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Economic implications of a phased-in EV mandate in Canada

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*Abstract***.** Canada plans to phase out internal combustion engine vehicle (ICEV) sales in favour of electric vehicles (EVs) by 2035 as part of its climate policy. Herein I examine the economic implications of a phased-in EV mandate. I show using partial equilibrium analysis that when both types of cars are available, auto companies will overproduce EVs and earn scarcity rents on ICEVs that partially offset the revenue loss on EVs. I then present a numerical general equilibrium model of the Canadian economy to assess the overall macroeconomic consequences of the policy. The results depend critically on the assumed pace at which EVs achieve cost parity with ICEVs on a quality-adjusted basis. An EV mandate will have manageable economic consequences if technology improves so rapidly that the mandate is unnecessary. If the mandate outpaces achievement of cost parity the economic consequences can be severe and would likely cause the auto manufacturing sector to shut down. The cost per tonne of emission reductions are at least ten times the Canadian carbon tax rate while the mandate is binding. The analysis provides insight into why automakers have been willing hitherto to develop and sell EVs even though they currently lose money on them.

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1 Introduction

Many jurisdictions, including Canada, have mandated that their auto sectors must switch over to electric vehicle (EV) sales such that new internal combustion engine vehicles (ICEV) will be virtually eliminated by 2035 (Government of Canada 2023). Analyses of the implications of expanding the EV industry have focused heavily on technical questions such as the likely trajectory of the costs of manufacturing batteries (Nykvist et al. 2019, Hsieh et al. 2019), implications for the electricity grid of the increased load (Schwab et al. 2022) and whether life-cycle carbon dioxide emissions rise or fall from switching to EVs (Neuegebauer et al 2022). Economic questions analyzed previously include the marginal costs of EV mandates relative to other policies (Rivers and Wigle 2018), consumer responses to sales incentives (Azarafshar and Vermeulen 2020), life-cycle ownership costs (Raustad 2017), comparative effectiveness of subsidies to EV purchases versus charging stations (Springel 2021) and consumer preferences regarding EVs. There is evidence that at present they mainly serve as secondary cars for affluent households (Burlig et al. 2021), that most subsidies go to people who would have purchased an EV anyway (Azarafshar and Vermeulen 2020) and that sales are highly dependent on government subsidies (Paton 2019), which suggests they may have a limited voluntary market ceiling. Also since they tend to displace small, relatively fuel-efficient vehicles (Xing et al. 2021) the short-term potential for EV sales to yield greenhouse gas (GHG) emission reductions are small (Muehlegger and Rapson 2021).

An important feature of the Canadian policy proposal is its extended phase-in period. The EV sales mandate begins in 2026 with the requirement that 20% of passenger vehicle sales (including SUVs and pickup trucks) must be EVs, then it rises to 60% by 2030 and to 100% as of 2035. This paper explores the question of how a phased-in EV mandate might affect the overall auto sector including the market for ICEVs, and the overall viability of the auto sector during the phase-in period. An EV mandate is a non-trivial policy. It amounts to a removal from the market of one of the most popular and ubiquitous consumer products ever, the manufacture of which is a major part of the modern industrial economy. During the phase-in period both types of vehicles are available so people have the option to buy either an ICEV or an EV. In order to meet the binding sales mandate auto companies could raise the selling price of ICEVs thereby earning rents on each unit, but at the same time the overall vehicle market will shrink due to the rising purchase prices. I first examine the effect of the mandate phase-in using a simple partial equilibrium model, then simulate its impact in a numerical general equilibrium model of the Canadian economy. The EV mandate allows the automotive sector to earn substantial economic rents on ICEV sales but these are more than offset by the overall drop in market revenue. The model suggests that, despite the ICEV rents, the EV mandate will push the Canadian automobile industry into a large loss position and negatively affect growth in the wider economy. Auto sector losses will last through the 2030s depending on how quickly EV production costs drop. The prospect of returning to a profitable state depends on optimistic assumptions about the pace at which the manufacturing cost of EVs drops to parity with ICEVs for models that buyers consider to be perfect substitutes. At present there is not a sufficiently reliable empirical basis for determining if this is a likely outcome so the numerical analysis proceeds based on two assumed timelines.

In the first, it is assumed optimistically that EVs will be at cost parity with ICEVs such that all buyers are indifferent between them by 2035. In the second, cost parity is not achieved until 2050. Thus, in the first scenario the mandate is effectively redundant by the time it goes fully into force whereas in the second it is necessary for another 15 years. The model simulations can be summarized as showing that an EV mandate is economically feasible only to the extent it is unnecessary. In years when the policy attempts to close a large gap between base case and target EV sales rates there are large negative effects on income, employment, output and corporate earnings, especially in the automotive sector. In the case in which cost parity takes until 2050 the costs for the auto sector mount so rapidly that the industry will almost certainly close permanently.

Assessing the economic impact of an EV sales mandate depends critically on assumptions about the pace of autonomous technological change. A mandate that forbids rotary dial phones or eight-track cassettes would have virtually no effect today and would therefore cost nothing. Some observers believe the EV mandate will likewise have little or no effect since the market is rapidly shifting away from ICEVs anyway. They often point to Norway and California as supporting examples. Neither of these jurisdictions has a domestic auto industry so their experience does not involve dealing with negative effects on an important income-producing industry. Norwegians have indeed opted for EVs in very large numbers: they currently comprise about 90% of new vehicle sales and the government is aiming for a complete phase-out of ICEVs by 2025.[1] But it is difficult to generalize from this example because the change has coincided with unusually generous subsidy policies over the past 15 years, including substantial cash incentives for buyers, the right to free parking and access to a large network of free charging stations. Holtsmark and Skonhoft (2014) estimated these policies have cost Norway an average of US$13,500 per tonne of CO_2 abated, making it an extremely inefficient climate policy and one which could not realistically be adopted everywhere, nor maintained indefinitely. California also provides large subsidies for EV purchases and accounts for 40% of all US EV sales. Again, however, its subsidies are unusually generous compared to other US states and imply a heavy and growing fiscal burden on the state (Muehlegger and Rapson 2018). Because the high EV sales in these jurisdictions have coincided with large subsidies, and EV sales have not shown similar tendencies in other jurisdictions that lack such policies (also recent reports indicate large drops in EV demand in Germany and China once their subsidy programs were scaled back[2])

[1] See Bello, Camille, "Europe's electric future: How Norway came to lead the charge in the EV revolution" euronews.next May 31 2023, https://www.euronews.com/next/2023/05/31/europes-electric-future-how-norway-came-to-lead-the-charge-in-the-ev-revolution Accessed January 24, 2024.

[2] See B. Anderson (2023) EV And Hybrid Sales Fall In Germany After Government Reduces Subsidies https://www.carscoops.com/2023/02/ev-and-hybrid-sales-fall-in-germany-after-government-reduces-subsidies/ and

Norway and California may be policy-driven outliers rather than signals of a widespread shift in consumer preferences.

Within Canada, Quebec and British Columbia likewise stand out as having experienced higher EV adoption rates compared to other provinces while also imposing EV sales mandates of their own (Navius 2020) and offering generous subsidies for buyers, which range from (CAD) $2,000 to $5,000 per vehicle in BC and $4,000 to $8,000 in Quebec. EV subsidies were zero in all other provinces except Ontario, which also offered subsidies up to 2018 but did not impose a mandate. Its EV sales rate didn't differ from the average in the rest of Canada (Azarafshar and Vermeulen 2020). EVs across Canada comprised around three percent of new car registrations as of 2017 but trended up thereafter (Statistics Canada 2023b). Sales increased especially rapidly in Quebec and British Columbia and by the end of 2022 they comprised more than 12% of annual passenger vehicle sales in both provinces. Sales elsewhere also grew as a fraction of the total but to a lesser extent, reaching about eight percent nationally by 2022. However the EV growth spurt in Canada and elsewhere seemed by summer 2023 to have stalled and automakers are reporting large losses[3], partly due to rising interest rates, the enduring price differential between EVs and ICEVs and elimination of some government subsidies.

Consumer resistance is also an issue. Hertz recently announced a decision to sell 20,000 EVs and replace them with ICEVs due to low consumer demand and unexpectedly high maintenance costs.[4] There may also be a market saturation effect. Xing et al. (2021) report that introduction of US federal income tax credits boosted EV sales by 29%, but 70% of the credits were obtained by households who would have bought an EV even without the credits. Likewise Azarafshar and Vermeulen (2020) concluded that three-quarters of Canadian recipients of EV subsidies would have bought one anyway. Hence the introduction of government subsidies for EVs largely brought forward in time purchases that were already going to happen, but did not win over many new buyers to the EV side of the market.

P. O'Hara (2023) Slowdown in China EV sales expected as subsidies end https://www.fastmarkets.com/insights/slowdown-in-china-ev-sales-expected/ accessed January 25, 2024.

