équiterre

ACCELERATING THE TRANSITION TO ELECTRIC MOBILITY IN CANADA

The case for a zero-emission vehicle mandate

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ABOUT ÉQUITERRE

Équiterre is Quebec's largest and most influential environmental organization, with 20,000 members, 200 volunteers, and a staff of 40 people.

Mission

Équiterre offers concrete solutions to accelerate the transition towards a society in which individuals, organizations and governments make ecological choices that are both healthy and equitable.

Vision

By 2030, **Équiterre**, in partnership with local communities, will have contributed to the development of public policies as well as civic and business practices that lead to a low-carbon economy and an environment free of toxic substances.

Areas of Intervention

Since its creation in 1993, **Équiterre** developed projects on key issues such as food, agriculture, transportation, buildings, consumption and climate change.

For example, Équiterre…

- Testifies before parliamentary committees in Quebec City and Ottawa;
- Participates in public consultation processes such as the BAPE (environmental public hearings bureau), the National Energy Board and the OPCM, (Montreal's public consultation agency);
- Participates in public debates in traditional and social media;
- Publishes pleas and research to support its positions;
- Meets elected representatives of the three levels of government;
- Launches petitions and organizes public events such as press conferences, mobilizations and marches.

EXECUTIVE SUMMARY

Background : Various studies, including those by the International Energy Agency, find that plug-in electric vehicles (PEVs) likely need to play a strong role in the decarbonisation of the transportation sector—making up at least 40% of new light-duty vehicle sales by 2040. In the Pan-Canadian Framework on Clean Growth and Climate Change released in December 2016 (Canada, 2016), the Canadian Government expressed an intention to develop a zero-emissions vehicle strategy to reduce emissions in the transportation sector. Our report uses a vehicle adoption simulation model to explore the policies required to induce ambitious sales of PEVs in Canada's passenger sector.

Methods : We develop a Canada-wide version of the REspondent-based Preference and Constraint (REPAC) model to simulate PEV new market share by representing key components of PEV demand, PEV supply and relevant policy (Figure E-1). REPAC uses a latent class discrete choice model previously estimated from data collected in a 2013 survey of over 1500 new vehicle-buying households in Canada. REPAC treats these choice model results as a measure of unconstrained demand for PEVs, and then adds consumer constraints (PEV awareness and home charging access) as well as supply constraints (limited variety and availability of PEV models).

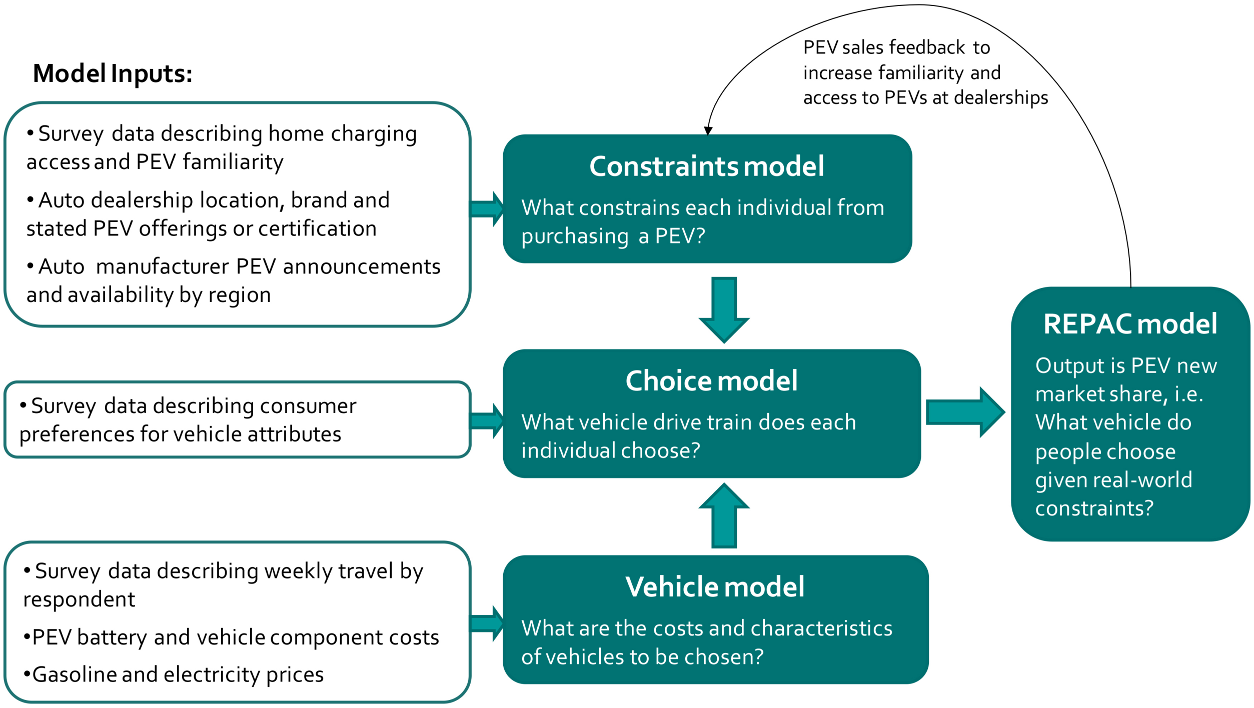

Figure E-1: Structure of the REPAC-PEV market share simulation model, Source: Wolinetz and Axsen (In Press)

Figure E-2 Illustrates the individual and combined effects of the three constraint categories applied in REPAC in the year 2015: home-charging access, PEV familiarity, and PEV availability. Applying all three constraints yields a constrained demand (CD) of 1% in 2015, which is very similar to the actual PEV market share in Canada in that year.

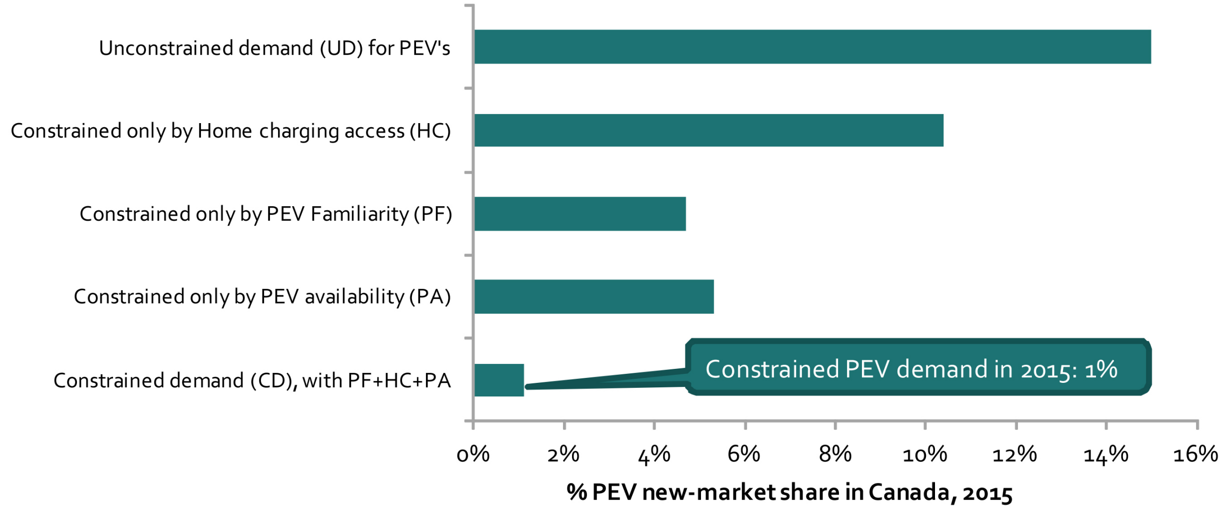

Figure E-2 : Impact of REPAC constraints on PEV new vehicle market share in Canada, 2015

Policy Scenarios : We use REPAC to explore three policy scenarios for Canada.

1. Current policy (BAU) : includes Canada's policies as of December 2016 (business as usual or BAU), including existing PEV-supportive policies nationally and provincially, as well as recently announced plans for carbon pricing and a clean fuel standard.
2. "Strong" demand-focused policy : adds to the BAU scenario a Canada-wide $7500 per vehicle purchase incentive for four years (2018-2021) as well as an ambitious schedule of charging infrastructure rollout.
3. ZEV-mandate : includes the BAU policies, a two-year $7500 per PEV purchase incentive (2018-2019), ambitious charging infrastructure rollout, and then adds a Zero-Emissions Vehicle (ZEV) mandate. We model such a mandate to be slightly more ambitious than those already implemented in California and Quebec, requiring PEVs to be at least 20% of new vehicle market share by 2025, and 30% by 2030. We model automaker compliance with the policy through: i) increasing the availability of PEV make and model variety, and ii) performing internal cross-subsidization to lower the prices of PEVs and raise the prices of non-PEVs.

Results : Figure E-3 depicts the modeled PEV new market share trajectory in each of the three policy scenarios for 2015 to 2030. The shaded areas represent the uncertainty in the forecast resulting from variation in four parameters identified in the sensitivity analysis; the lower boundary of each shaded region is defined by the most "pessimistic" values used for parameters in the sensitivity analysis (PEV familiarity constraint, the PEV availability constraint, gasoline price and PEV purchase price), while the upper boundary is the opposite. Results for each scenario are as follows:

1. Current policy (BAU) : PEV new market share grows to 4-17% in 2018, declines in 2019 when purchase incentives are removed, and then slowly grows to 6-17% of new market share by 2030.
2. “Strong” demand-focused policy : PEV new market share peaks at 13-32% in 2021, only to fall back to 4-13% in 2022 when the subsidies expire, and reaches 10-20% in 2030.
3. ZEV-mandate : Assuming that automakers comply with the ZEV mandate’s requirements, we find that automakers can comply with the sales requirement schedule in each year. Even with the most pessimistic assumptions (including low oil prices and high battery costs), PEV new market share can reach 30% by 2030. 2030 market share increases to 48% in 2030 with the most optimistic assumption.

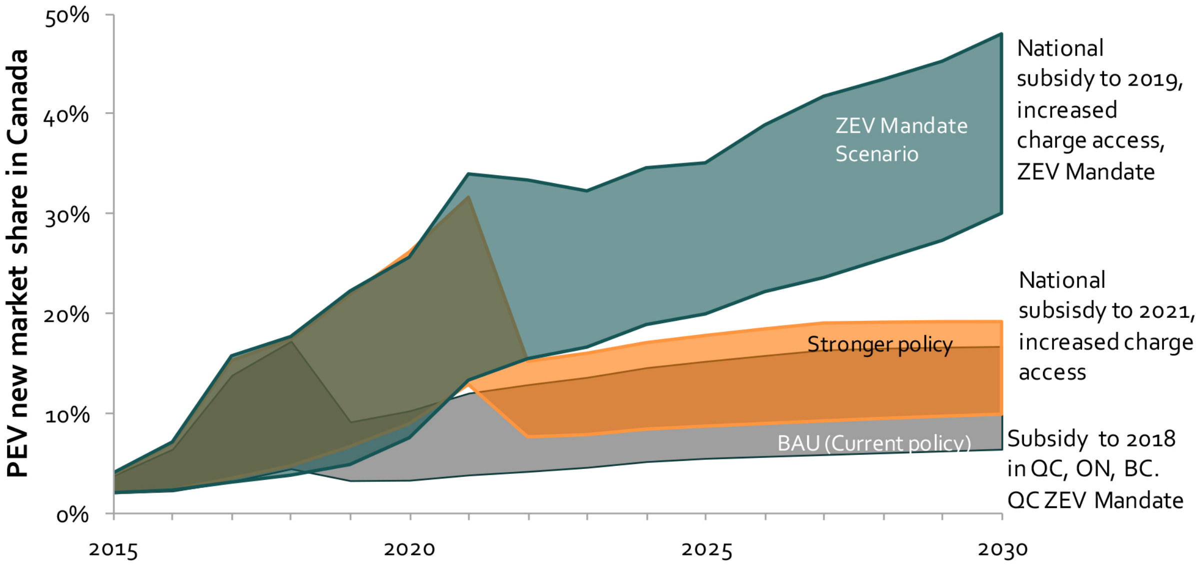

Figure E-3 : PEV new market share under policy scenarios (with shading representing uncertainty the PEV familiarity constraint, the PEV availability constraint, gasoline price and PEV purchase price)

Policy Recommendations : Our results yield several implications for Canadian policymakers, and in particular for the Pan-Canadian Climate Frameworks' zero-emissions vehicle strategy:

1. Canada's present suite of climate and PEV-supportive policies are not strong enough to induce a PEV new market share beyond 6-17% by 2030.
2. Even an ambitious suite of "strong" demand-focused policies is not likely to surpass 10-20% new market share for PEVs by 2030.
3. A ZEV Mandate can be effective in the long-term, where automakers can comply with PEV sales requirements for 20% of light-duty vehicle sales by 2025, and 30% by 2030—even under more pessimistic conditions (high battery prices and low oil prices).
4. In our scenarios, a ZEV mandate would be complemented by a temporary PEV purchase incentive and ambitious charging infrastructure deployment (home, work and public).
5. In short, the combination of a stringent ZEV mandate, strong but temporary PEV purchase incentives and ambitious charging infrastructure deployment could be an effective part of the Pan-Canadian Climate Change framework.

1. INTRODUCTION

In the Pan-Canadian Framework on Clean Growth and Climate Change released in December 2016, the Canadian government expressed an intention to develop a zero-emissions vehicle strategy to reduce emissions in the transportation sector (Canada, 2016). This framework does not identify specific policies, but does allude to the Zero-Emissions Vehicle (ZEV) mandate recently implemented in Quebec. To aid the Canadian government's consideration of effective policy, our report uses a vehicle adoption simulation model to explore the policies required to induce ambitious sales of plug-in electric vehicles (PEVs) in Canada's passenger sector—in line with over 30% new market share by 2030.[1]

Over a quarter of Canada's total greenhouse gas emissions come from the transportation of goods and people (2016), so deep reductions in greenhouse gas emissions from transportation are essential to meeting national and provincial climate reduction targets. Plug-in electric vehicles (PEVs), including pure battery electric and plug-in hybrid vehicles, could reduce emissions 45% to 98% compared to a conventional gasoline vehicle (Axsen et al., 2015b). Research indicates that widespread adoption of PEVs will likely be necessary to meet longer-term climate targets (Williams et al., 2012). For example, the International Energy Agency suggests that to limit global warming to 2 degrees Celsius, 40% of new passenger vehicle sales must be electric by 2040 (IEA, 2015). Canada-based studies suggest that even more rapid PEV adoption may be needed, perhaps reaching up to 80–90% of passenger vehicles sales by 2050 to meet national and provincial greenhouse gas targets (Bahn et al., 2013; Sykes, 2016).

In light of such climate goals, many policymakers and stakeholder want to forecast the sale of PEVs, and to understand how to influence those sales through policy. In this report we utilize the REspondent-based Preference And Constraint Model (REPAC), which was initially developed to simulate the effects of policy on PEV market share in the Canadian province of British Columbia (Wolinetz and Axsen, In Press). We expand this model to represent consumer demand and emissions impacts for all of Canada, focusing on three primary goals :

1. Identify the suite of policies likely needed for PEVs to reach at least 30% of new vehicle market share by 2030.
2. Quantify the greenhouse gas and energy impacts of these PEV market penetration scenarios.

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[1] Sections of this report are published in a recent journal article in Technological Forecasting & Social Change by Wolinetz and Axsen (In press), focusing on the case of British Columbia. However, the Canada-wide model and analysis presented in this report is novel and has not yet been published elsewhere.not yet been published elsewhere.Wolinetz and Axsen (In press), focusing on the case of British Columbia. However, the Canada-wide model and analysis presented in this report is novel and has not yet been published elsewhere.

3. Differentiate between the impacts of demand-focused policies and supply-focused policies in achieving these penetration levels.

Broadly speaking, forecasts of alternative-fuel vehicle sales are inherently uncertain and often unduly optimistic. A scan of the PEV market literature yields a wide range of forecasts, where in "no policy" scenarios PEVs make up as little as 1% of new vehicle market share out to 2030, or up to 5% of new market share as early as 2020 (Gnann et al., 2015; Sullivan et al., 2009). Studies in the grey literature (i.e. non-peer reviewed publications) can be even more optimistic, forecasting PEV sales of 17-28% in 2020 and 30-70% in 2030 without supportive policy in place (AECOM, 2011; Becker and Sidhu, 2009).

