been the most influential charging location in the decision to purchase a PEV in some studies. Households living in multi-unit dwellings are adopting PEVs at a lower rate than households in single family dwellings and have less access to home charging. Discontinuing PEV adoption is correlated to a lack of home charging access.	
	Is infrastructure sufficiently accessible in all communities? What are the charging needs for underserved and disadvantages communities? What charging will best support these communities PEV charging needs?	Charging infrastructure has not been evenly distributed in some regions, and the understanding of infrastructure needs often focuses on current PEV adopters. Underserved. Low income, and minority community charging needs are not well understood.	(*62*, *133–135*)
	Will issues with charging reliability impact demand for PEVs?	Public charging is experiencing reliability issues which may impact the experiences of PEV adopters, and could negatively impact PEV demand.	(*35*)
Energy prices	Will higher electricity prices and lower fuel prices impact PEV demand?	Gasoline fuel prices are related to PEV demand, though demand may be less sensitive to electricity prices at present potentially due to a lack of awareness of electricity prices.	(*106*, *125*, *136–138*, *162*)
	What relative fuel and electricity prices can motivate PEV adoption?		

8. CONCLUSION

In this paper, we considered potential demand side challenges in moving toward 100% ZEV sales (focusing on PEVs), something that is necessary to meet net zero emissions targets, and future research needs to understand and guide this transition. Most studies do not consider 100% PEV sales targets, and their aim was not to understand potential challenges to 100% PEV sales. PEVs remain a minority of vehicles on the road in all regions at 2.1% in the USA, 5.0% in the UK, 5.4% in Germany and 7.6% in China (*6*). We therefore use the literature to identify trends that may relate to challenges in increasing PEV sales and future research needs based on the findings of prior studies. Since all studies are conducted in the context of the PEV transition being in its infancy relative to the goal of 100% sales and eventually 100% adoption, some trends and issues may only reflect the early stage of the PEV market, but if they continue could make reaching 100% sales more difficult. The current understanding of buyer attitudes, demographics, charging behaviours, and other issues represent an understanding of the earliest PEV adopters. We may not understand mainstream buyers and how their perceptions, motivations, and needs differ from early PEV buyers, nor how they may use PEVs, such as for long distance, vacation travel, or for general travel for single vehicle owners.

We identify challenges related to consumer characteristics, consumer perceptions, consumer engagement, PEV use, incentives, charging infrastructure, and energy prices. Challenges related to sociodemographic and lifestyle factors include needing to engage female car buyers (in some markets) and renters or apartment dwellers, understanding the needs of single vehicle owning households, understanding how to support lower income households, and understanding needs and perceptions of buyers who are not early adopters. Challenges related to consumer engagement with PEVs include a lack of change in consumer awareness of PEVs overtime and in some cases worsening perceptions of PEVs and resistance to PEV related policy. Challenges for incentives include potential impacts to the PEV market from incentive discontinuities and incentive designs that are not sufficient for lower income buyers. Challenges related to infrastructure include needing to address 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 other engagement strategies to increase awareness of charging, consideration of infrastructure planning to meet all travel including long distance travel, and understanding whether issues with infrastructure could impact PEV demand. Challenges related to energy prices relate to regions with cheaper liquid fuel and more expensive electricity prices.

Many regions are introducing 100% ZEV sales targets or mandates, and it could be argued that since automakers must only sell ZEVs by a certain date some 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, without widespread support, policies can fail (*152*) and as the ZEV market expands beyond motivated and interested early buyers to consumers who do not support ZEV policy and those that indicate they would never purchase a ZEV (*44*, *88*), incentives, engagement strategies, and infrastructure may be needed to broaden support for ZEV policy and convince those resistant to ZEVs to purchase them. Interventions by policymakers may also make it easier for automakers to sell ZEVs, which may increase their support for the policy and prevent them from seeking changes to policy as they have in the past (*166*). Policymakers may also need to intervene where automakers and infrastructure providers may not, for example in making ZEVs more accessible and ensuring charging infrastructure is deployed in regions where automakers and infrastructure providers may not install charging infrastructure.

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