[3] See Johnson (2023) Volkswagen says EV orders are down 50% in Europe, https://electrek.co/2023/10/26/volkswagen-ev-orders-down-50-europe/ ; Mihalescu (2023) Ford Cuts EV Investment After Losing $36,000 On Every EV Sold In Q3 https://insideevs.com/news/693626/ford-cuts-ev-investment-after-losing-36000-usd-every-ev-sold-q3/; Subramanian (2023) Ford, GM, and even Tesla are warning about the EV market https://finance.yahoo.com/news/ford-gm-and-even-tesla-are-warning-about-the-ev-market-194905657.html, accessed January 25, 2024. Also Naughton (2024) Ford cuts battery order as EV losses top $100,000 per car https://financialpost.com/pmn/business-pmn/ford-cuts-battery-orders-as-ev-losses-top-100000-per-car accessed May 14, 2024.

[4] See D. Welch and R. Clough, Hertz to Sell 20,000 EVs in Shift Back to Gas-Powered Cars, https://www.bloomberg.com/news/articles/2024-01-11/hertz-to-sell-20-000-evs-in-shift-back-to-gas-powered-cars; N. Gomes and J. White Rental giant Hertz dumps EVs, including Teslas, for gas cars https://www.reuters.com/business/autos-transportation/hertz-sell-about-20000-evs-us-fleet-2024-01-11/ accessed January 25, 2024.

It is also notable that while the number of EVs as a fraction of the vehicle fleet grew, the fraction of energy used in transportation by EVs did not. Natural Resources Canada (2023)[5] reports that from 2016 to 2020 the fraction of energy (in petajoules) used in transportation by gasoline and diesel vehicles grew from 87.3% to 90.7% while that used by electric vehicles remained steady at 0.2%. This supports findings in Burlig et al. (2021) that many EV owners also own an ICEV, therefore even EV owners are not abandoning ICEVs for some purposes.

Thus, leaving aside jurisdictions that have heavily subsidized or mandated EV purchases, while there appears to be a slow and steady penetration of EVs into the automobile market, sales based solely on consumer preferences remain modest compared to those of traditional ICEVs. The analysis herein therefore proceeds on the assumption that the proposed mandate will be binding, in other words it will force consumers to change their automobile purchase decisions. We will, however, consider different scenarios that encompass optimistic and pessimistic outlooks on how strictly the mandate will bind based on how rapidly the cost of making and using EVs declines.

An analysis similar to the present paper was conducted by Bhardwaj et al. (2021) using a partial equilibrium model of the Canadian automobile sector. They looked at scenario where a 30% EV sales mandate is to be achieved by 2030 but production cost parity is also achieved by the same date. They also assume lower baseline EV sales than are assumed herein. Their results were qualitatively the same as those herein, namely firms cross-subsidize EV production with ICEV profits, while overall industry profits decline due to the mandate. In addition to differing scenario assumptions their model only includes direct sectoral effects, whereas the model employed herein captures indirect general equilibrium effects as well.

Environmental regulations applied to the motor vehicle and motor fuels sectors has long attracted the attention of the economics literature, with the inherent inefficiency of many such measures a recurring theme. Holland et al. (2009) discussed the use of a low-carbon fuel standard as a greenhouse gas control measure and found that any emission reductions cost several times more than more efficient alternatives. Durrmeyer and Samano (2018) contrast US fuel economy standards against a feebate system and found for equivalent mileage improvements the standards were up to 70% costlier. Reynaert (2021) examined vehicle carbon dioxide emission standards introduced in the EU and found that while they led to improved technology, firms largely complied by "gaming" the standards, namely finding ways to pass pre-sale tests without changing the actual vehicle operating characteristics on the road. With regards to EV policies specifically, Gillingham and Stock (2018) rated EV subsidies as the costliest in a list of standard greenhouse gas policies in the US on a per-tonne abated basis (although the costs fell within the upper end of the uncertainty ranges of low carbon fuel

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[5] See https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=tran&juris=ca&year=2020&rn=1&page=0 Table 1.

standards and solar photovoltaics subsidies).[6] Azarafshar and Vermeulen (2020) estimated that the costs per tonne of CO_2 abatement from Canadian EV sales incentives over 2012 to 2016 ranged from (CAD) $500 to $1,100, far above the Government of Canada's estimate of the social costs of CO_2 emissions. Note that this only included the direct program costs, not any secondary costs associated with economic distortions. The abatement costs per tonne herein exceed the carbon tax rate by at least an order of magnitude while the mandate is binding, but fall to zero by assumption once technological progress eliminates any cost difference between ICEVs and EVs.

The next section models the EV mandate phase-in using a partial equilibrium model. Section 3 explains the numerical general equilibrium model of the Canadian economy, Section 4 discusses the simulation results and Section 5 presents discussion and conclusions.

2 Phasing in an EV mandate

2.1 Simultaneous EV and ICEV markets

Auto companies offer both types of vehicles for sale. Suppose the mandate is that EV sales must be the fraction α of total sales in a given year. If q_e^i denotes firm *i*'s EV sales and q_g^i denotes its gasoline-powered vehicle (ICEV) sales then $q_e^i/(q_e^i + q_g^i) = \alpha$ which implies $q_g^i = \theta q_e^i$ where $\theta = (1-\alpha)/\alpha$. Note that $\alpha \to 1 \Rightarrow \theta = 0$. Denote industry-wide quantities as $Q_e = \Sigma_i q_e^i$ and $Q_g = \Sigma_i q_g^i$. Firms are assumed to be price-takers in both markets. For a given level of EV sales θq_e^i defines the maximum number of ICEVs that an individual firm can sell assuming the mandate applies to each firm individually.

In the absence of a mandate the combined profit function for firm *i* is

$$\pi^i = p_e q_e^i + p_g q_g^i - C^i(q_e^i, q_g^i)$$

where p_e and p_g denote prices and C^i is the cost function. The first order conditions are the usual marginal cost rules $p_e = C_1^i$ and $p_g = C_2^i$ where the numeric subscripts denote the partial derivatives. Denote the corresponding optimal quantities as q_e^{i*} and q_g^{i*}.

An EV sales mandate takes the form $q_g^i \leq \theta q_e^i$. We assume the policy exists because the policymaker wants EVs to achieve a greater market share than the market agents prefer, hence the constraint is binding. The firm's Lagrangian becomes

[6] These authors noted, however, that over time as technology improves EV production costs will decline, so there may be uncounted learning-by-doing benefits associated with such subsidies.

$$\mathcal{L} = p_e q_e^i + p_g q_g^i - C^i\left(q_e^i, q_g^i\right) - \lambda(q_g^i - \theta q_e^i)$$

and the first order conditions are

$$p_e - C_1^i = -\lambda\theta \qquad [1a]$$

$$p_g - C_2^i = \lambda \qquad [1b]$$

$$\tilde{q}_g^i - \theta\tilde{q}_e^i = 0 \qquad [1c]$$

where λ is the Lagrange multiplier representing the marginal profit associated with a one-unit relaxation of the sales mandate and ~ denotes the constrained optimal output levels. Since λ and θ are both positive, equation [1a] implies $p_e < C_1^i$ hence the firm overproduces EVs relative to the unrestricted optimum and it is earning losses at the margin. Equation [1b] implies $p_g > C_2^i$ at the (mandate-restricted) optimum so the firm is under-producing ICEVs relative to the unrestricted case and earning rents on that market segment.

An alternative to the command-and-control form of the policy would be to define the industry-wide sales target θ then impose a charge whereby firms pay a fee of τ per unit if $q_g^i > \theta q_e^i$ or earn a corresponding credit if $q_g^i < \theta q_e^i$. The proposed Canadian policy is like this, taking the form of a tradable credit system with a backstop price. Firms that sell EVs generate credits[7] which determine the number of ICEVs that can be sold. Firms with surplus credits can sell them to those in a deficit position. If the market price for credits goes above $20,000 a firm can opt instead to pay that amount as a tax per ICEV. The charge thus acts as a "safety valve" and, if the price of credits goes high enough, the EV mandate converts to a tax on ICEV sales. Under this policy the firm's profit function becomes

$$\pi^i = p_e q_e^i + p_g q_g^i - C^i\left(q_e^i, q_g^i\right) - \tau\left(q_g^i - \theta q_e^i\right).$$

If the market price of permits is below the safety-valve price and automakers are price-takers in the permits market this equation describes the profit function treating τ as the market price for permits. The first order conditions will be the same as equations [1a] and [1b] with τ replacing λ. If the equilibrium price of permits exceeds the safety valve price, so firms prefer to pay the fee rather than purchase credits, then, denoting the outcome in this case using ^, we will observe

[7] The credits are only partial for short-range plug-in hybrid EVs (PHEVs). Full credits are earned for battery EVs (BEVs) and long-range PHEVs.