It is therefore important for PEV simulation model to represent the effects of different policy types, in particular "demand-focused" and "supply-focused" policies s (Axsen et al., 2016b). Demand-focused policies seek to directly increase consumer interest in PEVs through purchase subsidies, rollout of recharging infrastructure or the provision of non-financial incentives such as HOV-lane access and free parking. Norway is an example of a country with very aggressive demand-focused policies, including high PEV subsidies and non-financial incentives, as well as high taxation on gasoline and conventional vehicles. Largely due to these policies, Norway is currently the world leader in national PEV new market share at 22% in 2015 (EAFO, 2016). Of the previous PEV market share simulation studies that explicitly model policy, the vast majority only represent demand-focused policies, mainly subsidies and recharging infrastructure.

Supply-focused policies, on the other hand, are policies that put direct pressure or incentivize vehicle or fuel suppliers to develop, market and sell PEVs. Examples include California's Zero-Emissions Vehicle (ZEV) mandate and low-carbon fuel standard, as well as subsidies for R&D activities. Supply-focused policies have received less attention in the literature (Greene and Ji, 2016), though a few studies suggest their importance. For example, recent analysis of U.S. PEV sales data from 2014 shows that cities in "ZEV mandate" states had higher PEV availability (more models available for sale) and generally higher sales than other US cities (Lutsey et al., 2015). Further, two other modeling analyses indicate that a ZEV mandate, in addition to strong demand-focused policy, is likely needed to achieve deep GHG reductions in the US passenger vehicle sector (De Vos et al., 2016; Greene et al., 2014).

Some researchers argue that supply-focused policies can play an important role in channeling innovation activities to improve future low-carbon technology. Although automotive firms tend to have effective innovation systems, they are likely to need additional support to produce low-carbon vehicles, for example with government funded R&D (Köhler et al., 2013), particularly to overcome the dominance of fossil-fuel vehicles (Oltra and Saint Jean, 2009).

The reasoning is that the automotive sector faces a number of "failures" that prevent a transition to low-carbon technologies: in addition to the market failures of negative externalities such as greenhouse gas emissions, there are "system failures" that include a lack of shared goals and expectations about technology development, infrastructure provision and environmental regulation (Melton et al., 2016; Weber and Rohracher, 2012). In short, a large-scale transition to low-carbon vehicle technology is likely to require strong government support through some combination of demand-focused and supply-focused policies.

The REPAC model is designed to address the limitations of past models noted by Al-Alawi and Bradley's (2013) literature review, where previous models are said to provide a poor representation of consumer behavior, fail to represent the supply of vehicles and neglect to fully represent the effects of national and regional policy. We refer to REPAC as "respondent-based" because it is informed by survey data collected from a sample of over 1700 new vehicle buying households in Canada. Our present focus on PEVs includes both plug-in hybrid vehicles (PHEVs), which can be plugged and refueled using gasoline, as well as pure battery electric vehicles (BEVs) that can only be powered with electricity. We focus on passenger vehicles for private use, where fleet-based passenger vehicles account for about 18 percent of new light-duty vehicle sales in Canada (30% of which is commercial or government fleets, with the remainder being rental fleets) (Canadian Automotive Fleet, 2016; Statistics Canada, 2016). We believe the omission of fleets is reasonable for a passenger vehicle model of Canada—where we implicitly assume that fleet purchase decisions would be equivalent to those of the private car buyers we model. However, future exploration of fleet decisions would improve such a model

In the remainder of this paper we provide a more detailed literature review, and then further explain the Canada-wide REPAC model including its survey data inputs and its three sub-models. We then apply REPAC to the case of PEV-supportive policies in Canada, with three policy scenarios: 1) present Canadian policies, 2) the addition of strong demand-focused policy, and 3) the addition of a national ZEV mandate requiring 20% PEV new market share by 2025 and 30% by 2030. For each scenario we present simulated PEV new market share results out to 2030, as well as resulting energy use and GHGs. The end of our report highlights implications for Canadian climate policy.

2. SUMMARY OF PEV SUPPORTIVE POLICY OPTIONS

Research and real-world experience demonstrate that strong PEV supportive policy can encourage sales to approach the levels needed to meet long-term greenhouse gas targets (Axsen et al., 2016b). Research on the North American vehicle market suggests that strong policies that remove both demand side and supply side barriers can boost future PEV market shares to 24–40% by 2030 (Lin and Greene, 2011; Sullivan et al., 2009; Tran et al., 2013). Globally, we can see that the regions with the strongest PEV supportive policies—Norway, the Netherlands, and the State of California—also have the highest PEV market shares. Canada's PEV market share is likely to remain low unless similarly strong supportive policies are adopted.

A wide range of policies can stimulate uptake of PEVs. In general, policies can be categorized as demand-focused or supply-focused. Demand-focused policies aim to support or encourage consumer demand for PEVs by, for example, offering financial incentives, PEV-supportive building codes or providing charging infrastructure. Supply-focused policies encourage or require suppliers such as auto manufacturers, dealerships and fuel suppliers, to develop and sell PEVs by, for example, specifying that a certain share of vehicles sold in a jurisdiction have zero tailpipe emissions, or through support for research and development or Low Carbon Fuel Standards.

Examples of demand-focused include :

- Financial incentives reduce the cost of PEVs and charging infrastructure.
- Non-financial incentives offer other benefits to consumers including unrestricted access to lanes reserved for high-occupancy vehicles (HOV), and free parking.
- Public charging deployment provides access to charging away from home and is often funded by regional governments and utilities.
- Carbon pricing increases the price of fuels and activities that generate carbon emissions and make low-carbon electricity even cheaper than gasoline via carbon taxes or cap-and-trade programs.
- Building regulations can make the installation of home charging cheaper and easier, for example via building codes or by-laws, which mandate a certain level of charging access in new buildings.
- Information campaigns educate the public about PEVs and charging and include public-sponsored advertising, consumer outreach, informational websites, and vehicle labeling.

Examples of supply-focused policies include :

- Zero Emission Vehicle (ZEV) mandates require auto manufacturers to sell a minimum percentage of PEVs or hydrogen fuel-cell vehicles. This encourages automakers to research, develop, and market a wider variety of models and potentially lower sales prices as well.
- Research and Development (R&D) support provides government funding for technology innovation and development related to PEVs.
- Low-carbon fuel standards (LCFS) require fuel suppliers to reduce the carbon intensity of the fuels they sell in a regulated region. An LCFS can support PEV adoption because electricity is considered a low-carbon "fuel." A fuel supplier might be able to meet some or all of its LCFS requirement by purchasing credits from electric utilities that supply electricity to PEVs, creating an incentive for electric utilities to support PEV deployment (e.g. by using revenue from credit sales to build more chargers or lower electricity rates for PEV users).
- Vehicle emissions standards specify a required maximum level of tailpipe emissions for each vehicle class. Because PEVs produce zero tailpipe emissions their sale can help automakers comply with this policy.

3. THE PEV MARKET AND POLICIES IN CANADA

Our group, the Sustainable Transportation Action Research Team (START), recently released a report summarizing and evaluating the PEV-supportive policies in place in Canada (Axsen et al., 2016b). In this section we summarize some information from our report regarding the PEV market and types of PEV-supportive policy.

The market for PEVs in Canada has been growing, but remains small. As of June 2016, over 20,000 electric vehicles had been sold in Canada, and in 2015 about 1% of new vehicles sales were electric vehicles (CANSIMS, 2015; Klippenstein, 2016). Sales of PEVs in Canada have largely been concentrated in Quebec, Ontario, and British Columbia—which account for over two-thirds of the Canadian population. These three provinces also have relatively strong PEV supportive policy compared to other Canadian provinces. Table 1 shows PEV new markets share for each province in 2015, as well as total PEVs sold from 2011 to June 2016.

Table 1 : Market share and total sales of electric vehicles by province

REGION	NEW PEV MARKET SHARE (2015)	TOTAL PEVS SOLD (2011– 2016)*
Canada (nationwide)	0,9 %	22 763
British Columbia	2,0 %	4 190
Alberta	0,3 %	537
Saskatchewan	0,1 %	60
Manitoba	0,2 %	125
Ontario	0,7 %	7 248
Quebec	1,4 %	10 503
New Brunswick	0,1 %	87
Nova Scotia	0,1 %	94
Prince Edward Island	0,0 %	11
Newfoundland and Labrador	0,0 %	15

Sources : (CANSIMS, 2015; Klippenstein, 2016; Trochaniak, 2016), summarized in Axsen et al. (2016b)
*Electric vehicle sales data are as of June 2016.

In conducting a scan of PEV-supportive policies in Canada, our report identified 96 PEV-supportive policies in Canada. Of these policies, 8 have expired, 60 are active, and another 28 have been proposed (as of October 2016) (Axsen et al., 2016b). Across Canada, the number of PEV-supportive policies varies significantly by province (Figure 1), with the majority being demand-focused – primarily financial incentives (for PEVs and home chargers), public charging infrastructure deployment, and information campaigns. In contrast, there are only a few supply-focused policies in Canada: the federal vehicle GHG emissions standard, British Columbia's Low Carbon Fuel Standard and Quebec's ZEV mandate.

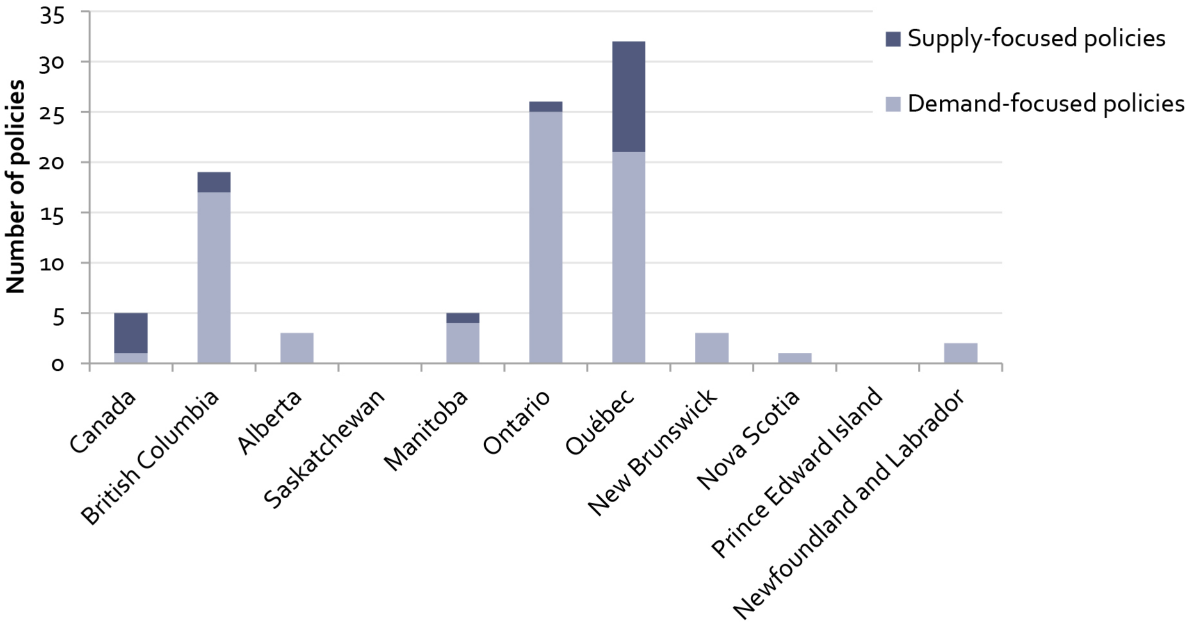

Figure 1 : Number of demand-focused and supply-focused policies by province (includes expired, current, and proposed), Source: Axsen et al. (2016b)

4. LITERATURE REVIEW : APPROACHES TO PEV MARKET SHARE SIMULATION

This section provides a literature review of the different approaches to PEV market share simulation, as has been published in our recent journal article (Wolinetz and Axsen, In Press). To summarize and compare different modeling approaches, we use a three-category framework we adapted from Al-Alawi and Bradley's (2013) recommendations, summarized in the rows of Table 2.

The first category accounts for representations of the PEV demand, where an excellent PEV forecast model will :

1. utilize a rich set of consumer data (likely collected via a large sample survey);
   - have empirical-based representations of consumer preferences that include more than just financial motives (e.g. cost savings) or functional motives (e.g. driving range), but also symbolic motivations (e.g., Heffner, 2007);
   - and account for consumers' lack of technology awareness or familiarity, which can be very low for PEVs (Axsen et al., 2015b; Axsen and Kurani, 2008) and can prevent preferences from forming in the first place (Bettman et al., 1998; Kurani et al., 1996).
2. The second category is the model's representation of PEV supply, which should account for the number and variety of PEVs available for sale in each vehicle class, where size, comfort, style and brand can influence consumer interest (Choo and Mokhtarian, 2004). Further, the model should represent the fact that some automotive dealerships might not carry such PEVs in stock or aggressively try to sell such vehicles—as found in Ontario and California (Cahill et al., 2014; Clairman, 2014).
3. The final category is policy, where an excellent model will explicitly represent the various effects of demand-focused (e.g. purchase subsidies and charging infrastructure rollout) and supply-focused policies (e.g. a ZEV Mandate, R&D funding, or low-carbon fuel standard).

There are a number of ways to classify models types; we presently summarize three categories (Table 3) : constraints-based models, discrete choice models, and agent-based models. Al-Alawi and Bradley (2013) also include a category called diffusion and time-series models that typically seek to fit "S-curves" to existing sales data in order to forecast future market share using a number of assumptions, as based on the Bass (1969) model. While such models have been applied to alternative fuels (e.g., Becker and Sidhu, 2009), we put less emphasis on this model type for our present research objective of simulating the effects of policy on PEV penetration.

Table 2 : Illustrative summary and comparison of PEV forecast model qualities (comparison framework adapted from Al-Alawi and Bradley, 2013), Source: Wolinetz and Axsen (In Press)

	CONSTRAINTS		CHOICE MODELS			AGENT-BASED MODELS				
Study citation	Williams et Kurani (2006)	Lopez et coll. (2014)	Potoglou et coll. (2007)	Glerum et coll. (2013)	Tran et coll. (2013)	Sullivan et coll. (2009)	Eppstein et coll. (2011)	Lin et Greene (2011)	Shafiei et coll. (2012)	Gnann et coll. (2015)
Model name/acronym						VAMMP		MA3T		ALADIN
Alternative vehicles included	Plug-in fuel cell	BEV	Generic alternative fuels	BEV	PHEV, BEV, Fuel cell	HEV, PHEV	HEV, PHEV	PHEV, BEV	VEB	PHEV, BEV
DEMAND SIDE QUALITIES										
Consumer survey data	Yes	Yes	Yes	Yes				Yes	Yes	Yes
Empirically-based preferences			Yes	Yes					Yes	Yes
Consumer awareness							Yes	Yes	Yes	
Heterogeneous preferences		Yes			Yes	Yes	Yes	Yes	Yes	Yes
SUPPLY SIDE QUALITIES										
Model variety						Yes				Yes
Model availability								Yes		
Multiple fuel types						Yes	Yes	Yes		Yes
Multiple vehicle classes						Yes		Yes		Yes
Recharge infrastructure	Yes	Yes			Yes			Yes	Yes	Yes
POLICY SIMULATION QUALITIES										
Demand-focused policy		Yes	Yes			Yes	Yes	Yes	Yes	Yes
Supply-focused policy										
PEV NEW MARKET SHARE, NO POLICY										
2020 estimate	15 %	2 %		27 %	4 %	1 %		4 %	6 %	5 %
2025-2030 estimate				27 %	4 %	1 %		8 %	6 %	
PEV NEW MARKET SHARE, WITH STRONG DEMAND POLICY										
Policy or driver		Price reduction			Install chargers + price reduction	Price		Install charger	Price reduction	Fuel costs +price reduction
2020 estimate		6%			40%	5%		10%	100%	10%
2025-2030 estimate					40%	24%		25%	100%	

First, constraints models produce forecasts of PEV market penetration based on vehicle buyers' physical, resource, or functional constraints such as home recharge access and driving patterns. Such models have a fairly crude representation of the demand side, where consumer demand or interest in PEVs is neither stated nor revealed, but instead inferred from constraints. For example, two studies estimated the potential market share of PEVs based on the proportion of households with characteristics likely to make home charging feasible (Nesbitt et al., 1992; Williams and Kurani, 2006). Pearre et al. (2011) used driving diary data to conclude that a 160 km range BEV (with home charging only) could meet the travel needs of 17 to 32% of US drivers. Another constraints analysis sought to identify the potential BEV market in Lisbon, Portugal, via measures of households' socioeconomic traits and mobility patterns, including the ability of a household to afford a BEV, the extent to which the vehicle would meet household travel needs, and the opportunity to charge the BEV at home and work (Lopes et al., 2014). Such models provide little insight into actual consumer motivation or decision making and also neglect vehicle supply, and thus tend to be ineffective in understanding the potential effects of PEV-related policy. At best, such models provide an "upper bound" on PEV sales under present conditions, but only if the proxies for consumer PEV interest (e.g. driving patterns) align with actual preferences—though even these assumptions are often not supported by literature.