$\hat{Q}_g > \theta\hat{Q}_e$ and the net proceeds of the charge will be positive. If the safety-valve price is adjusted upwards until $\hat{Q}_g = \theta\hat{Q}_e$ the mandate will hold in the aggregate (though not necessarily for each individual firm) and the net proceeds of the charge will be zero. This will be a more efficient outcome compared to the command-and-control case since the constraint does not apply to each individual firm, only to the industry as a whole.

For a firm like Tesla that only produces EVs, its profit function can be derived by setting $q_g^i = 0$ which implies it will produce where $p_e + \tau\theta = C_1^i$. As before this implies a production level beyond the point where price equals marginal cost, but if the mandate is fully implemented such that $\alpha = 1$ then $\tau\theta \rightarrow 0$ and production will move back to the optimal point.

Depending on the magnitude of the gains and losses in the two markets, due to the creation of rents the phase-in of an EV mandate can, at first, yield a potential net benefit to the ICEV sector and even for the auto sector as a whole. It allows manufacturers to act as an effective oligopoly, constraining supply and generating marginal rents. Figure 1 shows a stylized example of the effect of the mandate in twin car markets on the assumption that marginal production costs for both vehicle types are constant but higher for EVs than for ICEVs. The Figure also assumes that current demand is lower for EVs, has a higher (negative) demand elasticity and ignores cross-price effects between EVs and ICEVs. When ICEV sales (right panel) are capped at $\theta\tilde{Q}_e$ the firms in that market segment restrict production and earn the rents shown as the striped rectangle. They also overproduce EVs and sell the marginal units at a loss as indicated by the shaded area in the left panel. The rents made available in the ICEV market provide the rationale for overproducing in the EV market. As the mandate tightens, for a given level of $\tilde{Q}_e$ the rent rectangle in the ICEV market will at first grow then shrink to zero.

The Figure can be modified to allow demand in each market to respond to price changes in the other. The increase in p_g would cause D_{EV} to shift to the right, thereby increasing allowed ICEV sales $\theta\tilde{Q}_e$. The figure redrawn would look the same as the version shown, but the rent and loss rectangles would be of different dimensions.

Automobile production has large fixed costs so even with the rents shown in Figure 1, the reduced sales quantity means that average costs may exceed average revenues overall and the sector may operate at a loss. Also note that although Figure 1 assigns the rents to the respective market segments, if the policy allows for tradable compliance permits the EV manufacturer would capture some or all of the ICEV rents.

The prospect that automakers may sell EVs at a loss has long been a concern to the auto industry. In a submission to the government of Quebec in 2016, which was considering imposing its own EV sales mandate, the Canadian Vehicle Manufacturers Association stated that its members were incurring losses of $12,000 to $20,000 on each EV unit produced (CVMA 2016). This figure presumably includes all fixed and variable costs. Current data and news sources echo these concerns. While Tesla reports positive net earnings on EV sales (inclusive of subsidies and tax credits) it is also seen as an outlier in this regard. Ford reported expected losses on EV sales of between US$3 and US$4.5 billion in 2023.[8] Volkswagen recently agreed to build an EV battery plant in Ontario but only after securing a $13 billion subsidy from the federal and provincial governments,[9] a deal which then prompted Stellantis to halt construction on its battery plant and demand subsidies of its own.[10] Over time scale economies may arise such that the marginal cost of EV production may fall below consumer willingness to pay, but as worldwide production grows some key input costs may also rise. For instance while the cost of manufacturing EV batteries and the supporting infrastructure has dropped and is expected to continue doing so (Nykvist et al. 2019), some current projections have been criticized as overly optimistic (Hsieh et al 2019). Also the specific type of magnets critical to EV motor design (sintered neodymium iron-boron (NdFeB) magnets) are dependent on a supply chain that is almost entirely located in China, especially at the separation, refining and manufacturing stages (US Department of Energy 2022), raising the prospect that the government of China will exploit its market power.

In the next section we examine the consequences for the Canadian economy of phasing in an EV mandate using a model that takes account of the pricing effect described above and embeds it into a large-scale computable general equilibrium model. We find in the short run that positive rents are generated on the ICEV side but they do not compensate for the overall loss of revenue as the total automobile market shrinks due to the required increase in the price of cars. The model predicts that the losses will run a long time depending on how quickly EV production costs fall.

3 Simulation model of EV transition policy

3.1 Brief description of macro model

A detailed description of the model can be found in the Appendix. The model resolves annual economic activity in each of 10 Canadian provinces and the northern territories jointly, thus covering 11 jurisdictions. The model is solved annually over the 2019 to 2050 interval and employs myopic, recursive dynamics to update the capital stock each period. Within each jurisdiction there is a single aggregate household which supplies labour and owns capital. Production occurs in 26 sectors which are listed in the Appendix. Trade occurs inter-provincially and internationally. The government in each jurisdiction is represented on a consolidated basis, combining provincial and federal operations. The government collects taxes, services its debt, purchases labour, goods and services, and supplies transfers to households.

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[8] See https://www.cnn.com/2023/03/23/business/ford-ev-losses/index.html; https://fortune.com/2023/07/28/ford-earnings-report-q2-2023-ev-losses/ accessed November 17, 2023.
[9] See https://www.bloomberg.com/news/articles/2023-04-20/ev-incentives-canada-matched-biden-subsidies-to-win-volkswagen-battery-plant#xj4y7vzkg accessed October 16, 2023.
[10] https://www.msn.com/en-ca/money/topstories/stellantis-stops-construction-on-windsor-ont-ev-battery-plant-amid-fed-dispute/ar-AA1bd1zE accessed October 16, 2023.

The household supplies labour and spends its disposable income on savings and consumption. Consumption is disaggregated down to 26 types of goods and services through a series of nesting operations listed in the Appendix. At each nesting level the consumer derives optimal nominal budget shares using a Constant Elasticity of Substitution (CES) aggregator. Elasticity parameter selection is described in the Appendix. Producers disaggregate intermediate input demands using a CES aggregator that yields endogenous input-output coefficients following the derivation in Berck and Sydsaeter (1993). Thus, for a given price vector, the model computes nominal share functions for households and input-output coefficients for firms.

Within a province, given prices, tax rates, government spending and trade volumes the model computes the intermediate input-output (IO) coefficient matrix, the labour supply and final demand, consisting of household consumption, government purchases, business investment or Gross Fixed Capital Formation, exports and imports. Denote final demand as F, the matrix of input-output coefficients as A and real output as Q. The Leontief market clearing condition is $AQ + F = Q$. The model generates A where each element is a function of prices and solves for F as a function of prices then solves for Q using the matrix equation $Q = (I - A)^{-1}F$. This clears all goods and service markets at the existing prices, which is equivalent to assuming constant returns to scale in each sector. Then input-output coefficients for labour and capital are used to determine factor demands by sector and province.

The model adjusts the national wage rate to clear the national labour market, the capital price to equate the demand for capital with the current capital stock, the international exchange rate to balance the currency inflows and outflows and the real interest rate to balance savings and investment. Labour markets within a jurisdiction do not necessarily clear: there can be surpluses or shortage of labour within a province but they add up to zero nationally. The program verifies that unit profits are zero within each sector and Walras' Law holds nationally at every iteration.

Readers should bear in mind the many limitations of large-scale models such as the one used herein. The technologies governing production sectors are summarized by columns of input-output matrices the elements of which are based on values observed over the 2014-2018 interval and which are assumed to be functions of relative prices, but which may also be subject to exogenous changes over time following processes not captured herein. In order to keep the model computationally tractable constant returns to scale are imposed on all sectors including automobile manufacturers. A more detailed representation of the auto sector would attempt to take account of oligopolistic behaviour especially within differentiated market segments. The model also does not impose intertemporal optimization, so the base case does not necessarily represent the optimal savings and investment path for the economy. There are also many ad hoc assumption needed to complete a policy simulation. For instance government tax rates and spending levels are taken as exogenous, while the budget balance is endogenous. A small increase in the budget deficit occurs as a result of the policy experiment. If this were prevented by assumption then alternative assumptions about taxation or spending would be needed and the overall economic effects would be slightly different. The utility function is assumed to be separable between consumption and leisure. Since there is no unemployment there is no disutility associated with an involuntary increase of leisure. Other assumptions and ad hoc parameterizations are discussed in the Appendix.

3.2 Automobile sector and the EV mandate

Data for the automobile parts and assembly sector is taken from the provincial IO use tables. The Use tables have 543 rows, comprising individual inputs, taxes and payments to factors, and 554 columns, corresponding to intermediate industries and final demand sectors. The automotive manufacturing industry is defined herein as the sum of columns 104 to 114, which include car and truck manufacturers and all vehicle parts manufacturers. The IO tables do not distinguish between ICEV and EV manufacturers. The products are contained in rows 245 to 259 which includes passenger cars, light, medium and heavy-duty trucks, buses, trailers, motor homes, vehicle bodies and all vehicle parts. Again, EVs or EV components are not separately identified.

Data for 2018 on the vehicle fleet size and sales by province are taken from Natural Resources Canada (2023). Sales figures were combined with final demand data for the automotive sector from the input-output tables to compute coefficients that estimate annual vehicle sales (in thousands) which, combined with an assumed three percent scrappage rate, allows the model to update the vehicle fleet by province each year. EV fractions of sales by province were obtained from Statistics Canada (2023b). Estimation of the assumed baseline trend over 2019 to 2050 is described below.

The policy mandate is for the auto sector to ensure the fraction α of auto sales is comprised of EVs. The policy is assumed to hold at the aggregate level for the entire sector, which corresponds to a binding overall mandate with tradable credits among firms. In the theoretical model above the perspective was the individual price-taking firm. Here the modeling perspective is the industry as a whole. Suppose the market-driven EV fraction in the absence of a mandate is α_0. As shown in the previous section a binding sales mandate forces firms to operate where prices differ from marginal costs. Since the policy forces consumers to buy a costlier option we assume the overall effect is to increase the cost of purchasing additions to the vehicle fleet, in other words that the policy is not augmented by subsidies that eliminate the price effects. The price index P^{Auto} for automobiles can be written

$$P^{Auto} = (1 - \alpha_0)p_g + \alpha_0 p_e.$$

Note that p_g and p_e are not separately observed (even within the model), only α_0 and P^{Auto} are known. We assume α_0 is below α_t, the policy target at time *t*. We also assume that on a quality and characteristic-equivalence basis (see discussion below) EVs are more expensive than ICEVs until the year cost parity is attained. We can parameterize the cost differential as $p_e = CD_t p_g$ where $CD_t \geq 1$ and is declining over time. Faced with a gap between α_t and α_0 each automaker must sell more EVs or fewer ICEVs or both. We assume that the automakers respond to the mandate by increasing the selling price of ICEVs (earning rents) rather than cutting the price of EVs (incurring losses). This inflates the ICEV price by the factor $RG_t \geq 1$. In effect the sales mandate allows the firm to depart from strict price-taking behaviour and act as if it is part of a cartel, since each automaker knows that the mandate is binding on all firms collectively, and none is free to sell its preferred EV/ICEV mix.[11] The price index for automobiles is now $P^{Auto} = (1 - \alpha_t) RG_t p_g + \alpha_t CD_t p_g$. RG_t and CD_t are not individually observable but we will assume that RG_t is constrained by CD_t, in other words automakers would not have to boost the prices of ICEVs above those of EVs in order to achieve the target mandate. To make the calculation tractable we will further assume $RG_t = CD_t$ which implies $RG_t p_g = P^{Auto}$. Hence the effect of the mandate is to boost the cost of annual additions to the vehicle fleet, but the magnitude of the cost increase is constrained by the (declining) price gap between ICEVs and EVs.

There is very little guidance in the literature on key parameter values such as $\varepsilon_{\alpha g}$, the elasticity of EV market share with respect to p_g. Hosamaldin and Olofsson (2021) report a marginally significant estimate of $\varepsilon_{\alpha g}$ of 0.9 (standard error = 0.5), meaning that every one percent increase in the cost of ICEVs results in a 0.9% increase in the EV market share. If the mandated value in period t is denoted α_t then the% change in the ICEV price required to meet the mandated sales fraction is $(\alpha_t - \alpha_0)/\varepsilon_{\alpha g}$. The main analysis herein will be run assuming $\varepsilon_{\alpha g} = 0.9$ but 1-σ sensitivity analyses will be conducted by varying the parameter up and down by 0.5.

We can expect, additionally, changes in EV production costs over the coming 30 years. It is very important to note that we are defining the "cost parity" to mean life-cycle transportation service on a quality-equivalent basis across the entire category of vehicles subject to the EV mandate. "Quality-equivalence" means achieving performance, operating convenience and reliability levels such that even dedicated ICEV users would be indifferent between EV and ICEV options. This includes not only size and acceleration characteristics but ease and speed of refueling (charging), reliability in cold weather, towing capability, maintenance costs etc. While the cost of manufacturing entry-level compact EVs has been steadily falling, many aspects of EV ownership have not evolved in the same way. As noted above, Hertz is selling 20,000 EVs and replacing them with ICEVs due to unexpectedly high maintenance costs and the reluctance of consumers to use EVs for holiday trips.

In the absence of clear empirical guidance it will herein be assumed that of the two contrasting forces learning-by-doing has the stronger effect, but that owing to the ongoing challenges of achieving quality-equivalence for larger vehicles the net drop in production costs is linear rather than exponential. The ICEV cost premium is reduced by the factor $(1 - \nu N)$ where N is the number of years after 2019 and ν is a parameter chosen so that quality-equivalent cost

[11] The alternative would be to assume firms cut the prices of EVs, deepening their losses. This might be rational if the policy included a guaranteed subsidy, but we assume no new subsidies are introduced as part of the sales mandate. Thus it is more rational for automakers to try to boost revenue by price markups on ICEVs.

parity is achieved by an arbitrary date, though it is assumed that EV production costs do not go below those of ICEV's.[12] Combining these we get an expression for RG_t which is the factor by which auto prices are inflated over the baseline level in each year in each province due to the EV sales mandate:

$$RG_t = \max\left(1 + \left(\frac{\alpha_t - \alpha_0}{\varepsilon_{\alpha g}}\right)(1 - \nu N), 1\right) \quad [2]$$

where *t* is the current year.

Table 1 shows average values of the cost premium based on equation [2]. α_0 is determined in the model for each jurisdiction and each year based on current and historical data on new vehicle registrations by vehicle type, which are obtained from Statistics Canada (2023b). The simulations reported herein were done before the federal government announced a $20,000 cap on the price of ICEV permits (Government of Canada 2023). This effectively caps the cost premium that will be induced by the mandate and, if the price of EV credits hits the cap, would dampen the macroeconomic consequences. But in such a case it also creates a contradiction between the stated aim of the policy, namely ICEV phaseout by 2035, and the actual outcome. This will be discussed further in Section 5 below. The sequence of mandate values α_t employed herein also differs slightly from that in the Government of Canada (2023) announcement. The targets for 2026, 2030 and 2035 were known at the time of doing these simulation and α_t was linearly interpolated for the other years in the two intermediate intervals. The announced sequence differs slightly from linear interpolations, being slightly back-loaded in the first interval and front-loaded in the second. However this implies only minor changes for the specific years in question and none for 2030, 2035 and all subsequent years.

To quantify the effect of the EV sales mandate, provincial base case EV sales as a share of new vehicle registrations were obtained up to 2022 and projected forward until 2030 on the assumption of a continuation of the 2015-2022 trend increase in the EV share of new vehicle sales, with the growth spurt in BC and Quebec reverting to trend after 2023. Because the EV sales rates in these two provinces are relatively high the mandate does not become binding until 2027. After 2030 it is assumed that the share of EVs in new vehicle sales continues to grow by 0.5% annually in each province. Note that we treat the EV sales levels attributable to the BC and Quebec EV mandates as part of the base case so the policy cost estimates estimated herein are only for the federal sales mandate. As of 2040 the base case shares range from a low of 13% in

[12] This assumption is applied not as a specific forecast but to make the projections consistent with the policy. If it were reasonable to suppose that, on a quality- and characteristic-equivalent basis, the cost of EVs will fall below that of ICEVs on a foreseeable timetable, the EV mandate would not be needed. The premise of this policy experiment is that the EV mandate is needed through 2050.

Alberta and Saskatchewan to a high of 39% in Quebec.[13] These EV share estimates are well above the path forecast by Navius (2020), which projected national EV adoption of only 11% to 14% depending on vehicle classes as of 2040. A higher base case EV market share implies smaller macroeconomic costs due to a sales mandate. In 2030 the mandate is assumed to require EVs to take a market share averaging about 41% greater than they would otherwise have. On its own this would require a 45.6% increase in the price of ICEV's to induce the change. But if costs are falling such that parity will be achieved by 2035 the premium is only 14.3%, and if costs are falling toward parity at 2050 the premium is 29.6%.[14] In each case the entirety of the premium accrues as pure rent on ICEVs, though as noted the rents may be partially or entirely captured by EV manufacturers. As long as the constraint binds ($\alpha_t > \alpha_0$) an ICEV price increase of some magnitude is needed, but for a fixed mandate, due to the assumption of declining production costs the increment shrinks over time. Also, after 2035 since ICEVs are banned the rents likewise vanish.

In effect the EV mandate sets up a race between the policy of forcing a growing fraction of buyers to choose something other than what they prefer and the pace of cost reduction in EV production that would lead them to being indifferent. Pushing the EV sales requirements before the cost reductions have been realized will prove to be extremely costly since the price markup applies across the car market. At present the mere prospect of ICEV rents appears to be inducing many automobile manufacturers to develop EV product lines even though, with the apparent exception of Tesla, average costs exceed average revenues. As we will see, this may not suffice to prevent the auto sector from bankruptcy, but in subgame sense attempting to capture ICEV rents through EV production is likely better than sticking with ICEV production only.