Second, consumer discrete choice models seek to directly represent consumer preference and decision-making through a utility function, which in turn can simulate vehicle market share via some form of logit model (McFadden, 1974; Train, 1980). Such choice models can be directly estimated through survey data such as a stated choice experiment (Hidrue et al., 2011; Potoglou and Kanaroglou, 2007), through statistical analysis of market data (Brownstone et al., 2000), or through "data-less" parameters tested with Monte Carlo analysis (Tran et al., 2013). In some cases, consumer demand is assumed to be driven solely by total cost of ownership (the net present value of the vehicle), although empirical research demonstrates that consumers do not purchase passenger vehicles based only on financial and functional motivations (Heffner et al., 2007; Turrentine and Kurani, 2007). Discrete choice models can be relatively effective in representing the demand-side, but tend to ignore real-world consumer constraints such as lack of awareness, instead assuming that consumers have perfect information. Because stated choice models are based on preferences elicited through hypothetical choice sets, results can be biased if consumers are not prompted to fully consider the patterns and constraints of their real lives, such as limitations in consumer income (e.g. where respondents might assume unrealistically high budgets in making their purchase decisions). As a result, stated choice models tend to provide particularly high estimates for alternative fuel vehicle valuation and market share (e.g., Tran et al., 2013), and may be unreliable if not combined with real-world revealed preference or market data (Axsen et al., 2009). Further, the supply side is typically not represented in discrete choice model, making choice models ineffective in representing the effects of supply constraints and supply-focused policy.

Third, agent based models simulate the choices and interactions of agents, such as consumers, auto makers and government, as they seek to attain their objectives subject to some set of constraints. Agent-based models are very flexible because they can be constructed to represent PEV sales using aspects of choice models while accounting for constraints on agents such as vehicle charging access (Lin and Greene, 2011), vehicle variety (Gnann et al., 2015), and consumer awareness or willingness to consider purchasing a PEV (Shafiei et al., 2012). Agent based models offer the potential to endogenously model the supply side by explicitly representing the decision making of automakers (Sullivan et al., 2009) or by representing PEV model availability as a function of market share (Lin and Greene, 2011). Agent based models can also represent spatial and social relationships between agents, such as how physical or social proximity can influence the purchase decisions of other agents (Eppstein et al., 2011; Shafiei et al., 2012). Because the agent-based framework is so flexible, the approach itself does not necessarily have limitations—instead limitations vary case by case (as illustrated in Table 2). As examples of such criticisms, otherwise well-designed models have neglected to use empirically derived data to represent consumer preferences (Eppstein et al., 2011; Lin and Greene, 2011; Sullivan et al., 2009), not represented constraints in consumer familiarity (Gnann et al., 2015; Sullivan et al., 2009), and failed to account for limited PEV availability or variety (Eppstein et al., 2011; Shafiei et al., 2012). Gnann et al. (2015) provide a recent example of a sophisticated agent-based PEV forecast model for Germany that accounts for several of the ideal model aspects described by Al-Alawi and Bradley (2013); however, consumer preferences in the model are primarily based on financial costs and savings, which inherently limits behavioral realism.

In terms of model outputs, PEV market share forecasts generated by literature using all three model types tend to be highly sensitive to demand-focused policies, notably purchase subsidies and increased charger availability. As examples, PEV subsidies in the range of US$ 5,000 (or an equivalent reduction in purchase price due to reduced battery cost) are found to double or triple PEV demand forecasts (Gnann et al., 2015; Lopes et al., 2014; Shafiei et al., 2012), or in one case to increase sales from 1% to 5% in 2020 and to 24% in 2040 (Sullivan et al., 2009). In contrast, Eppstein et al. (2011) estimated that a similar incentive has little impact if it is maintained for short period, e.g. less than five years. A second common finding is a sensitivity of market share forecasts to charger access, where aggressive deployment of public and home charging infrastructure was found to double or even triple the rate of PEV adoption in the U.S. from 2020 through to 2025 (Lin and Greene, 2011). Of the models reviewed, none have explored the effects of supply-focused policies (e.g. a ZEV mandate, R&D subsidies or low-carbon fuel standard) on PEV market share.

5. THE RESPONDENT-BASED PREFERENCE AND CONSTRAINTS (REPAC) MODEL

The REPAC model seeks to draw strengths from all three of the modeling approaches reviewed above, while addressing the recommendations provided by Al-Alawi and Bradley (2013) to produce policy-relevant PEV adoption forecasts. Although the first version of REPAC was developed to focus on passenger vehicle buyers in British Columbia (Wolinetz and Axsen, In Press), in this report we expand REPAC to be Canada-wide, utilizing the full set of Canadian new vehicle buyer data from over 1700 Canadians that we collected as part of the Canadian Plug-in Electric Vehicle Study or CPEVS (Axsen et al., 2015b) – described in Section 5.1.

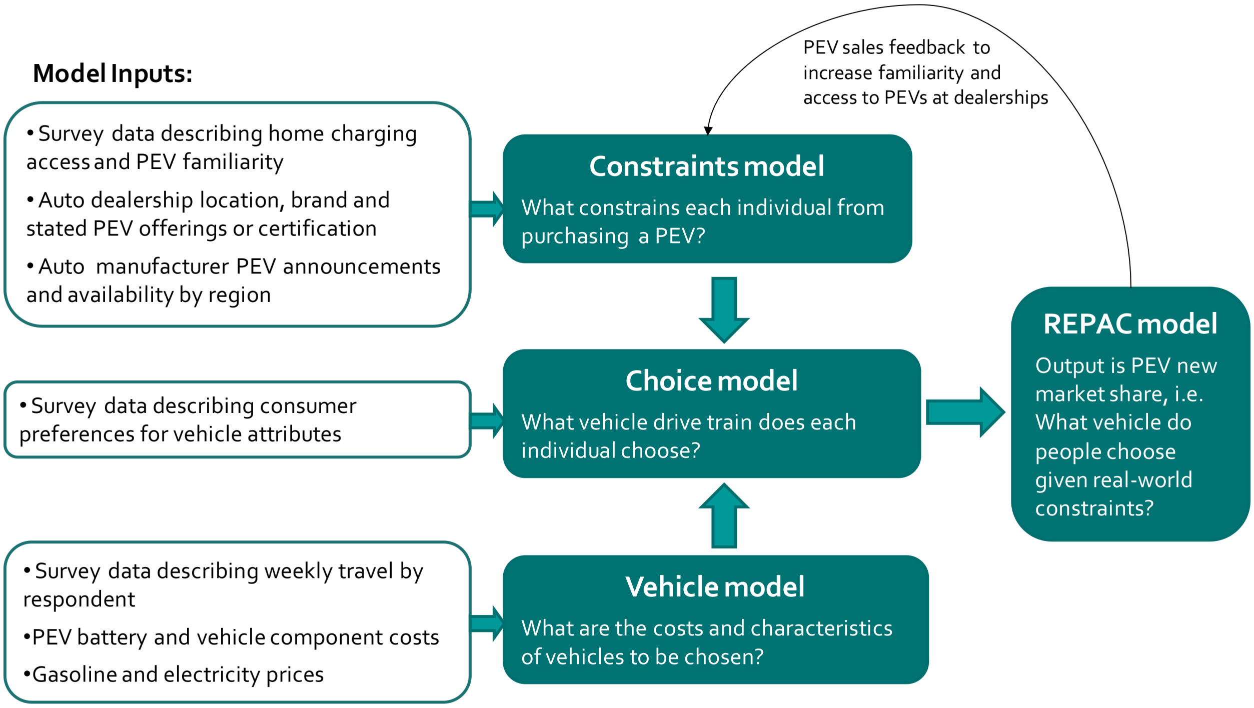

Figure 2 : Structure of the REPAC-PEV market share simulation model, Source : Wolinetz and Axsen (In Press)

REPAC consists of three sub-models (Figure 2) : the choice model, the constraints model and the vehicle model.

1. The choice model (an empirically-derived discrete choice model) estimates the probability that each CPEVS respondent will choose four different vehicle drivetrain types (i.e., conventional, hybrid, PHEV or BEV) in the absence of constraints on the choice (e.g. home recharge access). The output of this sub-model should be thought of as unconstrained demand (often known as "latent" demand among economists)—PEV market share that might not be realized as demand due to constraints.

2. The vehicle model describes the cost and performance of the archetypal vehicles (one for each drivetrain) that we used to set up the choice model attributes in CPEVS.
3. The constraints model represents three factors that prevent unconstrained demand from being realized as sales : lack of familiarity with PEVs, lack of PEV supply (variety and availability) and lack of home recharge access.

There are many endogenous parameters that could be included in a PEV market share simulation model, such as positive feedbacks between increased PEV sales and R&D activities, learning by doing, spillovers with related industries (e.g. electronics) and consumer preference formation (Struben and Sterman, 2008). We do not include all of these possible feedbacks in REPAC due to our efforts to simulate PEV adoption in a small country—Canada. An increase in PEV market share in Canada is only likely to endogenously change factors that are affected locally (within the region). REPAC endogenously models two such parameters: consumer PEV familiarity and the availability of PEVs at auto dealerships. Conversely, REPAC does not endogenize PEV cost reductions or PEV model variety as these dynamics are globally determined and unlikely to be affected by sales in a small country. Further, one of our objectives is to model the effects of “supply-focused" policies through an increase in model availability and variety, meaning that we want to exogenously represent this factor to address our research objectives (i.e. include it as an assumption in a policy scenario). Similarly, REPAC does not endogenize PEV charger access because infrastructure rollout is one of the "demand-focused" policies we test in our policy scenarios. Energy prices are also exogenous in REPAC; PEV demand in Canada will not strongly affect the global price of oil, while PEV electricity demand may slightly affect electricity prices, but not in a way that noticeably affects model simulations. Moreover, the choice model used in REPAC indicates that PEV demand is not highly sensitive to changes in electricity prices (Axsen et al., 2015a).

The following subsections provide further detail on the survey used to collect respondent data, the three sub-models that make up REPAC, and the scenarios we analyze, which include demand- and supply-focused policies.

5.1. Survey data collection

Consumer data for the REPAC model are drawn from the Canadian Plug-in Electric Vehicles Study (CPEVS), which included a three-part survey completed by a sample of 1,754 new vehicle buying Canadian households in 2013. The full Canadian sample is representative of the populations of new vehicle buying households, as depicted inTable 3. Survey respondents were recruited from all Canadian provinces except for Quebec (Quebec was omitted due to the lack of budget to cover costs of French language translation). To represent Quebec in the REPAC model, we utilize a choice model estimated from the residents of the other nine Canadian provinces and inform the model with data from the Ontario sample. The next iteration of this survey will include a Quebec sample.

The full survey instrument is detailed and replicated in the CPEVS report (Axsen et al., 2015c); here we summarize only questions used to elicit data to inform the REPAC model. These data include :

- Each respondent's geographical location (Canadian province and city or municipality).
- PEV awareness, which was assessed via a question in Part 1 that asked "How familiar are you with the following vehicles or technologies? For example, do you know how you would drive and refuel them?" The technologies included hybrid-electric vehicles, PHEVs and BEVs. Response categories included "not familiar", "somewhat familiar", "familiar" and "very familiar".
- Weekly driving distance for each respondent, which was approximated based on a 3-day driving diary in Part 2.
- Respondent access to Level 1 (110/120 V) charging for a PEV at home, which was assessed via three questions in the home recharge assessment in Part 2, namely i) "When at home, where do you usually park your vehicle?" (For charge access to exist, response needed to be a privately owned parking space: a carport, garage or driveway), ii) "Roughly how long an extension cord would you need to connect your vehicle to the nearest normal outlet ?" (response needed to be 25 feet (7.6 m) or less), and iii) "Imagine your vehicle is an electric vehicle. Realistically, would you consider regularly plugging in your vehicle to this outlet using an extension cord ?" (response needed to be "yes").
- The potential for each respondent to install a Level 2 (220/240V) charger at their home, which was assessed in Part 2 questions asking if they currently parked within 25ft of a 220/240V outlet, and if not, then a question asking "To directly connect your electrical panel to your vehicle, how long would this extension cord need to be?" If the distance was less than 25ft, we considered respondents to have the potential to install a 240V charger at their home. We assume that only respondents with Level 1 charge access could have the potential for Level 2 access.
- The vehicle class of the respondent's next likely new vehicle purchase, which was assessed in Part 3 via the question "If your household were to buy a new vehicle this year, what model would you be likely to buy?" Specific vehicles were collapsed into four basic classes: compact car, sedan, mid-sized SUV/van/truck, or full-size SUV/van/truck.
- Preferences for PEVs and their attributes, which were assessed in Part 3 using the stated choice experiment, detailed next.

Table 3 : Demographic comparison of CPEVS sample with the Canadian census data, Source: Axsen et al. (2015b)

	ALL RESPONDENTS	CENSUS (CANADA)
SAMPLE SIZE	**1,754**	**33,476,688**
HOUSEHOLD SIZE		
1	13.1%	27.6%
2	40.0%	34.1%
>2	47.0%	38.3%
Female (respondent)	58.4%	51.0%
AGE (RESPONDENT)		
<35	30.0%	25.9%
35-44	18.2%	13.4%
45-54	19.5%	15.9%
55-64	19.2%	13.1%
>64	13.1%	14.8%
HIGHEST LEVEL OF EDUCATION COMPLETED (RESPONDENT)		
High school or less	18.4%	49.3%
Some university, college, trade, diploma	43.0%	32.6%
University degree (Bachelor)	26.2%	13.5%
Graduate or professional degre	12.4%	4.6%
HOUSEHOLD INCOME (GROSS, $CDN)		
Less than $40,000	14.8%	24.9%
$40,000 to $59,999	20.5%	19.3%
$60,000 to $89,999	27.8%	24.3%
$90,000 to $124,999	24.6%	16.8%
Greater than $125,000	12.3%	14.7%
Own residence	77.9%	68.7%
RESIDENCE TYPE		
Detached House	66.7%	61.9%
Attached House	15.3%	17.0%
Apartment	16.4%	14.0%
Mobile Home	1.6%	1.2%

Note : Data on household size, sex, age, and residence type are from the 2011 Canada Census. Data on work status, education, and income are from the 2006 Canada Census. Data on home ownership are from the Canadian Mortgage and Housing Corporation

Although this survey data was collected in 2013, we anticipate that most of the data we collected from Canadian "mainstream" new vehicle buyers would not substantially differ if we collected it in present day (late 2016). Respondents' driving patterns, vehicle class preference and home recharge access are all likely to be identical. Since, 2013, vehicle consumers may have become slightly more aware of PEVs, as the variety of PEV makes and models has increased and PEV sales in Canada have increased from about 0.3% to 1% of new market share. However, even in present day this PEV market share is relatively low, and mainstream consumers are likely to have similar perceptions of PEVs in 2016 as they did in 2013. In short, we believe that this 2013-based data is sufficient to suitably inform our present REPAC simulations. That said, our research group (START) will be implementing a new Canadian based survey in late 2016, where we will be able to quantify any changes in consumer preference and awareness.

5.2. Choice sub-model

The choice sub-model was previously estimated by Axsen et al. (2015a) using respondent data collected via the stated choice experiment in the CPEVS survey. Stated choice models quantify consumer preferences and are based on random utility theory, assuming that overall consumer utility for a product is based on components that are observable and unobservable (McFadden, 1974; Train, 1986). The observable portion of utility is represented by a vector of coefficients weighted to the specified attributes of the product in question, e.g. purchase price, electric driving range and fuel costs for a PEV. The alternative specific constant (or vehicle-specific constant in our case) represents the average effect of the utility of each choice not captured by attributes specified in the model. The unobservable utility is specified with a random parameter, with a mean of zero, where the assumed distribution varies by model type.