According to Statistics Canada (2023a) the passenger vehicles covered by the mandate make up about 89% of registered vehicles in Canada (excluding trailers) over the 2015-2019 interval so it is assumed that the mandate does not apply to 11% of the annual sales of the Canadian automobile sector.

The date at which quality-equivalent cost parity between EVs and ICEVs is achieved turns out to be highly influential on the simulation results. Since it is an unknown parameter we will herein examine two arbitrarily-selected options: 2035 and 2050. The former is justified by the choice by the Government of Canada to make 2035 the target date, prior to which a mandate is necessary to move consumer purchases towards EVs. Hence cost parity after 2035 can be considered the most optimistic case. In effect it proposes that by the time the mandate goes fully into effect it has become unnecessary because purchasers of any class of passenger ICEVs will have EV options which they deem to be perfect substitutes and if obliged to select would readily do so with no price inducement necessary. 2050 is a suitably pessimistic target for assuming cost parity in the sense defined above, namely on a full quality-equivalent basis, since parity would

[13] Bear in mind the mandate covers not only small passenger cars but also large sedans, SUVs and pickups.

[14] These illustrative figures are not exact because they are based on an unweighted national average EV mandate gap. In the model the exact price factor is computed within each jurisdiction.

require an enormous change in the refueling infrastructure across North America as well as development of EV options that to date have proven infeasible, such as electric pickup trucks with cold weather range and towing capabilities to rival eight cylinder diesel ICEVs. 2050 is also relevant as the target date for the government's target of Net Zero.

4 Simulation Results

4.1 Cost parity at 2035

The model is trained on data over the 2014 to 2018 interval. For the 2019 economic outcome the model takes in estimates of population, prices, tax rates, government spending levels and other model parameters and solves for an economic equilibrium. The predicted 2019 Canadian auto sector operating surplus is $3.7 billion. 2019 input-output tables are now available and report an observed Canadian operating surplus of $4.5 billion, somewhat outperforming the equilibrium projection. Figure 2 shows the sequence of model-predicted after-tax operating surpluses of the Canadian automobile sector from 2024 to 2040 assuming EV/ICEV cost parity is achieved in 2035. The black line shows the base (no-policy) projection of the auto sector operating surplus, which is about $5.2 billion in 2024 and reaches $15.2 billion in 2040. Imposition of a 20% EV sales mandate in 2026 requires a price increase that reduces auto sector earnings gross of ICEV rents from $6.2b to -$2.3b but generates ICEV rents of $6.8b resulting in net earnings of $4.5b, a 28% drop compared to the base case. By 2030 the operating surplus gross of rents has fallen to -$28.5b and the ICEV rents are $14.5b yielding net losses of $14.0b. Throughout the implementation of the EV mandate despite the generation of rents on ICEV sales from 2026 to 2035 the auto sector always loses money relative to the base case and experiences absolute losses from 2028 to 2034. From 2025 to 2050 the losses in the auto sector relative to the base case add up to $138.7b, assuming the sector never shuts down.[15]

Figures 3—6 summarize changes over time in some key macroeconomic indicators at the national level. Figure 3 shows that relative real GDP drops slightly until 2031, bottoming out at 1.2% below the base case, then recovering to parity by 2035. Thereafter a slight gap opens up over time reaching 0.2% as of 2050, which appears to be attributable to the decline in the fossil fuels sector not being offset by gains in the electricity and EV sectors. Consumer Utility and Real Industrial Output both decline over this time relative to the base case (not shown). Table 2 summarizes the sequence of changes in somewhat more detail. The first group shows results for Canada and each jurisdiction for 2030. For the other years (2035, 2040, 2050) only the results for Canada and selected provinces are shown, for brevity. By 2030 real GDP has gone below the

[15] The model does not contain a provision requiring a sector to shut down even under permanent losses. It experiences negative investment depending on Tobin's q, but it continues to operate. To add a shutdown provision would require either including perfect foresight or an *ad hoc* rule prescribing shutdown after an arbitrary accumulation of losses, however these modifications would not add insight beyond the obvious point that eventually a money-losing sector will shut down.

baseline level mirroring the change in output and utility. Note that GDP continues to increase, but more slowly than without the mandate. Because the capital accumulation process in the model does not include perfect foresight once the ICEV/EV cost difference vanishes as of 2035 the GDP gap also closes. Figure 4 shows that the cost of the mandate per worker, measured as lost real earnings per employed person, begins rising in 2027 to a peak of about $1,064 by 2031, falling initially to zero at 2035 then rising again to about $191 by 2050. Table 2 and Figures 2-5 show that, according to the model, once cost parity is achieved and the mandate no longer binds, real output and earnings temporarily return to their baseline levels then slightly diverge downwards. Table 2 also shows that a small permanent substitution away from automobiles occurs, and real earnings and utility remain permanently below the baseline in some provinces. Figure 5 indicates that the employment impact of the mandate peaks at a loss of about 38,000 jobs in 2031, returns to baseline as of 2035 then begins diverging slightly downwards through 2050.

Demand for motor vehicles drops by 3.9% nationally compared to baseline as of 2030, driven by increases in the purchase price of cars. Note that the car markets in each province are assumed to be separate. Since baseline EV sales are much higher in Quebec and BC than, for instance, Saskatchewan, the ICEV price increase in Saskatchewan is higher. In the real economy it could be expected that interprovincial shipments of vehicles would to some extent dampen the price differences, but this mechanism is not represented in the model.

Figure 6 shows that greenhouse gas (GHG) emissions reductions are modest but grow over time as the vehicle fleet changes over to electric. As of 2030 emissions are only 1.5% below the baseline level, or about 9.1 megatonnes CO2 equivalent, with the gap widening to 2.8% as of 2035 and 7.8% as of 2050. Rivers and Wigle (2018) used a different modeling framework and estimated an EV mandate would achieve short run GHG emission reductions of about seven megatonnes. Rivers and Wigle (2018) estimated the EV mandate emission reductions would cost about $1,200 per tonne. By contrast, as shown in Figure 7, the overall economic costs in this model simulation are initially over $2,800 per tonne as of 2030, though they fall (by assumption) to near zero as of 2035. As of 2050 the model projects that the overall vehicle fleet will be 0.6% smaller than the base case and 39% of the cars on the road will be EVs. As a result of the fleet change national household electricity demand will have increased by 14%, and refined fuel use will have declined by 33% compared to the base case.

4.2 Cost parity at 2050

The transition costs of the EV mandate under the 2035 parity assumption are large, especially the peak cost per worker of over $1,000 annually in the early 2030s, but the economy returns to baseline by 2035 and it might be reasonable to suppose that the temporary costs would not prohibit implementation of the policy. At the same time, the key assumption in the previous section is that technology will change so quickly the policy is not actually needed. In this section we extend the interval required for cost parity another 15 years, so that it takes until 2050 for the market to advance to the point where consumers across all vehicle classes are perfectly indifferent between EVs and ICEVs. Figure 8 shows the results for the auto sector. Again, despite large rents accruing to the ICEV part of the market over the 2026-2035 interval, earnings net of rents go below baseline earnings right away and stay below until 2050. Moreover earnings are negative until 2048 and the losses are very large. By 2030 gross earnings are -$62b, ICEV rents are $28b and net losses are $34b. Net losses peak in 2035 at $91b. Over the 2025 to 2050 interval the auto sector loses $1.3 trillion relative to baseline earnings. As noted above the model does not include a shutdown mechanism for a sector enduring permanent losses but in this case it is safe to assume that the EV mandate would lead to the permanent closure of the Canadian auto sector, likely by the early 2030s.

These are large deviations from the historical financial conditions in the auto sector, however it should also be noted that the proposed policy imposes a very large deviation in operations: banning one of the most popular consumer products of all time, the manufacture of which is a major component of modern industrial activity and final consumer demand, while imposing a requirement to purchase instead a product that to date has only received limited consumer approval even with substantial consumer subsidies and which is currently leading to significant losses for most automakers in the sector. The severe dislocation of the auto sector gives rise to equally severe effects on the rest of the economy, as shown in Figures 3—6 and Table 3. Relative real GDP drops to 4.8% below the baseline as of 2035. In absolute terms although the economy continues to grow it does so much more slowly. From 2025 to 2035 it grows by 1.5% per year as opposed to 2.0% without the mandate. As Table 3 indicates the relative loss of GDP is most severe in Ontario (8.9%) where most of the Canadian auto sector is located. Indicators are negative across the board as of 2035: Real Industrial Output (-2.6%), Real Earnings per Worker (-4.3%), returns to capital (-16.8%), household demand for cars (-10.5%) and Utility (-0.8%). In all cases the impacts in Ontario are largest. GHG emissions fall by more (-5.5% nationally as of 2035) in this case largely because of the slowdown in economic activity. Figures 3—5 show that the economy eventually returns to trend as of 2050. Figure 6 shows that GHG emissions decline relative to the base case across the whole period as the vehicle fleet changes over. As of 2050 the model projects that the overall vehicle fleet will be 3.8% smaller than the base case and 39% of the cars on the road will be EVs. As a result of the fleet change national household electricity demand will have increased by 13.7%, and refined fuel use will have declined by 32.4% compared to the base case.

The macroeconomic consequences in this scenario are sufficiently harsh that it is not likely the policy could be maintained as proposed. For instance as of 2035 the EV mandate will have caused a drop in employment of about 137,000 jobs and a cost per employed person exceeding $4,600. Moreover it yields only modest progress towards the goal of reducing GHG emissions. As of 2035 emissions are only 5.5% below the baseline, at an economic cost of over $3,400 per tonne (Figure 7). The overall implication of this simulation is that even if the cost of EV manufacturing declines at such a rate that parity with ICEVs on a quality-equivalent basis across all passenger vehicle types is achieved by 2050, this will still not be fast enough to make a 2035 EV mandate economically feasible.

4.3 Effect of a Price Cap on EV Credits

As mentioned above, the Canadian government has capped the value of EV credits at $20,000. Taking the average cost of new cars in Canada as $66,000[16] such a charge is, on average, about 30% of the vehicle price. As shown in Table 1 the vehicle cost increases under the 2035 timeline never go this high so the cap is too high to affect the results. But under the 2050 timeline the cost adjustments for the years 2031-2038 would be capped, the macroeconomic consequences would be attenuated and the sales mandate would not be achieved. This implies a contradiction between the effects of the policy and the stated goal of phasing out new ICEV sales by 2035. There is no guidance at present on how the government would reconcile this situation. If it kept the cap at a rate consistent with an approximately 30% cost increase on ICEVs the economic losses in the 2030s would be less than those reported herein, as would the reductions in GHG emissions, and new ICEVs would continue to be sold past 2035, at least to wealthier buyers.

4.4 Sensitivity analysis

As noted above there is very limited empirical guidance regarding $\varepsilon_{\alpha g}$, the elasticity of EV market share with respect to p_g. To investigate sensitivity to this parameter the model was re-run changing $\varepsilon_{\alpha g}$ first to 1.4 and then to 0.4, which is a $\pm 1\sigma$ interval. Table 4 summarizes some key results as of 2030 under the assumption of cost parity at both 2035 and 2050 (more detailed results are available on request). The middle column repeats the results for $\varepsilon_{\alpha g} = 0.9$. The first column shows the results for $\varepsilon_{\alpha g} = 0.4$ and the third column shows results for $\varepsilon_{\alpha g} = 1.4$. The latter implies relatively smaller price increases on ICEVs are needed to induce a switch to EVs, whereas the former indicates larger price increases are needed. While these counterfactuals are implemented as a change in the share elasticity term $\varepsilon_{\alpha g}$, they could equivalently be thought of testing the effects of relaxing the assumption of constant returns to scale in the EV manufacturing sector, so that the $\varepsilon_{\alpha g} = 0.4$ case corresponds to an increase in the marginal cost of EV production and the $\varepsilon_{\alpha g} = 1.4$ corresponds to a decrease.

The macroeconomic results follow in the expected directions but are not symmetric, with costs rising in a convex manner as $\varepsilon_{\alpha g}$ drops. The change from $\varepsilon_{\alpha g} = 0.9$ to 1.4 on the 2035 timeline yields an approximately one-half drop in the utility loss, a one-third drop in the magnitude of losses in GDP, employment, income, auto demand and capital returns and 13% drop in the magnitude of GHG emissions declines. On the 2050 timeline the magnitude of reductions in losses are about the same. By contrast the decrease in the elasticity to 0.4 roughly doubles the size of losses in GDP, real industrial output, employment, earnings per worker,

[16] This is the 2023 estimate based on automobile sector data, see G. Rivard, Average New Vehicle in Canada Now Costs a Whopping $66,288, https://www.guideautoweb.com/en/articles/71369/average-new-vehicle-in-canada-now-costs-a-whopping-66-288/ accessed January 25, 2024. Since this represents a 20% increase over the previous year and a nearly 70% increase over the 2019 price it will likely revert to trend in subsequent years rather than continuing to climb at this rate.

household auto demand and capital returns on both the 2035 and 2050 timelines. GHG emissions fall by more under both scenarios as well. These results indicate the importance of obtaining more precise estimates of $\varepsilon_{\alpha g}$ since the costs of the EV policy are sensitive to its magnitude.

5 Discussion and Conclusions

The phase-in of an EV sales mandate forces a reduction in ICEV sales which creates an opportunity for automakers to earn rents on conventional cars. At the same time the market for cars in general will shrink until such time as EVs can be produced at cost parity with ICEVs, taking into account not only the cost of manufacturing basic electric vehicles themselves but also matching power and range characteristics of all classes of ICEVs and providing fast charging infrastructure of comparable convenience to the current availability of gasoline and diesel fuel stations. If the EV mandate is phased in faster than cost-parity can be achieved the rents on ICEVs will not suffice to offset the losses in auto sector revenue. Simulations in a large-scale numerical general equilibrium model of the Canadian economy trained on provincial-level input-output data over 2014-2018 suggests that moving to a 100% EV sales mandate by 2035 will move the automotive sector into a loss position in the early 2030s. The severity of the losses and the overall macroeconomic consequences depend on assumptions about the speed of technical progress in the EV sector. Put simply, the mandate is potentially affordable only if it is also unnecessary. If EV production technology improves so quickly that cost parity is achieved by 2035, there will be some large temporary transition costs but the economy will return to baseline in 2035. If full cost parity does not happen until 2050, which is still an optimistic time horizon with regards to larger utility vehicles essential in many Canadian regions, a 2035 EV mandate will have sufficiently large negative consequences that it will effectively destroy the Canadian auto industry and will cause widespread economic losses elsewhere. It is not plausible in this case that the policy would be sustainable. While the mandate is binding the costs per tonne of emissions abated are at least 10 times the Canadian carbon tax rates.

The pace of achieving cost parity is partly constrained by technological progress and also, to some extent, by geopolitical factors including China's market power over NdFeB magnet production. To the extent governments try to mandate a switch from ICEVs to EVs faster than technology and prices permit they need to be aware of the likelihood of causing substantial economic losses.

The analysis herein provides some insight into why automakers appear willing to build EV product lines even though most of them have lost money on them and expect to continue to do so. If imposition of an EV mandate is a credible threat and the policies are structured in such a way that manufacturers on the EV side of the market can capture most or all the ICEV rents then the worst scenario for an automaker is to be focused solely on ICEV production. Not only will the product be either banned or taxed so heavily as nearly to be unsellable in just over a decade, but there will be no prospect for rent capture during the phase-in, and earnings gross of rents are always below earnings net of rents. However this strategy is only advantageous in a subgame sense: given the inevitability of an EV mandate it is better to produce EVs than not, even if they are not profitable, at least up to a point. But more generally it would be better for the auto sector as a whole, and the economy too, to wait until EVs achieve something close to cost parity with ICEVs before attempting a sales mandate. Implementing a mandate on a schedule that outpaces achievement of cost parity risks the destruction of the auto sector in its entirety as well as substantial losses to the rest of the economy.

The numerical model used herein does not resolve the EV sector in isolation, so the reason for auto sector losses is not the need to invest in R&D or to incur large fixed costs related to tooling up new types of plants. Instead they arise in the model because the input-output coefficient equations take in relative prices and prescribe sectoral input requirements (including labour) that don't adjust sufficiently when output demand declines, so the sector loses money on each unit produced. This is an imperfect representation of the processes described in the theoretical model of Section 2 and the anecdotal information in the Introduction, but is the best that can be done with the current resolution of the Canadian input-output tables.

The recent policy announcement by the Government of Canada (2023) raises issues that merit investigation in future modeling work. The $20,000 cap on the EV credit price will not only affect the overall market response but also the distribution of vehicles being sold. At the low end of the ICEV market this allows for near doubling of the cost of a new car, whereas at the high end it only adds about 20% to the cost, thus creating differential incentives by vehicle class and raising issues of unequal impacts across income classes. The general equilibrium model used herein does not break down consumer behaviour by income group so we are not able to investigate these changes currently.

Other forms of market heterogeneity will matter for determining the ultimate effects of EV policies. Even if purchase costs fall sufficiently rapidly to shield consumers from some of the negative effects described herein, it will not necessarily be because domestic producers achieve the required efficiencies. If Chinese EV manufacturers gain a significant price advantage the federal mandate might end up causing a substantial switch to imported vehicles which would have negative sectoral and economy-wide implications. The model used herein is currently not equipped to address this aspect of the issue.