In the stated choice experiment, every survey respondent indicated the make, model, purchase price and fuel costs of their next anticipated new vehicle purchase. This information was then used to present six customized choice sets to the respondent, where each choice set presented four different vehicle drivetrains: a conventional vehicle (CV, their next anticipated vehicle purchase), and a hybrid (HEV), PHEV and BEV version of that vehicle. The vehicles in the choice sets were offered in one of four vehicle classes based on the respondent's desired base model: compact, sedan, and small and large SUV/Van/Truck. The stated choice experimental included four attributes: purchase price, weekly fuel cost, vehicle electric range, and home charging speed, either Level 1 (110/120 V) or with the potential to install Level 2 (220/240 V). Home charging speed was included as an attribute in the stated choice experiment because a respondent may have greater utility for a PEV if they can charge it faster, potentially allowing them to use it more easily, or to use more electricity rather than gasoline in the case of a PHEV. The experimental design is detailed in full by Axsen et al.

(2015a), where the selection of attributes and attribute levels are consistent with previous research—see reviews by Hidrue et al. (2011) and Tanaka et al. (2014). Axsen et al. did not include a representation of public or non-home charging infrastructure. Empirical research suggests that home charging infrastructure is more likely to be important among potential early mainstream PEV buyers (Bailey et al., 2015); however, this exclusion means that REPAC cannot explicitly simulate the impact of policies that increase non-home charging access (although REPAC can represent the increase of public charging infrastructure as its equivalent in terms of increased home charging access).

Although stated choice experiments are useful for eliciting preferences for new products that are not yet extensively available in the market, the hypothetical nature of this method can potentially bias results. The CPEVS survey design has taken steps to minimize this bias in several ways, including use of a “reflexive design” that carefully explains the new technology in easy-to-understand language, prompts respondents to consider if the technology would fit within the opportunities and constraints of their lifestyle, and reminds respondents to consider their present budget (Turrentine and Kurani, 1998). Further, the REPAC model is designed to adjust the “unconstrained demand” elicited through a stated choice experiment to account for real-world constraints (which should better align PEV market share forecasts with the real world sales). That said, stated choice results should still be interpreted with caution due to the hypothetical nature of the survey method.

To quantify heterogeneity in consumer preferences, we use the latent-class choice model previously estimated by Axsen et al. (2015a). Latent-class models divide the sample into a pre-defined number of classes (or segments) and estimate separate sets of coefficients for each class (Greene and Hensher, 2003; Shen, 2009), thus explicitly representing heterogeneity as consumer segments that have different preferences. Table 4 summarizes Axsen et al.’s coefficient estimates for each of the five classes, as well as the probability of membership for each class (i.e. the percentage of respondents within that class). There is a small class of “PEV-enthusiast” respondents (8% of sample) with extremely high valuation of PHEVs and EVs; the simple willingness-to-pay calculation (coefficient ratio) indicates that the average respondent in this class would pay more than $130,000 extra for a PHEV or a BEV, even if fuel costs are identical to those of a conventional gasoline vehicle. Such a willingness-to-pay ratio seems highly inflated and should be interpreted with caution—for example, we do not use REPAC (or this choice model) to simulate the purchase of PEVs that cost well over $100,000. Instead, this willingness-to-pay ratio should be taken to indicate that respondents in this class have very strong positive preferences for PEVs (which is how the authors determined the “PEV-enthusiast” label). For comparison, a sample of PEV owners or “pioneers” from the same region completing the same stated choice experiment indicated similarly high willingness-to-pay values (Axsen et al., 2016a). The second class, labeled “PHEV-oriented”, accounts for a larger proportion of respondents (25%) who express moderately positive valuation of PHEVs, and are more in line with the potential “early mainstream” PEV buyers that could enter the market after the initial high-enthusiasm “pioneers” (Axsen et al., 2016a). The remaining three classes generally have a negative valuation of PEVs relative to conventional vehicles, controlling for purchase price and fuel costs. Although class membership is probabilistic, in REPAC we place each respondent in the latent class to which they had the greatest probability of belonging (determined by socio-demographic characteristics not shown here, but reported by Axsen et al. (2015a)).

Table 4 : Latent-class results for 5-class solutions, n = 1754, Source: Axsen et al. (2015a)

CLASS LABEL	PEV-ENTHUSIAST	PHEV-ORIENTED	HEV-ORIENTED	HEV-LEANING	CV-ORIENTED
PROBABILITY OF MEMBERSHIP	**0.080**	**0.254**	**0.159**	**0.277**	**0.230**
HEV constant (VSCHEV)	0.64**	2.30***	2.65***	0.88***	-2.91***
PHEV constant (VSCPHEV)	2.09***	3.22***	-1.37***	-0.11	-4.72***
BEV constant (VSCBEV)	2.14***	-1.16**	-5.07	-3.10***	-2.15
Vehicle price (PP), CDN $	-0.00002***	-0.0002***	-0.0002***	-0.0006***	-0.0003***
Fuel cost (FC), CDN $/week	0.0002	-0.0407***	-0.0079***	-0.0387***	-0.0197***
PHEV range (ERPHEV), km	-0.0035	-0.0033	0.0118**	0.0065**	0.0039
BEV range (ERBEV), km	-0.0017	0.0038	0.0003	0.0057**	-0.0195
PHEV x Level 2 charging at home (L2PHEV)	0.11	0.51***	1.04***	0.51***	-0.20
EV x Level 2 charging at home (L2BEV)	0.62***	1.20***	3.67	0.26	-1.08
IMPLIED WILLINGNESS-TO-PAY[a]					
Saving $1000/year in fuel		$3,781	$670	$1,258	$1,126
HEV (relative to conventional)	$41,245	$11,090	$11,692	$1,493	-$8,637
PHEV (relative to conventional)[b]	$135,026	$15,568	-$6,028		-$14,021
EV (relative to conventional)[b]	$137,794	-$5,612		-$5,246	
PHEV with Level 2 charging		$2,444	$4,602	$856	
EV with Level 2 charging	$39,981	$5,805	$670	$1,258	

* Significant at 90% confidence level
** Significant at 95% confidence level
*** Significant at 99% confidence level
a We only depict willingness-to-pay calculations where the coefficient estimates are significant at a 95% confidence level or greater. As of February 12, 2015, $1.00 CDN is equivalent to $0.80 USD and €0.70 EUR
b Because the coefficient estimate for PHEV and EV range are not statistically significant, our willingness-to-pay calculations for PHEV and EV are not based on the range of a given PHEV or EV (e.g. PHEV-16 vs. PHEV-32).

The REPAC model uses the estimated coefficients in Table 4 to populate the utility function for a respondent in a given consumer preference class. REPAC uses the coefficients as shown in

Table 4 without modification, including those that are not significant at a 90% confidence level. The utility function is :

(Eq. 1) $$\boldsymbol{U_{i,j,k,l} = VSC_{j,l} + p_{j,k} * PP_l + f_{j,k} * FC_l + r_j * ER_{j,l} + L2_{j,l}}$$

Where Ui,j,k is respondents i's utility for vehicle drivetrain type j in the vehicle class they will buy next, k, based on their assigned latent class l; VSCj,l is Vehicle Specific Constant, the constant specific to each vehicle drivetrain; PPl is the purchase price coefficient and pj,k is the incremental purchase price of each option; FCl is the weekly fuel cost coefficient and fj,k is the weekly fuel cost of each option; ERj,l is the electric range coefficient and r is the electric driving range of each option; and L2j,l is the constant for Level 2 (220/240 V) charging potential at home, based on each respondent’s reported potential to install a level 2 charging station at home.

In REPAC, each respondent’s unconstrained choice is represented as a probability of choosing each of the four vehicle drivetrains (summing up to 100%). A respondent’s unconstrained demand (UD) for a vehicle type is the probability of choosing that vehicle type in the absence of other constraints on that choice. The UD of respondent i for vehicle drivetrain type j in vehicle class k is the ratio of the exponent of utility for that drivetrain divided by the sum of the respondent's exponent utilities for all drivetrain types (Train, 2009) :

(Eq. 2) $$\boldsymbol{UD_{i,j,k} = \frac{e^{U_{i,j,k}}}{\sum_j e^{U_{i,k}}}}$$

5.3. Vehicle sub-model

The vehicle sub-model specifies the attributes of each vehicle in the stated choice model. Each respondent was given a choice set within one of the four vehicle classes that they indicated would be their next likely vehicle purchase (compact, sedan, small and large SUV/Van/Trucks); we do not represent a choice between vehicle classes, assuming that respondents would not change vehicle classes to attain a desired drivetrain that isn’t otherwise available. However, future research could explore using a nested logit specification to represent class choice also. Within each class are four possible drivetrains : conventional gasoline, hybrid, PHEV, and BEV. While a variety of electric ranges are possible, we specify only a PHEV with a 64 km range (approximating a Chevrolet Volt), and only a BEV with a 120 km range (approximating a Nissan Leaf) for our simulations. Because coefficient estimates for electric range were not statistically significant in the respondent classes that are most likely to want a PEV (Table 4), altering the PHEV or BEV ranges would not noticeably affect results (which we depict in our sensitivity analysis).

Table 5 : Summary of PEV parameters for vehicle model Source: Wolinetz and Axsen (In Press)

	COMPACT CAR	SEDAN CAR	MID-SIZE SUV, VAN OR TRUCK	FULL-SIZE SUV, VAN OR TRUCK
INCREMENTAL PRICE (2015, CDN $)				
HEV	$1,292	$1,548	$1,794	$2,158
PHEV-64	$6,973	$8,500	$10,612	$13,056
EV-120	$8,252	$8,978	$11,678	$13,849
INCREMENTAL PRICE (2025)				
HEV	$822	$901	$983	$1,092
PHEV-64	$3,892	$4,971	$6,032	$7,354
EV-120	$3,286	$3,566	$4,570	$5,170
USABLE BATTERY CAPACITY (KWH)[a]				
HEV	0.9	1.3	1.8	2.1
PHEV-64	13.0	15.0	20.1	23.8
EV-120	24.4	28.1	37.8	44.5
GASOLINE CONSUMPTION (L/100KM)[b]				
Existing vehicles	6.8	8.2	9.7	11.8
Conventional[c]	6.0	7.2	8.6	10.4
HEV	4.0	4.8	5.8	6.9
PHEV64-	1.5	1.8	2.2	2.6
EV120-	n/a	n/a	n/a	n/a
ELECTRICITY CONSUMPTION (KWH/100KM)[b]				
Existing vehicles	n/a	n/a	n/a	n/a
Conventional	n/a	n/a	n/a	n/a
HEV	n/a	n/a	n/a	n/a
PHEV64-	7.1	8.9	10.7	12.9
EV120-	16.1	18.6	25.1	29.5
ILLUSTRATIVE ANNUAL ENERGY COSTS[c]				
Conventional	1,066$	1,279$	1,527$	1,847$
HEV	710$	852$	1,030$	1,225$
PHEV64-	391$	476$	579$	689$
EV120-	283$	327$	442$	519$

a Assuming 80% depth of discharge

b For PHEVs, we show average annual energy intensity, assuming a utility factor of 63%, similar to the 66% estimated by the US Environmental Protection Agency

c To account for compliance with the federal vehicle GHG emission standard, we assume the energy intensity of conventional vehicles declines by 19% from the values shown by 2025.

d Energy costs are calculated for this table assuming gasoline costs 1.11 $/L, electricity costs 11 cent/kWh, with 16,000 km annual travel. However, in REPAC, each respondent's annual driving distance is estimated from a driving diary.

Table 5 summarizes the relevant attributes of each drivetrain within each vehicle class that determine purchase price (PP) and weekly fuel cost (FC). We calculate the incremental purchase price of hybrids, PHEVs and BEVs relative to a conventional gasoline vehicle based on the ratio of battery power to capacity plus the net cost of other components, following the PEV cost model used by Axsen and Kurani (2013). These incremental prices correspond to a battery capacity cost of roughly 600 CDN $/kWh in 2015, which aligns with the 2014 values reported by Nykvist and Nilsson (2015). Based on their estimation of past reductions in battery costs, we assume that battery costs continue to fall by 8% annually with a lowest cost of 125 CDN $/kWh, based on US government targets (US Department of Energy, 2013). An alternative method would be to specify an endogenous learning curve (e.g., Löschel, 2002), but as noted above, Canada is likely too small a country for PEV sales to substantially impact global battery prices.

The weekly energy cost for each drivetrain/body combination is calculated for each respondent as a function of the vehicle's fuel and electricity consumption per kilometer, weekly usage (unique by respondent), and gasoline and electricity prices. Current retail gasoline prices by province are from Statistics Canada (CANSIMS, 2016a) and are escalated using the National Energy Board projection, with a high and low gasoline price defined by the high and low oil price scenario in that forecast (Table 6). Our reference scenario assumptions are based on the price of again reaching $73/bbl by 2030 (2015 USD), with the high and low range for gasoline prices used in this analysis based that price reaching $92/bbl and $53/bbl respectively in 2030 (2015 USD). These assumptions correspond to gasoline prices that range from 0.75 $/L to 1.36 $/L, excluding any carbon price. Current retail electricity prices are based on a survey of prices in North American cities (HydroQuébec, 2015), also escalated based on the rate of change in electricity prices by province from the reference scenario in the latest National Energy Board projection (Table 6) (National Energy Board, 2016). Our analysis does not include a high/low electricity price assumption because the REPAC model is less sensitive to electricity prices and electricity prices are less volatile than gasoline prices.

5.4. Constraint sub-model

Finally, the constraint sub-model applies several potential limitations to translate unconstrained demand (UD, from Equation 2) into constrained demand and "real-world" market share. Specifically, the constraint sub-model acts as a scalar within the logit function, producing constrained demand (CD), which is the probability of respondent i choosing a vehicle of drivetrain type j within the vehicle class k they buy, subject to constraints :

(Eq. 3)

$$CD_{i,j,k} = \frac{a_{i,j,k} * e^{U_{i,j,k}}}{\sum_j a_{i,k} * e^{U_{i,k}}}$$

ENERGY PRICES		REFERENCE CASE				LOW PRICE SCENARIO				HIGH PRICE SCENARIO			
TYPE	PROVINCE	2015	2020	2025	2030	2015	2020	2025	2030	2015	2020	2025	2030
OIL (BRENT, 2015 US$)		56.0	73.9	74.1	72.8	51.0	51.1	52.7	53.3	60.0	95.4	95.4	92.4
GASOLINE (2015 C$/L)	AB	0.96	1.05	1.02	0.98	0.96	0.78	0.77	0.75	0.96	1.30	1.27	1.21
	BC	1.13	1.16	1.11	1.05	1.13	0.90	0.87	0.83	1.13	1.41	1.35	1.28
	MB	0.97	1.04	1.01	0.97	0.97	0.77	0.77	0.75	0.97	1.29	1.26	1.20
	NB	1.04	1.11	1.07	1.03	1.04	0.83	0.81	0.79	1.04	1.37	1.34	1.27
	NL	1.09	1.16	1.12	1.08	1.09	0.87	0.85	0.83	1.09	1.43	1.40	1.33
	NS	1.06	1.12	1.09	1.05	1.06	0.84	0.82	0.80	1.06	1.39	1.35	1.29
	ON	1.08	1.15	1.11	1.07	1.08	0.86	0.84	0.82	1.08	1.42	1.39	1.32
	PE	1.06	1.13	1.10	1.06	1.06	0.84	0.82	0.81	1.06	1.40	1.37	1.31
	QC	1.09	1.21	1.16	1.10	1.09	0.95	0.92	0.89	1.09	1.48	1.43	1.36
	SK	1.00	1.07	1.03	0.99	1.00	0.80	0.78	0.76	1.00	1.32	1.29	1.22
ELECTRICITY (2015 C CENT/KWH)	AB	11.6	13.2	16.6	19.2								
	BC	10.3	10.8	11.0	11.2								
	MB	8.1	8.5	8.6	8.7								
	NB	12.3	12.4	12.5	12.8								
	NL	11.6	13.6	13.1	12.4								
	NS	16.0	16.1	16.2	16.4								
	ON	14.6	16.2	16.5	16.9								
	PE	15.6	15.8	15.9	16.1								
	QC	7.2	7.4	7.4	7.4								
	SK	14.4	15.3	16.0	16.9								

Table 6 : Assumed energy prices

Source : NEB. (2016). Canada's Energy Futures 2016: Energy Supply and Demand Projections to 2040. Available from https://apps.neb-one.gc.ca/ftrppndc/

Where ai,j,k is the product of three constraints (home charging access, PEV familiarity, and PEV availability) that can have values ranging from zero (total constraint) to one (unconstrained):

(Eq. 4) $$a_{i,j,k} = HC_i * PF_{i,j} * PA_{i,j,k}$$

Where HCi is the home charging constraint for respondent i, PFi,j is the PEV familiarity constraint on respondent i's choice for a vehicle of drivetrain type j, and PAi,j,k is the PEV availability constraint on respondent i's choice for a vehicle of drivetrain type j in the vehicle class k. We further describe all three constraints in turn.

First, HCi is the home charging constraint for a given respondent. HCi is equal to one (no constraint) if the respondent indicated that they can regularly park their vehicle within 25 feet of an outlet that they would be willing to use for vehicle charging (either 110/120 V or 220/240 V) and if that outlet is not common property (that is, the respondent is likely to be able to regularly use that outlet for PEV charging). Otherwise, HCi is zero (total constraint). As noted above, we do not specify non-home charging access as a constraint (workplace or public), but such charger availability can be represented as an equivalent change in home charging access.

Second, for PEV familiarity to exist (i.e. PFi,j equals one) in the initial simulation year, a respondent must have rated themselves as “familiar” with PEV technology at the outset of the CPEVS survey (i.e. before the survey instrument provided explanations of the technology). For other respondents, familiarity endogenously increases as a function of PEV new market in the respondent's Province (i.e. a change in familiarity is a provincial rather than national phenomenon). The change in familiarity follows a logistic curve:

(Eq. 5) $$PF_{i,j,t} = {}^{1}\!/_{\left(1 + a * e^{-CD_{p,t-1} * b}\right)}$$

Where PFi,j in a given year t, is a function of PEV new market share in the respondent's province p in the previous year (i.e. constrained demand for both PHEV and BEV, CDp,t-1) and a is a constant that defines the function shape while b defines the rate of change. Our base values for a and b are 100 and 150 respectively, resulting in no familiarity constraint once PEV market share reaches 5-6%. We calibrated these values to “neighbor effect” studies that find that the most social learning for new alternative-fuel vehicle technologies occurs before the new market shares approaches 5 to 10% (Axsen et al., 2009). REPAC does not allow PEV familiarity to decrease if sales subsequently decrease (e.g. after a subsidy is removed).

Third, the PEV availability constraint (PAi,j,k) is defined by three equations based on parameters representing the PEV model variety (ni,j,k) and dealership availability (di,j,k,m,t). The PAi,j,k constraint is completely eliminated where PEV availability is perceived by consumers as equivalent to conventional vehicle availability. It is first defined by Equation 6:

(Eq. 6) $$PA_{i,j,k} = \frac{2}{\left(1+e^{-c*n_{i,j,k}}\right)} - 1$$

Which assumes that a respondent is more likely to purchase a PEV if there are more PEV models available in their preferred vehicle class for a given drivetrain (PHEV or EV). Therefore, PAi,j,k is scaled from ni,j,k such that initial addition of PEV model offerings have a greater impact on demand, while later addition of PEV models within a vehicle class have a diminishing effect. For example, increasing the number of PEV sedan models from one to two will have a bigger effect on the constraint than an increase from four to five. The rate constant c has a base value of 0.7, meaning that PAi,j,k is non-binding once there are five vehicles in a given class and drivetrain available to a respondent (i.e. when ni,j,k =5).

Equations 7 represent the effects of dealership availability, which depends on whether a dealership local to the respondent sells and stocks a PEV made by its brand.

(Eq. 7) $$n_{i,j,k} = \sum_m n_{j,k} * d_{i,j,k}$$

Where vehicle class availability, ni,j,k , is a function of the PEVs sold by each brand m (i.e. n-j,k,m), and the dealerships of brand m that are local to a respondent that sell them (i.e. dealership availability, di,j,k,m). In effect, REPAC assumes that even if there are a variety of PEV models available in the respondents' preferred class, the respondent will not purchase a PEV if a dealership in their region does not carry one, where California research has highlighted the importance of dealerships in supporting PEV sales (Cahill et al., 2014). "In-region" means a dealership is within a 150km radius of each respondent's residence (as reported in the survey). We defined the dealership constraint through a web-search of auto dealerships by brand and location, noting which dealerships were certified to sell PEVs or stocked them. For example, of the 50 Ford dealerships in British Columbia, we found that approximately half are certified to sell PEVs as of 2016.

To illustrate the effects of Equations 6 and 7, consider the 2015 simulation year where REPAC accounts for ten PEV models available in Canada (based on manufacturer websites and excluding luxury vehicles—note that many more are available globally). Seven of the nine PEV models are compact cars, two are sedans, and one is a small SUV. To illustrate the effect of the PAi,j,k constraint, a respondent who plans to buy a new sedan chooses between two PHEVs, the Toyota Prius Plug-in and the Ford Fusion Energi (note that sales of the Prius plug-in were discontinued for 2016). Ignoring dealership availability, this respondent has a non-zero probability of choosing a PHEV because class availability is two (nj,k=2, for PHEV/sedan). However, in 2016 there are no BEVs available in the sedan class, so the respondent's probability of choosing a BEV would be zero (nj,k = 0 for BEV/sedan). Now adding the dealership availability constraint, if that sedan-demanding respondent lives "local" to only a Toyota dealership with a PEV in stock, but not a PEV-certified Ford dealership, then dToyota = 1 and dFord = 0 and that respondent's class availability is now equal to 1 one (nj,k = 1).

REPAC allows dealership availability to endogenously increase, assuming that more dealerships will stock PEVs if they anticipate being able to sell them. Like familiarity, we assume that changes to dealership availability are driven by provincial rather than national PEV demand. Dealership availability for each respondent in a year t is a function of constrained demand for PEVs in province p in the previous year (CDp,t-1):

(Eq. 8) $$d_{i,j,k,m,t} = {}^{1}/_{(1 + s * e^{-CD_{p,t-1} * r})}$$

Where s is a constant that defines the function shape, while r defines the rate of change, with base values of s = 100 and r = 75. Due to the lack of research on this area, these parameters are presently data-less. We select values that represent dealership responsiveness as fairly modest, assuming that consumer familiarity (PFi,j,t) is likely to respond more substantially to an increase in PEV market share.

REPAC calculates the total PEV new market share for a given year by summing constrained demand (CD) probabilities for PHEV and BEV designs across all respondents:

(Eq. 9)

$$PEV\ New\ Market\ Share = \frac{\sum_{n=531}(CD_{i,BEV} + CD_{i,PHEV})}{n}$$

Where n is the number of survey respondents represented in the model. Of the original 1754 that completed the survey, 1577 provided all the data needed for REPAC. In addition, we use the 544 respondents from Ontario as proxy respondents for Quebec, so in total we are modeling 2121 respondents (1577 + 544).

5.5. Regions within REPAC

REPAC represents vehicle adoption in each of the ten Canadian provinces, allowing us to account for the energy prices, policies, and constraints that are unique to each Province. As noted above, the CPEVS survey did not include a Quebec sample; however, we do represent vehicle adoption in Quebec as constructed by proxy from the Ontario respondents. Therefore, REPAC represents Quebec energy prices and policies, but the respondent behavior and constraints on PEV adoption are based on the Ontario sample.

5.6. Calculating Canada's passenger vehicle GHG emissions

To address our second research objective—quantifying how PEV adoption affects GHG emissions—we make a number of assumptions about the total stock of passenger vehicles in Canada. REPAC starts simulating in 2014 and the total stock of light-duty vehicles in that year by province is based on total light-duty vehicle registrations data from Statistics Canada (CANSIMS, 2016d), which is approximately 21.7 million vehicles in 2014. Through our 2015 to 2030 simulation period, total vehicle stock by province is based on current vehicles per capita multiplied by population forecasts for each province to 2030 (CANSIMS, 2016c). Population growth in Canada averages 0.9%/yr from 2015 to 2030. Accordingly, the total stock of vehicles is modelled to grow by 0.9%/yr.

The new market share equations noted in the previous section (i.e. constrained demand) apply to the new sales in each year, which makes up for growth in stock as well as retirements of old vehicles. Vehicle retirements are based on a logistic curve, where 50% of vehicles retire by the average retirement age, which is 11 years, based on a calibration with Statistics Canada new vehicle registrations (CANSIMS, 2016b). In 2015, there are roughly 2.0 million new vehicle sales per year, and this value rises to 2.4 vehicles per year in 2030.

To represent GHG emissions, we calibrate the average energy intensity of the existing stock of vehicles in the base year with the NRCAN comprehensive energy use database (GHG from cars and passenger light trucks) (NRCan, 2013). Activity per vehicle (vkm/yr) is 16,000km/yr, is based on the Canadian average from the same source. As further explained in Section 7, we assume that non-plug-in passenger vehicle GHG emissions will comply with Canada’s GHG emissions standards out to 2025. We simulate compliance with increasing adoption of hybrid-electric vehicles (HEV), combined with an external assumption for a decline in the energy intensity of conventional combustion vehicles.

To calculate the GHG emissions in each scenario, we calculate "well-to-wheel" (WTW) GHG emissions, including tailpipe emissions associated with driving and upstream emissions associated with producing the fuel or electricity, and transporting it to the point at which it enters a vehicle for consumption. We assumed gasoline has a direct GHG intensity of 70 g/MJ and an upstream GHG intensity of 20 g/MJ. Ethanol blended with the gasoline has zero net-tailpipe emissions, but upstream emissions of 50 g/MJ. We assume that the ethanol content of gasoline reaches 10% by 2030 in all scenarios under the assumed impact of a Canada-wide clean fuel standard. The upstream GHG intensity of electricity varies by province and year. We use the values in Table 7, which are derived from the most recent National Energy Board projection (NEB, 2016). We adjust these numbers to account for the impact of the recently announced commitment to phase-out of coal generation in Canada by 2030. Although the details of this policy are not yet defined, we approximate its impact by assuming the coal generation in the National Energy Board projection is replaced by high-efficiency natural gas-fired generation (55% energy efficient). The electricity generation carbon intensity in Alberta also includes the requirement for 30% renewable generation in that province by 2030.

	2015	**2020**	**2025**	**2030**		**2015**	**2020**	**2025**	**2030**
AB	790	573	390	252	**NS**	700	580	408	266
BC	15	11	14	14	**ON**	41	57	76	76
MB	3	0	0	0	**PE**	8	2	2	2
NB	300	258	192	112	**QC**	2	1	1	1
NL	31	3	4	3	**SK**	780	580	407	266

Table 7 : Exogenous electricity generation carbon intensity by province (kgCO2e/MWh)

Table 8 shows the WTW GHG intensities per vehicle (tCO2e/km) that result from our assumptions. The intensities are shown for each vehicle technology in REPAC, using the sedan vehicle class in three provinces with different archetypal electricity systems: Québec (hydro dominated), Alberta (thermal generation dominated) and Ontario (a mixed nuclear/thermal/hydro system). In Alberta, which currently uses mostly coal and natural-gas fired generation, the WTW emissions intensity of PEVs is slightly lower than HEVs in 2015, but there are further reductions over time as coal plants are closed in Alberta. In both Québec and Ontario, the WTW GHG intensity of PEVs is significantly lower than HEVs.

Table 8 : Examples of exogenous "Wells-to-Wheels" GHG intensity of new vehicles (sedan class) sold in Québec, Alberta and Ontario (gCO2e/km)

	2015	2020	2025	2030
QUÉBEC				
Gasoline	222	209	162	127
HEV	149	145	138	126
PHEV	56	54	54	54
BEV	0	0	0	0
ALBERTA				
Gasoline	222	209	162	127
HEV	149	145	138	126
PHEV	126	105	89	77
BEV	147	107	73	47
ONTARIO				
Gasoline	222	209	162	127
HEV	149	145	138	126
PHEV	59	59	61	61
BEV	8	11	14	14

6. POLICY SCENARIOS

We use REPAC to simulate Canada-wide PEV new market share and GHG emissions from 2015 to 2030, following three policy scenarios :

1. Business-as-usual (BAU) with current policies in place;
2. A "strong" demand-focused policy scenario with the addition of a national $7500 per PEV subsidy for four years (2018-2021) as well as ambitious charging infrastructure rollout; and
3. A Zero-Emissions Vehicle (ZEV) mandate requiring that automakers sell 20% PEV new market share by 2025 and 30% new market share by 2030—in addition to all BAU policies, ambitious charging infrastructure deployment, and a two year $7500 per PEV purchase subsidy (2018-2019).

These scenarios are further explained below.

6.1. Scenario #1: Business-as-usual (current PEV-supportive policies)

As noted in Section 3, in a separate report we identified a total of 60 active PEV supportive policies in Canada, and a further 28 proposed policies (Axsen et al., 2016b). According to our Report Card's analytical framework, only about a dozen of these policies are expected to impact 2030 PEV new market share in any substantial way, i.e. by 1% or more. For the sake of parsimony, our BAU scenario explicitly represents only a subset of these active policies. The BAU baseline policies are depicted for reach region in Table 9, which we summarize below by demand-focused and supply-focused categories (following the distinction we provide in Section 3).

Demand-focused policies in the BAU scenario are represented as follows :

- PEV financial incentives are represented for three provinces, with each in place from 2015-2018, and applying equally to an EV-120 or PHEV-64 (the two PEV archetypes we model) :
  - British Columbia : $5000 per PEV
  - Ontario : $10,000 per PEV
  - Quebec : $8,000 per PEV
- Carbon pricing includes the following policies :
- The Nationally proposed carbon price floor of $10-$50/tonne, from 2018-2022, staying at $50/tonne until 2030, which is applied to all provinces without an existing carbon price. This value is not adjusted for inflation.

  - British Columbia's carbon tax of $30/tonne, until the national carbon pricing scheme becomes more stringent.
  - The Western Climate Initiative cap-and-trade system, translated into a carbon price equivalent for Ontario and Quebec. The price is estimated at $18/tonne for 2020 (Sawyer et al., 2016) and remains in effect until the national carbon pricing scheme becomes more stringent.
- Charging access includes respondent access to home, work and public charging, where home-based access can be a particularly important determinants of PEV demand (Bailey et al., 2015). Our BAU scenario uses 2013 survey data to represent recharge access in 2015. We then approximate a change in charge access resulting from already announced changes to building codes in BC and Ontario and more generally, from an ongoing rollout of public charging across Canada. For respondents without charge access in 2015, we assume this constraint is 50% removed in BC and Ontario by 2030, and 20% removed for respondents in other provinces by the same year.
- HOV-lane access : British Columbia, Ontario and Quebec all have implemented HOV-lane access policies for PEVs, though the effect of these policies on PEV market share are very small, i.e. less than 0.1% PEV market share by 2040 (Axsen et al., 2016b). We simulate these policies by monetizing their value using a technique established by Lin & Greene (2011), where we represent this value as an annual benefit to the respondent (or PEV buyer). The value is based on the cost of traffic congestion by province and the proportion of roads that have HOV lanes. It works out to $11/vehicle per year in BC, $35/vehicle per year in Ontario, and $20/vehicle per year in Quebec.
- Other financial incentives : the current "Green Levy" is a fairly weak policy which is not likely to have a noticeable effect in our policy scenarios, so we omit explicit representation of this policy. Similarly, we do not model BC's "Scrap it program"—we expect the impact to be limited because it only applies to vehicles of model year 2000 or earlier.

Supply-focused policies in the BAU scenario will be represented as follows :

- A Zero-Emissions Vehicle (ZEV) mandate has been announced in Quebec, requiring zero-emissions vehicles to make up about 15% of new vehicle sales by 2025. We assume this requirement will hold until 2030 in that province. We assume that automakers comply with this ZEV mandate in Quebec by increasing the number of PEV makes and models (PHEVs and BEVs) across vehicle classes required for automakers to comply with the 2025 sales requirement.
- The federal vehicle GHG emissions standard requires that the average emissions intensity of light-duty vehicles sold decrease by about 5% per year from 2017-2025, with 2025

emissions reaching below 100 gCO2e/km. We model this policy as an increase in HEV adoption, and an exogenous decline in the carbon intensity (gCO2e g/km) of the new gasoline-powered vehicles represented in our model. In effect, we ignore the fact that present vehicle emissions standards earn "credits" from PEV sales due to their zero tailpipe emissions (0 gCO2e/km), which are further "multiplied" so that the sale of one PEV can count as more than one vehicle in calculating average emissions. An alternate modeling strategy would be to model the relationship between PEV sales and automaker compliance strategies with the vehicle emissions standard—however that is beyond the scope of the current project.