Acceptance of the EV product differs not only by income class but by living arrangement and local climate. People in detached houses or apartments with garages in which they can install overnight chargers may find EVs easier to adopt than people living in units with no assigned indoor garage space. Also there are persistent concerns about EV reliability in very cold weather which implies less willingness to switch car type at higher latitudes. Hence there is likely a "low hanging fruit" effect whereby some buyers are enthusiastic early adopters of EVs while others are very resistant to them. The empirical evidence suggests that most recipients of subsidies up to now are in the former group and would have bought an EV anyway (Xing et al 2021, Azarafshar, and Vermeulen 2020) so additional gains in EV acceptance will tend to require progressively larger price incentives at the margin which implies correspondingly larger welfare losses if the switch is achieved by compulsion. This will show up empirically as time-varying elasticities, where the underlying driver of the dynamics is consumer heterogeneity.

Supporting information

Additional supporting information can be found in the online version of this article.

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7 Tables

TABLE 1 Average price markup factor.

	Average mandate size	Markup factor 2035	Markup factor 2050
2019	0.000	1.000	1.000
2020	0.000	1.000	1.000
2021	0.000	1.000	1.000
2022	0.000	1.000	1.000
2023	0.000	1.000	1.000
2024	0.000	1.000	1.000
2025	0.000	1.000	1.000
2026	0.082	1.051	1.070
2027	0.165	1.092	1.136
2028	0.249	1.121	1.196
2029	0.333	1.139	1.250
2030	0.412	1.143	1.296
2031	0.472	1.131	1.321
2032	0.536	1.112	1.346
2033	0.599	1.083	1.365
2034	0.663	1.046	1.380
2035	0.737	1.000	1.396
2036	0.730	1.000	1.366
2037	0.724	1.000	1.337
2038	0.717	1.000	1.309
2039	0.711	1.000	1.280
2040	0.705	1.000	1.253
2041	0.698	1.000	1.225
2042	0.692	1.000	1.198
2043	0.686	1.000	1.172
2044	0.679	1.000	1.146
2045	0.673	1.000	1.121
2046	0.667	1.000	1.096
2047	0.660	1.000	1.071
2048	0.654	1.000	1.047
2049	0.647	1.000	1.023
2050	0.641	1.000	1.000

Notes: Column 1: unweighted national average mandate gap. Column 2: Price adjustment factor assuming cost parity achieved in 2035. Column 3: same but for parity year 2050.

TABLE 2 Summary of macroeconomic effects of EV mandate 2030–2050 assuming quality-equivalent EV production cost parity by 2035.

	Real GDP	Real industrial output	Real earnings per worker	Capital returns rel. to avg.	HH auto demand	Utility	GHG emissions
	2030						
Canada	-1.1	-0.8	-0.9	-3.6	-3.9	-0.2	-1.5
BC	-0.7	-0.3	-0.8	-1.1	-1.6	0.0	-0.6
Alberta	-0.7	-0.3	-0.7	-1.7	-2.4	-0.1	-1.0
Saskatchewan	-0.7	-0.3	-0.6	-2.1	-4.4	-0.2	-1.2
Manitoba	-1.0	-0.5	-1.0	-3.3	-4.8	-0.2	-1.8
Ontario	-2.1	-1.8	-1.6	-6.4	-6.1	-0.3	-2.5
Quebec	-0.7	-0.6	-0.7	-2.8	-3.6	-0.1	-1.1
New Brunswick	-0.3	-0.3	-0.5	-6.3	-1.9	-0.1	-2.1
Nova Scotia	-1.0	-0.5	-1.0	-3.0	-4.6	-0.1	-2.0
PEI	-0.3	-0.2	-0.5	-4.6	-0.5	-0.1	-2.0
Newfoundland	-0.7	0.0	-0.7	-2.1	-2.7	-0.1	-1.1
Far North	-0.4	-0.1	-0.7	-2.7	-0.5	-0.1	-1.7
	2035						
Canada	0.0	0.0	0.0	-0.1	-0.2	-0.1	-2.8
BC	0.1	0.0	0.1	-0.1	-0.1	0.0	-1.5
Alberta	-0.2	-0.1	-0.1	-0.1	-0.1	0.0	-2.4
Ontario	0.0	0.0	0.0	-0.1	-0.1	0.0	-3.0
Quebec	0.3	0.1	0.3	0.0	-0.2	-0.1	-2.4
Newfoundland	-0.2	-0.1	-0.2	-0.7	-0.3	-0.1	-3.1
	2040						
Canada	-0.1	-0.1	-0.1	-0.3	-0.3	-0.1	-5.3
BC	0.1	-0.1	0.1	-0.2	-0.2	0.0	-3.2
Alberta	-0.3	-0.2	-0.2	-0.2	-0.2	0.0	-4.5
Ontario	-0.1	-0.2	-0.1	-0.3	-0.2	0.0	-5.7
Quebec	0.4	0.0	0.4	-0.2	-0.4	-0.1	-4.7
Newfoundland	-0.4	-0.1	-0.3	-1.2	-0.5	-0.2	-5.8
	2050						
Canada	-0.2	-0.2	-0.2	-0.5	-0.3	-0.1	-7.8
BC	0.1	-0.1	0.1	-0.3	-0.2	0.0	-5.2
Alberta	-0.4	-0.3	-0.4	-0.4	-0.1	0.0	-7.3
Ontario	-0.1	-0.2	-0.2	-0.4	-0.2	0.0	-8.2

Quebec	0.3	0.0	0.3	-0.2	-0.4	-0.1	-6.6
Newfoundland	-0.5	-0.1	-0.5	-2.2	-0.6	-0.2	-9.3

TABLE 3: Summary of macroeconomic effects of EV mandate 2030–2050 assuming quality- equivalent EV production cost parity by 2050.

	Real GDP	Real industrial output	Real earnings per worker	Capital returns rel. to avg.	HH auto demand	Utility	GHG emissions
	2030						
Canada	-2.1	-1.6	-1.8	-7.0	-7.4	-0.3	-2.3
BC	-1.4	-0.5	-1.6	-2.2	-3.1	0.0	-0.9
Alberta	-1.4	-0.6	-1.4	-3.3	-4.5	-0.1	-1.4
Saskatchewan	-1.2	-0.6	-1.2	-3.9	-8.4	-0.3	-1.5
Manitoba	-2.0	-1.0	-2.0	-6.2	-9.1	-0.3	-2.4
Ontario	-4.2	-3.3	-3.2	-12.1	-11.4	-0.6	-4.0
Quebec	-1.5	-1.1	-1.5	-5.3	-6.9	-0.1	-1.6
New Brunswick	-0.7	-0.6	-0.9	-12.5	-3.6	-0.2	-2.8
Nova Scotia	-1.8	-0.9	-1.8	-5.7	-8.7	-0.2	-2.6
PEI	-0.6	-0.3	-0.9	-9.1	-0.8	-0.2	-2.4
Newfoundland	-1.3	0.0	-1.4	-4.0	-5.1	-0.2	-1.3
Far North	-0.8	-0.2	-1.2	-5.5	-1.0	-0.1	-2.0
	2035						
Canada	-4.8	-2.6	-4.3	-16.8	-10.5	-0.8	-5.5
BC	-3.6	-1.0	-3.9	-6.0	-4.9	-0.1	-2.8
Alberta	-3.1	-1.2	-3.1	-7.9	-6.2	-0.4	-3.7
Ontario	-8.9	-5.2	-7.4	-28.8	-16.6	-1.5	-8.4
Quebec	-3.3	-1.7	-3.3	-13.4	-9.7	-0.4	-4.2
Newfoundland	-3.1	-0.4	-3.1	-10.2	-7.3	-0.6	-4.3
	2040						
Canada	-3.0	-1.7	-2.6	-12.5	-6.8	-0.6	-6.7
BC	-1.9	-0.5	-2.2	-4.3	-2.8	-0.1	-3.8
Alberta	-2.1	-1.0	-2.1	-6.2	-4.1	-0.3	-5.2
Ontario	-5.4	-3.4	-4.4	-21.5	-10.7	-1.1	-8.6
Quebec	-1.6	-0.9	-1.7	-9.2	-5.9	-0.3	-5.4
Newfoundland	-2.2	-0.5	-2.2	-8.5	-5.1	-0.6	-6.5
	2050						
Canada	0.0	0.0	0.0	0.1	0.0	0.0	-7.6
BC	0.4	0.2	0.3	0.2	0.3	0.1	-4.9
Alberta	-0.3	-0.2	-0.2	0.0	0.1	0.1	-7.2
Ontario	0.2	0.0	0.1	0.2	0.3	0.1	-7.7

Quebec	0.5	0.2	0.4	0.5	-0.1	0.0	-6.2
Newfoundland	-0.4	-0.2	-0.4	-1.9	-0.4	-0.2	-9.1

TABLE 4 Sensitivity analysis to variations in $\varepsilon_{\alpha c}$

Elasticity:	0.4	0.9	1.4
	Parity:	2035	
Utility	-0.4	-0.2	-0.1
Real GDP	-2.3	-1.1	-0.7
Real Industrial Output	-1.7	-0.8	-0.6
Employment ('000)	-77.9	-38.0	-25.2
Real Earnings per Worker	-2.0	-0.9	-0.6
HH Auto Demand	-8.0	-3.9	-2.6
Capital Returns rel to. Avg	-7.5	-3.6	-2.4
GHG Emissions	-2.4	-1.5	-1.3
	Parity:	2050	
Utility	-0.6	-0.3	-0.2
Real GDP	-4.4	-2.1	-1.4
Real Industrial Output	-3.0	-1.6	-1.1
Employment ('000)	-139.5	-71.8	-48.6
Real Earnings per Worker	-3.8	-1.8	-1.2
HH Auto Demand	-14.2	-7.4	-5.0
Capital Returns rel to. Avg	-13.6	-7.0	-4.7
GHG Emissions	-3.8	-2.3	-1.8

Notes: All entries are % changes except where noted as of 2030. Top block: scenario assumes cost parity as of 2035. Bottom block: as of 2050.