- A low-carbon fuel standard (LCFS) is in place in British Columbia (the renewable and low-carbon fuel regulation, or RLCFR), requiring a 10% reduction in fuel carbon intensity by 2020. The British Columbia government has proposed to increase this requirement to a 15% reduction by 2030. Although specific details on the recently proposed Canadian "clean fuel standard" will not be announced for several months, we assume this national policy will be "BC-like. Such a policy can theoretically induce sales of PEVs, due to the credits that (low carbon) electric utilities can earn if more PEVs are on the road—thus prompting electric utilities to put more effort into PEV deployment. We represent this policy as a monetized annual benefit, as if electric utilities pass on the credit values to PEV buyers through preferential electricity rates of the deployment of beneficial infrastructure, using the method established by Yang (2014). This calculation adds the equivalent of $105 per PEV per year financial incentive in British Columbia after 2016, based on a $100 credit price in the RLCFR with one-third of that value being used in some way that benefits PEV owners. This value is lower in provinces that use higher carbon electricity sources ($50-$100 per PEV per year).

Note that vehicle supply (make and model variety and availability) increases somewhat in the BAU scenario (Tableau 9), due to three reasons. First, Quebec's ZEV mandate prompts an increase in overall PEV availability. Second, in initial model years we add some PEV models that are likely to occur, such as the release of the Chevrolet Bolt for sale in Canada in 2017. Third, in REPACs dealership function, the availability of PEVs sold in Canada at auto-dealerships can increase as a result of growing PEV sales.

Table 9 : Policies in place in the business as usual (BAU) scenario

POLICY BY PROVINCE	2015	2020	2025	2030
BRITISH COLUMBIA				
Financial incentives ($/vehicle), to 2018	$5000	-	-	-
Non-financial incentive (HOV lane access, equivalent $/PEV/yr)	-	$11	$11	$11
Carbon Tax (nominal CAD, $/tCO2e)	$30	$30	$50	$50
Charging access (in proportion of population with equivalent to home charging)	56%	62%	67%	73%
Low-carbon fuel standard (Equivalent value in $/PEV/yr)	-	$105	$105	$105
Vehicle availability (where 100% availability corresponds with at least 5 PEVs for sale in each class available to each respondent)	38%	45%	45%	45%
ONTARIO				
Financial incentives ($/vehicle), to 2018	$10,000	-	-	-
Non-financial incentive (HOV lane access, equivalent $/ PEV /yr)	$35	$35	$35	$35
Carbon Price (nominal CAD, $/tCO2e)	-	$18	$50	$50
Charging access (in proportion of population with equivalent to home charging)	63%	69%	75%	80%
Low-carbon fuel standard (Equivalent value in $/ PEV /yr)	-	$101	$99	$99
Vehicle availability (where 100% availability corresponds with at least 5 PEVs available for sale in each class)	39%	48%	49%	49%
QUEBEC				
Financial incentives ($/vehicle), to 2018	$8,000	-	-	-
Non-financial incentive (HOV lane access, equivalent $/PEV/yr)	$20	$20	$20	$20
Carbon Price (nominal CAD, $/tCO2e)	-	$18	$50	$50
Charging access (in proportion of population with equivalent to home charging)	63%	65%	67%	69%
Low-carbon fuel standard (Equivalent value in $/PEV/yr)	-	$106	$106	$106
Vehicle availability (where 100% availability corresponds with at least 5 PEVs available for sale in each class)	40%	55%	85%	85%
OTHER PROVINCES				
Financial incentives ($/vehicle)	-	-	-	-
Non-financial incentive (HOV lane access, equivalent $/PEV/yr)	-	-	-	-
Carbon Price (nominal CAD, $/tCO2e)	-	$30	$50	$50
Charging access (in proportion of population with equivalent to home charging)	66%	68%	70%	71%
Low-carbon fuel standard (Equivalent value in $/PEV/yr)	-	$50-100	$77-100	$77-100
Vehicle availability (where 100% availability corresponds with at least 5 PEVs for sale in each class available to each respondent)	13%	19%	28%	30%

6.2. Scenario #2 : Strong demand-focused policy

The second scenario adds to BAU a suite of "strong" demand-focused policies, as detailed in Table 10. The policies include :

A national PEV financial subsidy is enacted, which is similar to those implemented in Ontario, Quebec and British Columbia. The incentive is $7,500 per PEV sold in Canada, and in place for four years (2018 to 2021).

HOV-lane access is increased in all regions, which is modeled by applying a monetized equivalent of HOV-lane access to provinces that do not currently have HOV lane access for PEVs. In practice, this only creates a small change in one region, (Alberta, with a benefit of $3 per PEV per year) due to the low cost of traffic congestion and the lack of HOV lanes in other provinces.

Aggressive charging infrastructure rollout is modeled by linearly increasing home charging access from 63% of respondents with Level 1 charging access in 2015 (as estimated from the 2013 survey), to 95% of respondents in 2030. The remaining 5% are respondents with unassigned street parking at home. Because the discrete choice model we use does not differentiate between home, work and public charging (as described in Section 5.2), we approximate the rollout of home, work, and/or public charging only as its equivalent in terms of home charging access. For example, very high work/public charging availability might be equivalent to widespread home charging access.

6.3. Policy scenario #3 : Zero-Emissions Vehicle (ZEV) mandate

Our final policy scenario represents a ZEV mandate, similar to the mandates implemented in Quebec and California. However, we model a nation-wide ZEV mandate that would be more stringent, requiring PEVs to make up at least 7.5% of new vehicle sales in 2020, 20% of new vehicle sales in 2025, and 30% of new vehicle sales by 2030. While the Quebec and California ZEV mandates allow compliance through sales of PHEVs, BEVs and hydrogen fuel-cell vehicles, we presently model only PHEV and BEV sales (REPAC is not currently set up to model preferences and supply regarding hydrogen fuel cell vehicles).

This ZEV Mandate scenario includes all policies in BAU (Scenario #1), and the same ambitious schedule for PEV recharge infrastructure deployment in Scenario #2. We also model a similar national purchase incentive to Scenario #2, $7500 per PEV, but only for 2 years (2018-2019) rather than 4 years. We include this two-year incentive as a sort of initial assistance that the national government can offer to automakers for the initial years of compliance. However, this incentive ends in 2019, meaning that automakers will have to do more of the “work” to comply with the ZEV mandate.

We assume that automakers comply with the ZEV mandate requirements, rather than fight them (e.g. in court) or fail to comply (e.g. pay fines). We exogenously specify two mechanisms for compliance. First, we model increased variety and availability of PEVs such that, by 2030, the PEV availability constraint is essentially non-binding for all respondents in REPAC. That is, by 2030, all Canadian car buyers in our model (whom have PEV awareness and charging access) that want to buy a PHEV or BEV version of their base model can do so. Alleviation of this supply constraint in REPAC requires 60 PEV models fully available from all dealerships in

Canada, spread evenly across all four vehicle classes. As a point of reference, Lutsey et al. (2015) find that as of 2014, cities within US States subject to the ZEV mandate had significant sales of 16 to 22 different PEV models, while other cities had significant sales of only 4 to 14 models. We believe it is reasonable to assume that with strong enough policy signals, automakers could focus their innovation activities to develop and actively market and sell at least 60 PEV models in Canada by 2030. As of 2016, Canada has about 10 PEV models that are actively sold (excluding luxury-type PEVs).

Table 10 : Details of the Nation-wide "strong" demand focused policy and ZEV mandate scenarios

POLICY FOR ALL PROVINCES	2015	2020	2025	2030
SCENARIO #2: STRONG DEMAND-FOCUSED POLICY				
Financial incentives ($/PEV)	$7,500 (starts 2018)	$7,500 (ends 2021)	-	-
Non-financial incentive (HOV lane access, equivalent $/PEV/yr) a	BAU	BAU	BAU	BAU
Carbon Price (nominal CAD, $/tCO2e)	BAU	BAU	BAU	BAU
Charging access (in proportion of population with equivalent to home charging), national average	63%	74%	84%	95%
Low-carbon fuel standard (Equivalent value in $/PEV/yr)	BAU	BAU	BAU	BAU
Vehicle availability (where 100% availability corresponds with at least 5 PEVs available for sale in each class), national average	26%	41%	51%	51%
SCENARIO #3: ZEV MANDATE				
Financial incentives ($/PEV)	$7,500 (starts 2018, ends 2019)	-	-	-
Non-financial incentive (equivalent $/PEV/yr)	BAU	BAU	BAU	BAU
Carbon Tax ($/tCO2e)	BAU	BAU	BAU	BAU
Charging access (in proportion of population with equivalent to home charging) , national average	63%	74%	84%	95%
Low-carbon fuel standard (Equivalent value in $/PEV/yr)	BAU	BAU	BAU	BAU
Vehicle availability (where 100% availability corresponds with at least 5 PEVs for sale in each class available to each respondent), national average	26%	45%	82%	97%
Automaker internal cross-subsidy: Average premium on non-PEVs[a]	-	$520	$600	$1,300
Automaker internal cross-subsidy: Subsidy on PEVsa	-	$6,380	$2400	$3,000
Automaker internal cross-subsidy: Net change in PEV upfront cost[a]	-	$6,900	$3,000	$4,300

[a] The automaker internal cross-subsidies are illustrative and shown here only for the "pessimistic" conditions in the policy uncertainty range. The magnitude of the cross-subsidies would be lower for the median or optimistic conditions

The second mechanism for ZEV compliance is internal cross-subsidization. We assume that automakers will change the pricing of their vehicle fleets to increase PEV sale as needed. This works much like a feebate—though unseen to the consumer—where PEVs are sold at a cheaper price than they would be sold otherwise, while non-PEVs are sold at a higher price. Overall, such cross-subsidization is revenue neutral for the automaker. Table 10 summarizes the internal cross-subsidies that would be required for compliance with the ZEV mandate in the "pessimistic" scenario (including low oil prices and high battery prices), including the subsidies that automakers would provide on average per PEV sold, the premiums charged to non-PEV vehicles sold, and the resulting differences in price between PEVs and non-PEVs. For example, in 2025 the average subsidy for PEVs would be $2400, while the average cost of a non-PEV new vehicle would be increased by $600 for the cross-subsidies to be revenue neutral for automakers. This non-PEV premium increases in future years (e.g. 2030) because PEVs make up more of the total market (meaning that premiums are shared among less vehicles).

This transition from government-based subsidies (ending in 2019) to automaker-based subsidies (from 2020 onward) is just one pathway for ZEV mandate design and compliance. A government could design a purchase subsidy to be in place for less time (e.g. ending in 2018) or more time (e.g. ending in 2025). The idea is that if this ZEV mandate is complied with, then automakers will need to apply cross-subsidization to fill the gap between the PEV-inducing effects of other policies and strategies (e.g. non-financial incentives and increased PEV availability), and the ZEV sales requirement. In this example, the internal cross-subsidization would need to begin in 2020.

6.4. Limitations of policy scenarios and REPAC model

Because REPAC has constraints for individual respondents, in some ways we avoid “double-counting” policy impacts when we simulate multiple policies. In other words, if a respondent has no constraint on their purchase of a PEV, policies that further remove constraints will not increase their demand. REPAC can also represent some synergies between policies; for example if a policy removes certain constraints, more respondents have a non-zero probability of purchasing a PEV and the model becomes more sensitive to changes in purchase prices (e.g. a subsidy become more effective).

However, there are several limitations in our representations of policy, particularly regarding supply-focused policies, which are inherently difficult to model. We do not directly model the Canadian vehicle emissions standards, an LCFS or ZEV mandate—instead we approximate each through one or more exogenous assumptions. Further, there are potentially important dynamics and interactions between policies that we do not model in the present report, namely :

- Vehicle Emissions Standard : as currently designed, 2025 requirements for conventional vehicle will become more relaxed if more PEVs are sold. In other words, if PEV market shares becomes substantial, e.g. through a ZEV mandate, automakers could possibly sell more high-emissions conventional vehicles than they would if fewer PEVs were sold.
- LCFS : if PEVs reach high market shares by 2030, then the moderate 2020 and 2030 LCFS requirements could be easily met (10% and 15% reductions in carbon intensity,

respectively), and the LCFS would have no "additive" impact to, say, a ZEV mandate. We do not presently model this potential.

- ZEV mandate : as noted above, we model just one example of a ZEV mandate design in terms of sales requirement schedule, where other versions are possible. Further, policymakers could choose to offer a nation-wide PEV purchase subsidy for a shorter or longer duration compared to what we model here. Finally, automaker compliance could occur in a variety of ways, such as through different combinations of increased PEV availability versus the degree of internal price cross-subsidization. Our modeled scenario is meant to be illustrative of one ZEV mandate design, and one automaker compliance strategy.

That said, the policy scenarios we explore with the REPAC model will still yield insights into the types and stringency of policies required to achieve high levels of PEV market share in Canada by 2030.

7. RESULTS

In this section we first illustrate how the three constraints represented in the constraints model affect the simulated market share (i.e. constrained demand) in Canada in 2015 (Section 7.1). In Section 7.2 we examine how sensitive the model is to key parameters such as dealership availability and fuel costs. We then examine results from the simulated policy scenarios, including market share impacts (Section 7.3) and energy and GHG impact (Section 7.4).

7.1. The impact of constraints on market share

Figure 3 illustrates the individual and combined effects of the three constraint categories applied in REPAC in the year 2015 : home-charging access, PEV familiarity, and PEV availability. Unconstrained demand (UD) for PEVs in 2015 is 15% of new markets share. Applying only the home charging constraint (where 64% of respondents have reliable home charge access) reduces PEV demand to 10%. Applying only the PEV familiarity constraint (where 24% of respondents were familiar with PEVs prior to taking the survey) reduces the PEV new market share to slightly less than 5%. Applying only the PEV availability constraint reduces market share to just over 5%. Applying all three constraints yields a constrained demand (CD) of 1% in 2015, which is very similar to the actual market share in Canada in that year.

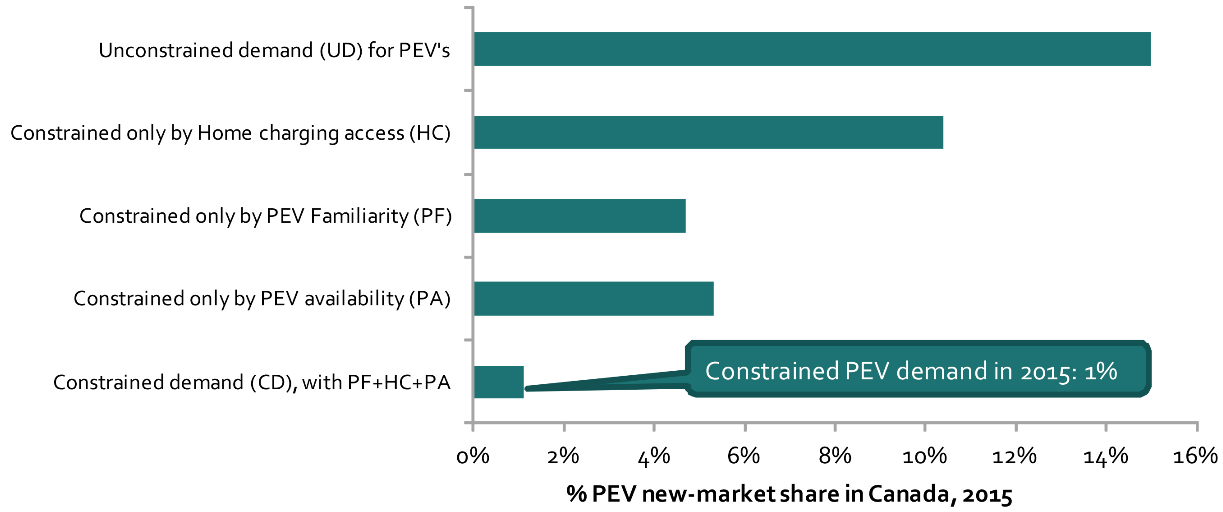

Figure 3 : Impact of REPAC constraints on PEV new vehicle market share in Canada, 2015

7.2. Sensitivity analysis of baseline results

Although, we have not performed a complete sensitivity analysis of the Canada-wide version of the REPAC model, we illustrate model sensitivity by reproducing the analysis previously completed with a BC-only version of REPAC (Wolinetz and Axsen, In Press). The nation-wide model is largely the same, so the sensitivities identified here are applicable.

We performed a sensitivity analysis on the BC-only REPAC model using a "no-policy" baseline scenario to explore how variation in nine parameter assumptions affected demand for PEVs in 2030 in the absence of any policy supporting their adoption, testing one assumption at a time. We tested the effect of varying the assumed values by plus or minus 25% for the following parameters :

- The rate at which PEV familiarity increases (+/- 25% in the PF rate constant b in Equation 5), affecting how quickly respondents become familiar with PEVs as market share increases;
- The availability and variety of PEVs (+/- 25% in the PAi,j,k rate constant c in Equation 6, ranging from 0.53 to 0.87), affecting how quickly the PA constraint becomes non-binding as PEV variety increases; and
- The endogenous increase in dealership availability (+/- 25% in the di,j,k,l.t rate constant r in Equation 8).

For the remaining parameters, we tested the effect of "high" and "low" parameter estimates drawn from data or literature, as follows :

- We vary home charging access (HC) based on CPEVS consumer data. The "low" access constraint is most conservative, assuming that respondents only have access if they identified an outlet within 15ft of their PEV's home parking rather than our base assumption of 25ft. The "high" access constraint is most permissive, assigning home charging access to any respondent that reports they would use the outlet nearest to where they would park their PEV (regardless of reported distance from their home parking spot).
- For the incremental purchase price of PEVs, we vary the exogenous rate of cost decline from a "low" price schedule following a 14% annual rate of decline in battery cost with a floor of CDN $100/kWh, to a "high" price schedule based on a 6% annual rate of decline with a floor of CDN $180/kWh—the high and low rate battery cost estimates made by Nykvist and Nilsson (2015). In effect, PEV incremental costs vary by -42% to +38% relative to the base value in 2030.
- We vary the gasoline price trajectory from a "low" price of CDN $0.95/Liter in 2030 to a "high" of CDN $1.78/Liter, corresponding to 60 US $/bbl and 200 US $/bbl oil price

scenarios (U.S. Energy Information Agency, 2015), or -14% to +60% of the base gasoline price assumption.

- We vary the electricity price trajectory from a "low" price of 9.5 cent/kWh (CDN) by 2030, to a "high" price trajectory of 11.7 cent kWh.
- We also tested the impact of electric driving range using PHEVs with a 16 km electric range (instead of 64km) as well as the impact of using BEVs with an 80 or 160 km range (instead of 120 km), with the vehicle incremental prices adjusted accordingly.

Figure 4 depicts the sensitivity of the PEV market share forecast in 2030 in BC without any policies. The figures show the variation in constrained demand, 7% of new sales in this case, in response to changes in each parameter, ordered from largest to smallest impact. Of the variations tested, REPAC results are most sensitive to changes in home charging access, PEV availability and variety, the rate at which PEV familiarity increases, and the incremental purchase price of PEVs. REPAC simulations are relatively less sensitive to changes in gasoline and electricity prices and electric driving range (includes associated change in upfront cost). In general, variation in individual parameters produces an asymmetric variation in PEV sales by 2030: the model is more sensitive to negative impacts on PEV sales, as negative effects inhibit further an endogenous increase in PEV sales.

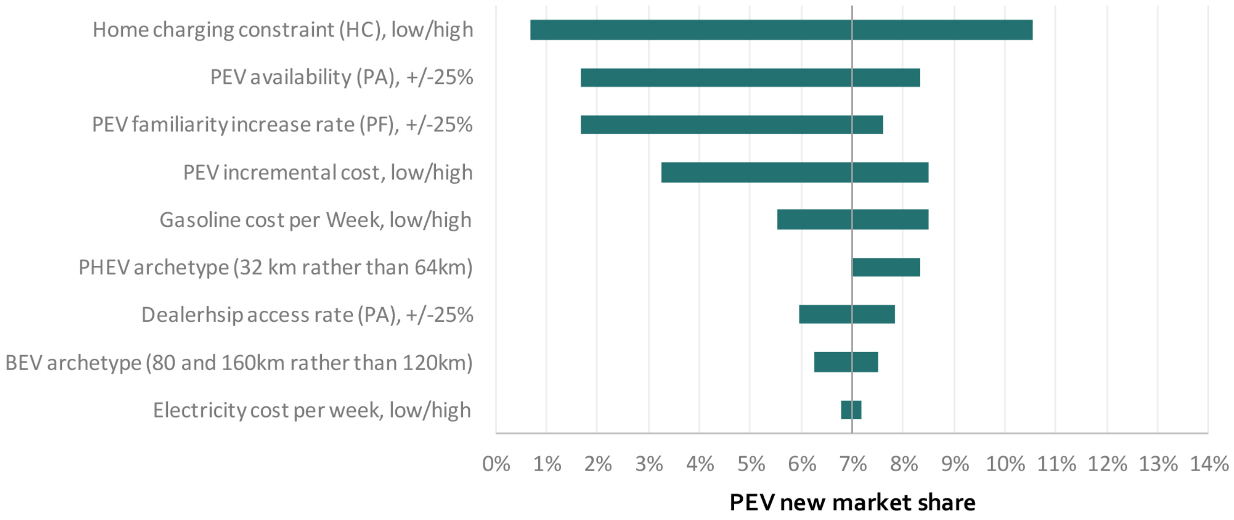

Figure 4 : Sensitivity analysis of REPAC's PEV new market share forecast in 2030, using the BC-only model, Source: Wolinetz and Axsen (In Press)

7.3. The impact of policy scenarios on PEV market share

Figure 5 depicts the modeled PEV new market share trajectory in each of the three policy scenarios for 2015 to 2030. The shaded areas represent the uncertainty in the forecast resulting from variation in four parameters identified in the (BC-based) sensitivity analysis[2]: the rate at which PEV familiarity increases, the extent to which PEV availability constrains sales, the incremental cost of PEVs, and the price of gasoline. The lower boundary of each shaded region is defined by the most "pessimistic" values used for each of these parameters in the sensitivity analysis (slower consumer learning, higher consumer need for PEV variety, higher PEV costs and lower gasoline costs), while the upper boundary is the opposite. We report our results according to these uncertainty ranges.

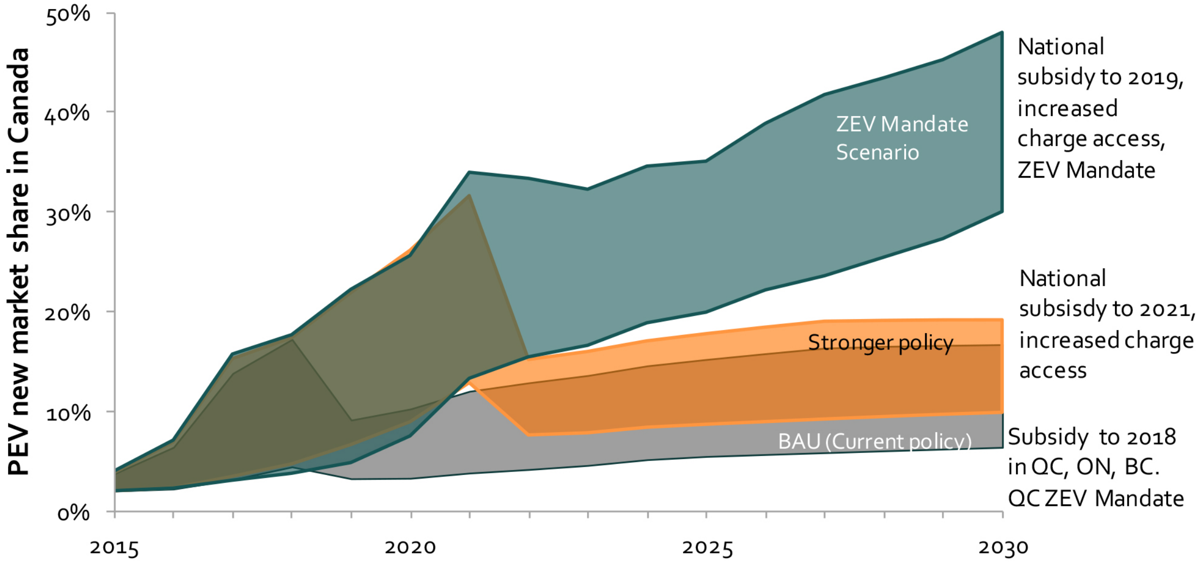

Figure 5 : PEV new market share under policy scenarios (with shading representing uncertainty the PEV familiarity constraint, the PEV availability constraint, gasoline price and PEV purchase price)

In the BAU policy scenario with current policies in place, we see that PEV new market share peaks at between 4 to 17% in 2018. Once the financial incentives in Ontario, Quebec and British Columbia are removed in 2019, new market share drops to 3-9%, and then grows slowly to 6-17% by 2030. Note that it is not actually clear how long the current Ontario, Quebec and British Columbia purchase incentives will be in place—recently announced funds for each will likely be expended by 2018, though such subsidies could be renewed multiple times.

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[2] These parameters are both uncertain and create the greatest sensitivity in the BC-based results. Although the home charging constraint strongly influences the results, we excluded it from our uncertainty ranges because it is not highly uncertain.

The "strong" demand-focused policy scenario with limited PEV supply adds several policies to BAU, including a $7,500 per PEV financial incentive applied Canada-wide 2018 to 2021. In addition, recharge infrastructure is substantially increased over time, and HOV-lane access is provided to PEV owners nationwide. In this scenario, PEV new market share continues to grow past 2018, reaching 13-32% by 2021, only to decline to 4-13% in 2022 once the subsidy expires. The new market share in 2030 is somewhat higher than in the BAU scenario, at 10-20%. In short, this scenario demonstrates that in the absence of a ZEV-mandate (or similarly strong supply-focused policy), PEV sales will be highly dependent on the existence of that purchase subsidy

The ZEV mandate scenario adds a gradual increase in PEV model variety and availability, reaching "full supply" by 2030—where the variety and availability of PEVs is almost on parity with that of conventional vehicles, across all vehicle classes. We also model the same increased recharge infrastructure availability as the previous scenario, as well as a similar $7,500 per PEV national incentive—but only for two years (2018-2019). Assuming that automakers comply with the ZEV mandate requirements (7.5% new market share by 2020, 20% by 2025 and 30% by 2030), we exogenously specify internal cross-subsidies that automakers would enact in order to boost their PEV new market shares to 7-26% by 2020, and up to 30-48% by 2030. Note that we take a conservative approach, where automaker compliance occurs in the most pessimistic assumptions (e.g. low oil price and high battery prices)—assuring that sales in each compliance year are at least at the required levels. Under more optimistic conditions, automakers would need to perform less compliance actions (e.g. less increase in PEV availability and/or less internal cross-subsidization).

Figure 6 depicts PEV total market share, that is, all passenger vehicles on the road, not just new sales. This figure accounts for the stock turnover rates of Canadian passenger vehicles and is thus slower to change. Under the BAU scenarios, PEV total market share is 5-15% of passenger vehicles by 2030. In the "strong" demand-focused policy scenario, the total market share of PEVs continues to grow out to 2030, reaching between 9% and 19% of all light-duty vehicles. In the ZEV-Mandate scenario, the total PEV market share reaches 19-37% by 2030.

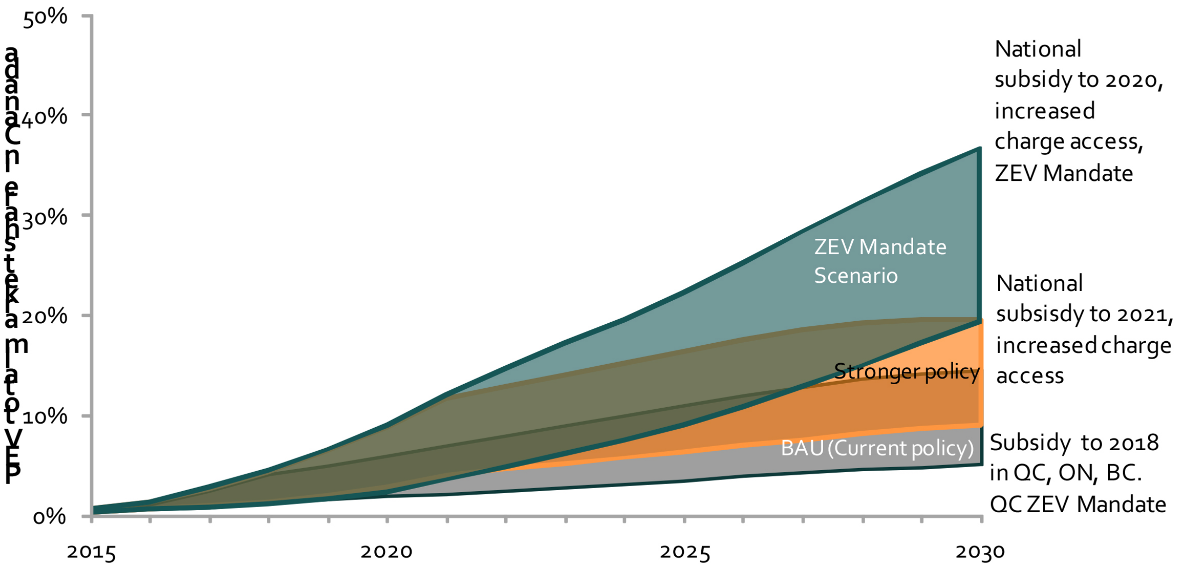

Figure 6 : PEV total market share under policy scenarios (with shading representing uncertainty in the PEV familiarity constraint, the PEV availability constraint, gasoline price and PEV purchase price)

7.4. The impact of policy scenarios on passenger vehicle energy use and GHG emissions

Section 5.6 details the assumptions we used to calculate WTW emissions for these PEV policy scenarios. Currently, "well-wheels" (WTW) GHG emissions from light-duty vehicle in Canada are roughly 93 MtCO2e per year. 70 MtCO2e per year are direct emissions resulting from fuel combustion by vehicles, and the additional 23 MtCO2e per year results from transportation fuel energy production. The WTW emissions are calculated assuming an upstream carbon intensity of 20 g/MJ for gasoline (for a total WTW carbon intensity of 90 g/MJ), 50 g/MJ for ethanol, and the provincial electricity generation carbon intensities noted in Section 5.6.

Figure 7 depicts our forecast for light-duty vehicle WTW emissions in two of our policy scenarios: BAU (Scenario 1) and the ZEV Mandate (Scenario 3). We omit Scenario 2 as the GHG impacts in 2030 are largely identical to those in BAU. Total WTW GHG emissions are a result of the total vehicle stock and are thus impacted by the inertia of vehicle stock turnover illustrated in Figure 6, as well as PEV composition –in all three policy simulations, more than half of the PEVs adopted are PHEVs, which we assume to use gasoline for about 37% of all km (a "utility factor" of ~63%).

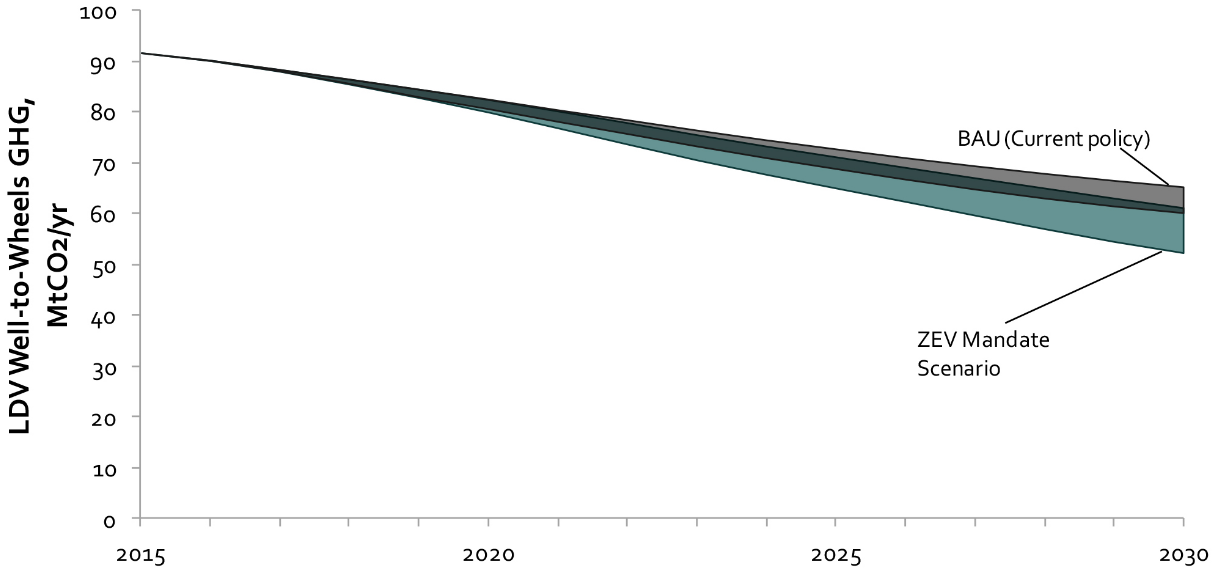

Figure 7 : Light-duty vehicle direct GHG emissions (with shading representing uncertainty in the PEV familiarity constraint, the PEV availability constraint, gasoline price and PEV purchase price), Only BAU and ZEV mandate scenario shown.

With current policy (BAU), notably the national GHG vehicle emissions standard, overall GHG emissions decline to 2025 (when the standard ends) and continues declining to 2030 as the stock of new energy-efficient vehicles increase. Furthermore, we have assumed that with a Canadian clean fuel standard, by 2030 all liquid fuels contain 10% biofuel, reducing the WTW carbon intensity of liquid fuel by roughly 5% relative to 2016. In 2030, BAU emissions are between 60 and 65 Mt/year, which is roughly 30-35% less than current emissions. With the "strong" demand-focused policy, emissions fall to 58-64 Mt/year by 2030, 31-38% less than current emissions (not shown in Figure 7). In the ZEV Mandate policy scenario, annual emissions fall to 52-61 Mt/year by 2030, or 34-44% less than current emissions. Put another way, the ZEV mandate policy scenario reduces WTW GHG emissions in 2030 by 6-13% relative to the BAU scenario.

Note however, that because vehicle stock turnover is slow, the emissions reductions in 2030 do not convey the full picture of GHG reductions. Looking only at the new vehicles sold in 2030, the ZEV-Mandate policy scenario would reduce the GHG emissions intensity from these vehicles by 12-22% in that year compared to BAU. Further reduction of WTW emissions can be achieved by complementary policies that further decarbonize electricity generation, require more renewable and low carbon fuel consumption, and reduce the upstream emissions associated with fuel consumption. Indeed, a longer-term analysis would be better suited to fully examine the GHG impacts of PEV-supportive policy, ideally modeling policy in the transportation, fuel and electricity sectors out to 2040 or 2050. Such a long-term analysis would better capture the lagged stock-turnover in each sector, the complementarity between electricity decarbonisation and electric mobility, and potential shifts in consumer preferences towards more electrified vehicles, e.g. BEVs over PHEVs.

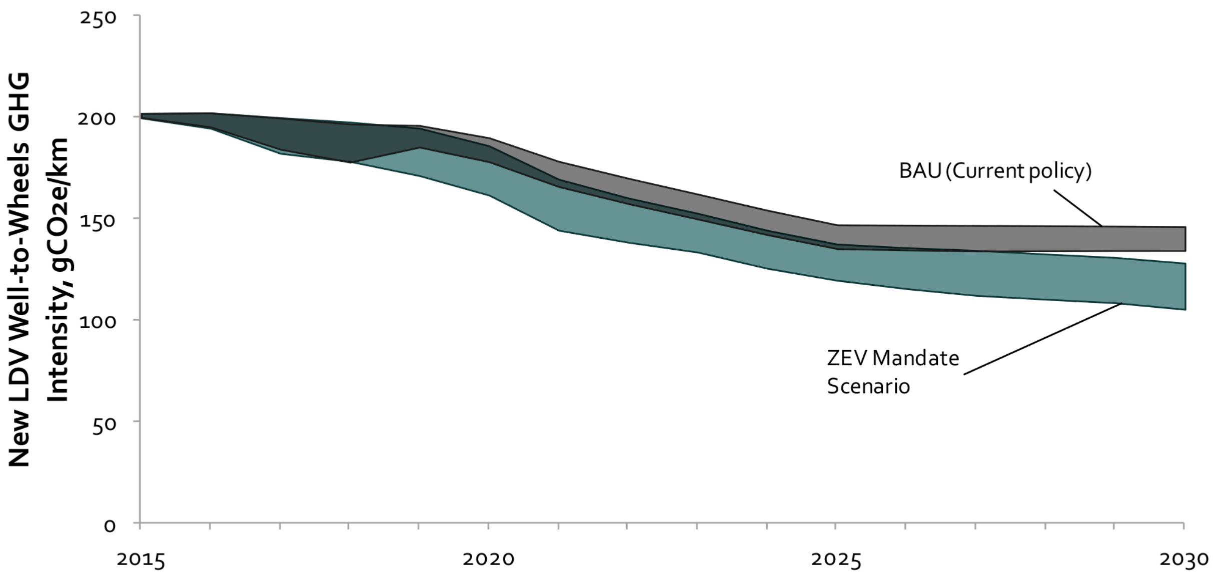

Figure 8 : New Light-duty vehicle well-to-wheel GHG emissions intensity (gCO2e/km), Only Scenarios #1 and #3 shown

Table 11 and Table 12 show the quantity of gasoline and electricity consumed by light-duty vehicles in each scenario. The gasoline quantity is what drives tailpipe GHG emissions, again under our assumption that there is a 10% biofuel blend with no net-tailpipe emissions by 2030. Both gasoline and electricity consumption contribute to the upstream portion of WTW GHG emissions.

Table 11 : Light-duty vehicle gasoline blend consumption, PJ/yr

		2015	2020	2025	2030
Current Policy (BAU)	low-PEV adoption	1043	955	845	758
	High-PEV adoption	1043	933	798	695
"Strong" Demand-focused policy	low-PEV adoption	1043	953	834	741
	High-PEV adoption	1043	926	771	668
ZEV-Mandate Scenario	low-PEV adoption	1043	955	827	708
	High-PEV adoption	1043	925	750	598

Table 12 : Light-duty vehicle electricity consumption, PJ/yr

		2015	2020	2025	2030
Current Policy (BAU)	low-PEV adoption	0	2	5	8
	High-PEV adoption	0	7	16	24
"Strong" Demand-focused policy	low-PEV adoption	0	3	9	14
	High-PEV adoption	0	9	23	33
ZEV-Mandate Scenario	low-PEV adoption	0	2	11	27
	High-PEV adoption	0	9	30	59

Note that there are roughly 20,000 PEVs on currently the road in Canada, so current PEV electricity consumption is not 0, just not significant at the number of decimal places shown.

8. DISCUSSION OF RESULTS

To inform the Canadian government's Pan-Canadian Climate Framework, this report models the effects of different policies on PEV passenger vehicle sales in Canada, using the REspondent-based Preference and Constraints (REPAC) model.

One point of comparison to previous literature is our baseline or "business as usual" (BAU) simulation, where REPAC simulates PEV new market share at 3-9% in 2020. Our 2020 simulations are similar to some other studies for the US, Germany and Iceland that estimate 4-6% PEV new market share by that year (Gnann et al., 2015; Lin and Greene, 2011; Shafiei et al., 2012; Tran et al., 2013). Generally, basic stated choice model-based studies are even more optimistic, e.g. with up to 27% PEV new market share being reached by 2020 (Glerum et al., 2013). With the endogenous effects modeled in REPAC (PEV familiarity and dealership availability, which act as positive feedbacks to sales), the market share under BAU increases to 6-17% by 2030 which is also in line with several other studies in the US and elsewhere (Lin and Greene, 2011; Shafiei et al., 2012; Tran et al., 2013). Similar to our observed drop-off in PEV demand once financial incentives are removed in 2018, Eppstein et al. (2011) find that financial incentives produce little long-term impact on PEV adoption if only implemented for a short time period.

Our policy scenario results are unique in that REPAC is one of the few models to explicitly represent (and distinguish) the effects of demand-focused and supply-focused policies on PEV new market share. We find that in a "strong" demand-focused policy scenario, 2030 PEV new market share is not likely to exceed 10-20%—that is, with an attractive Canada-wide PEV purchase subsidy ($7,500 for PEV for 4 years), substantial charging infrastructure deployment and HOV-lane access. Other models instead produce forecasts of 24-100% PEV market share for similar scenarios (Lin and Greene, 2011; Shafiei et al., 2012; Sullivan et al., 2009; Tran et al., 2013), but these models typically do not represent supply constraints, such as limited PEV model variety or availability.

Our ZEV-Mandate scenario is unique in that it is designed to represent the types of effects we can expect with a stringent, nation-wide ZEV mandate. While many different ZEV mandate designs are possible, we selected an illustrative case that is in line with other studies' (e.g. IEA, 2015) suggestion of the PEV trajectory needed to achieve deep GHG reductions by 2050—requiring PEVs to make up 20% of new vehicle market share in 2025 and 30% in 2030. We exogenously specify two compliance mechanisms for automakers. First is increasing the variety and availability of PEV models such that supply constraints are eliminated by 2030, where PEV availability is perceived by consumers as equivalent to conventional vehicle availability. Others find that such strong supply-focused policies are likely required to incentivize automakers to channel innovation in this direction (Köhler et al., 2013). The second mechanism is internal cross-price subsidization, where automakers lower the prices of the PEVs they sell and increase the prices of non-PEVs—such that PEVs sales comply with the ZEV mandate while not affecting overall automaker revenue. In these simulations, we demonstrate that automakers in Canada can comply with the ZEV mandate requirements even in the most pessimistic conditions—including low oil prices and high battery prices. With more optimistic assumptions, the scenarios we specify would exceed 2030 requirements, reaching new market share up to 48%.

Another theme of these policy scenarios is the dependence of PEV sales on purchase subsidies. In the BAU and strong demand-focused policy scenarios, PEV sales drop dramatically once the subsidies are removed—whether the policies are in place until 2018 or 2021. In our experience with REPAC (not shown in this report), this same effect is observed even if the purchase subsidy is in place for a longer time frame. In other words, a purchase subsidy does not seem to serve as a short-term "boost" to the PEV market that then becomes self-perpetuating—PEV sales continue to be dependent on the government-funded purchase subsidy, at least within the time frame that we model.

From a government perspective, multi-year provision of high purchase subsidies (e.g. $7,500 per PEV) can be very expensive. In contrast, the ZEV-Mandate scenario we model provides a two-year national PEV incentive to "help" automakers with the initial transition. And once the incentive is removed, automakers can step in and continue to keep PEV sales high and on track for ZEV mandate compliance by increasing PEV model availability and variety and implementing internal cross-subsidization. Such a scenario results in lasting PEV sales success with significantly less government expenditure than a high, long-term purchase subsidy. Of course, a ZEV-mandate isn't the only way to avoid high government expenditure—for example, a strong feebate scheme could achieve a similar effect (not modeled in this study).

Our analysis also summarizes a sensitivity analysis from the BC-only version of the REPAC model to demonstrate that REPAC forecasts are most sensitive to assumptions (parameters) relating to the home charging constraint, PEV availability, PEV familiarity, and PEV incremental costs. Results from REPAC demonstrating that increased home recharge infrastructure can have a strong impact on PEV market share is similarly found in a US agent-based model (Lin and Greene, 2011), though both analyses lack the detail needed to quantify the importance of home versus public charging. In contrast to REPAC, others' modeling results are most sensitive to PEV purchase price and fuel price parameters only (with sensitivities to both being higher than those found in REPAC). For example, Gnann et al.'s (2015) agent-based model finds that PEV new market share can be doubled through a 10% reduction in PEV purchase price or a 10% increase in gasoline costs. Conversely, REPAC shows that a similar reduction in purchase price may only increase sales by roughly 20%. Likewise, REPAC shows that gasoline costs might need to double to produce a doubling in market share.

Although REPAC provides a novel contribution to the literature, there remain limitations that should be improved upon with further research :

- Although we used a large amount of respondent data to inform model assumptions and parameters, three important parameters remain "data-less": the rate at which familiarity with PEVs may increase as PEVs sales increase, the extent to which a lack of variety in PEVs will scale back demand for these vehicles, and the rate at which increased PEV sales will prompt more auto dealerships to sell PEVs. Future research could seek to empirically estimate such parameters, or to better account for their uncertainty through Monte-Carlo analysis.
- For REPAC to be appropriate for longer term forecasts (i.e. beyond 10 to 15 years in the future), it needs to better endogenize dynamics such as shifts in consumer preferences (Axsen et al., 2009; Mau et al., 2008) or reductions in battery prices driven by manufacturing experience and R&D investment (Löschel, 2002)—though the magnitude of such effects will depend on the size of the region modeled.
- Representation of the PEV supply side could be further improved by endogenizing automaker decisions in the model and how they would be affected by policy (particularly supply-focused policy), though it would be challenging to inform such representation with empirical data.
- Future versions of REPAC could be constructed using stated choice models that collect data on elements not already included in the choice model (e.g. work charging access) or on how preferences might change as the PEV market expands (Mau et al., 2008).
- It would be useful to apply REPAC to a variety of other types of alternative fuels (e.g. hydrogen fuel cells and biofuels), and different consumer groups (e.g. fleets and medium- and heavy-duty vehicle users).
- As noted in Section 6.4, there are potentially important dynamics and interactions between policies that we do not model in the present report, especially regarding the vehicle emissions standard (which receives credits for PEVs), the low-carbon fuel standard (which also receives credits for the electricity used to power PEVs) and a ZEV mandate (which can in part be achieved through the implementation of demand-focused policies). Future modeling work on this topic could further explore the nuances of these policies' designs to better understand these interactions.
- This analysis only models the effectiveness of PEV-supportive policies, but does not model the costs of policy. Our research team has conducted separate work exploring

policy cost-effectiveness, where a technology-neutral carbon tax can potentially be half the cost of technology-forcing standards (Fox, 2013). However, we find that a very high carbon tax is likely needed to achieve deep GHG reductions (e.g. over $100/tonne), which so far has not been enacted in any jurisdiction. In the real-world, some technology-forcing policies are likely needed as they are considered more politically acceptable climate policies. That said, future research could explore how the optimal design of ZEV mandates, infrastructure deployment and purchase incentives could minimize climate mitigation costs.

- Lastly, we re-iterate the point that the literature (and models) on policy and PEV sales has largely failed to explore the impacts of a ZEV-mandate or other supply-focused policies. This study provides one effort to model a ZEV Mandate in Canada, and we find promise for such a policy in pushing PEV sales in the long-run. However, much more research needs to be done to better understand the potential impacts of a ZEV mandate in Canada, including exploration of different policy designs in terms of different schedules of PEV sales requirements, as well as different credit systems for various ZEV options (including hydrogen-fuel cell vehicles as well as PHEVs and BEVs). Further, the design of such a policy should complement the design of related climate policies, including a clean fuel standard, vehicle GHG emissions standard, infrastructure rollout, purchase incentives, and non-financial incentives.

9. POLICY IMPLICATIONS

In December 2016, the Pan-Canadian Framework on Clean Growth Climate Change stated an intention to develop a zero-emissions vehicle strategy to reduce emissions in the transportation sector. This framework does not identify specific policies, but does allude to the Zero-Emissions Vehicle (ZEV) mandate recently implemented in Quebec. We explore the potential effects of a ZEV Mandate and other PEV-supportive policies to see which policies boost PEV sales to near or over 30% new market share by 2030. Our results yield several implications for Canadian policymakers:

- Canada's present suite of climate and PEV-supportive policies are not strong enough to induce a PEV new market share beyond 6-17% by 2030. This uncertainty range includes optimistic technology assumptions, including if battery costs decline as low as CDN $100/kWh.
- Without changes in PEV variety and availability, even an ambitious suite of "strong" demand-focused policies is not likely to surpass 10-20% new market share for PEVs by 2030. This suite includes ambitious recharge infrastructure rollout, and a large national PEV subsidy of $7,500 per PEV for 4 years (2018-2021). Even if such a subsidy is in place for a longer time-frame, PEV sales substantially drop once the subsidy is removed.
- We demonstrate the potential long-term effectiveness of a ZEV Mandate, using the example of a requirement for PEVs to make up 20% of light-duty vehicle sales by 2025, and 30% by 2030. In our model, automakers are able to comply with this ZEV mandate even in the most pessimistic conditions, including high battery prices and low oil prices. We model automaker compliance to occur by increasing the availability and variety of PEV models, and by implementing internal price cross-subsidization within their own fleets—lowering the price of PEVs and increasing the price of non-PEVs.
- We also demonstrate that a ZEV mandate can effectively induce PEV sales in the long-term with significantly less government expenditure than a large, prolonged PEV purchase incentive. We model a scenario where the Canadian government provides a strong PEV purchase subsidy for two years to "help" automakers with the transition (in addition to ambitious expansion of recharge infrastructure). But automakers are modeled to take over with ZEV mandate compliance from 2020 onwards, which eliminates the reliance of the market on government-provided PEV purchase subsidies.
- In short, the combination of a stringent ZEV mandate, strong but temporary PEV purchase incentives and ambitious charging infrastructure deployment could be an effective part of the Pan-Canadian Climate Change framework.

ACKNOWLEDGEMENTS

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