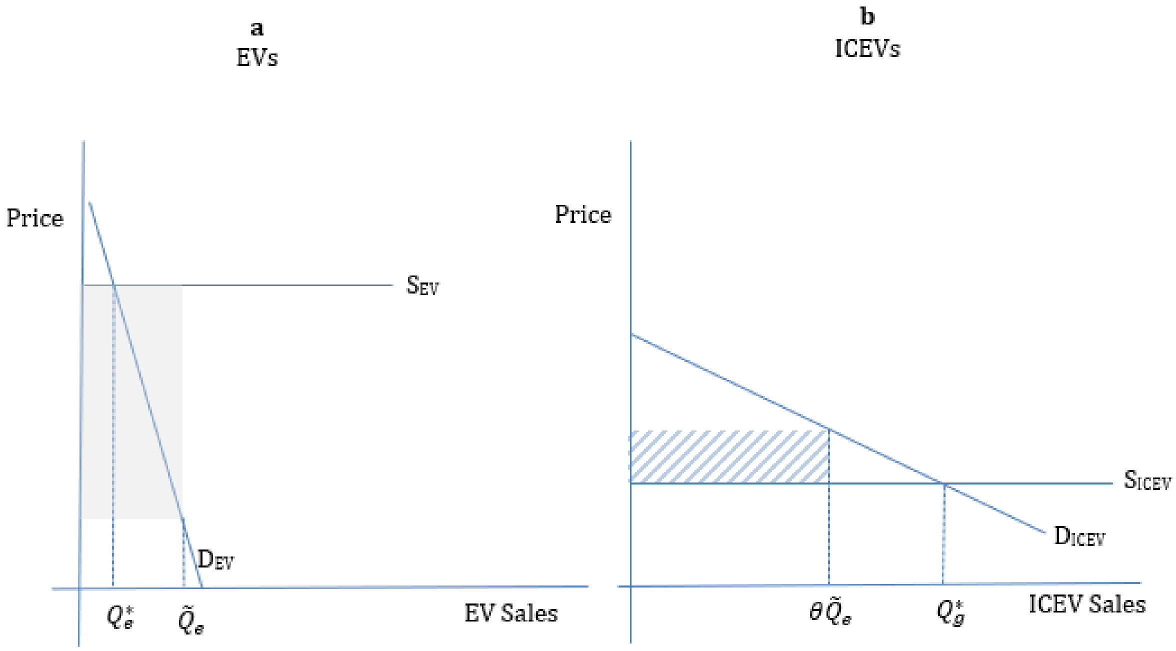

Figure 1. Simultaneous EV and ICEV markets with EV sales mandate.

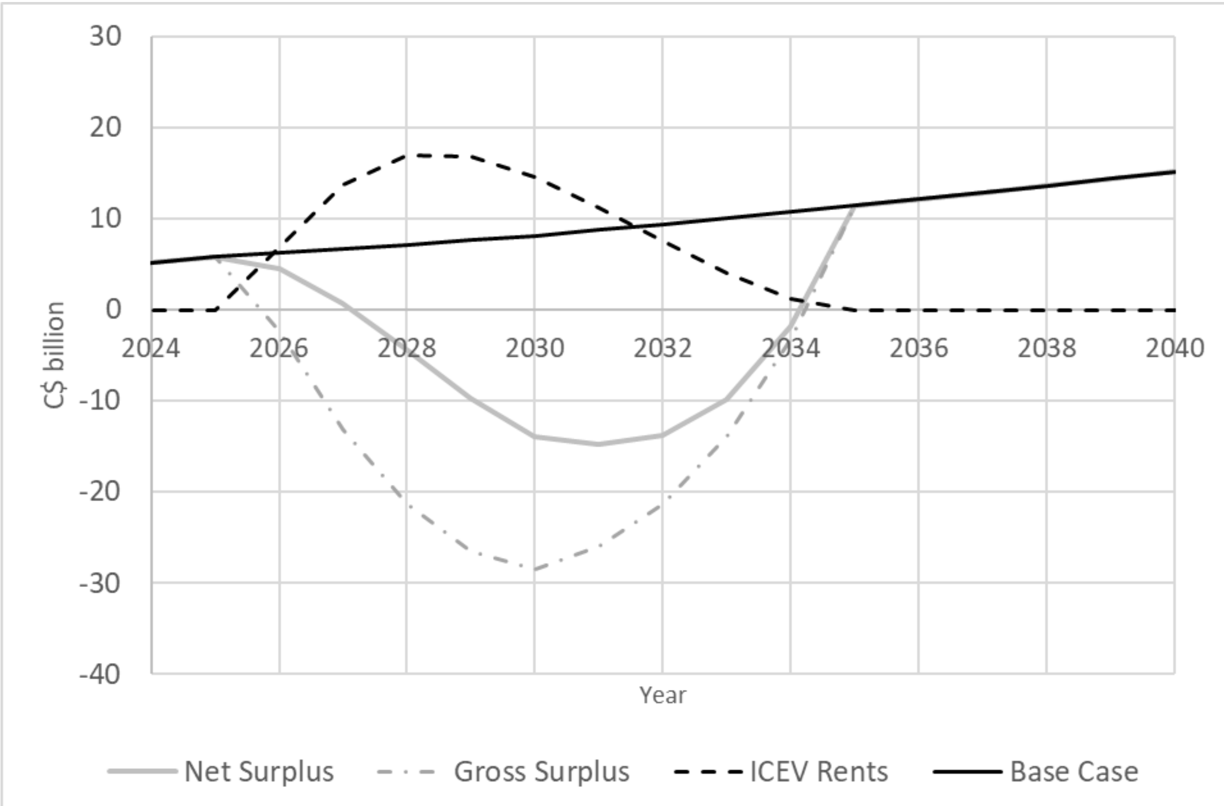

Figure 2: Base case earnings and earnings paths under EV mandate 2024-2040 assuming cost parity by 2035. Net Surplus denotes Gross Surplus plus ICEV Rents.

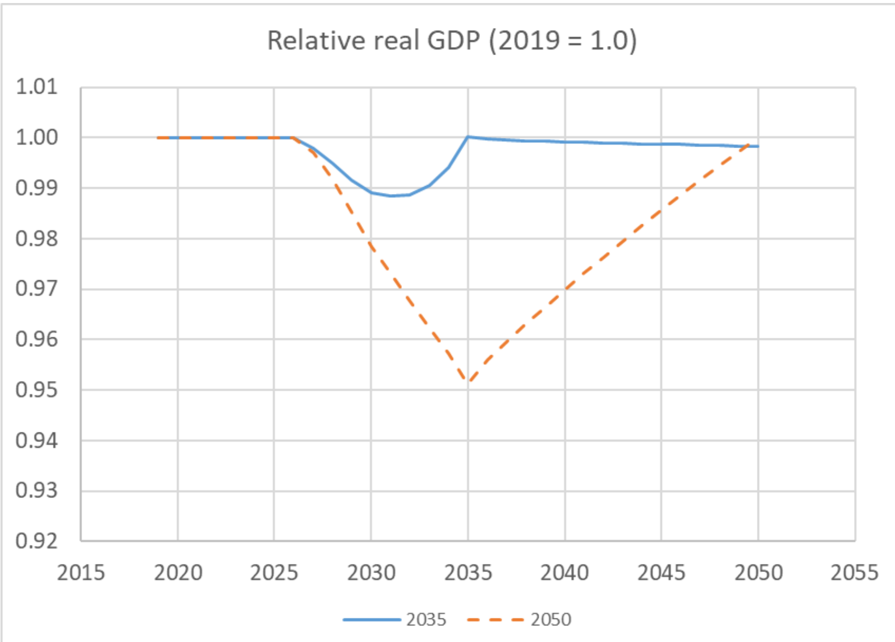

Figure 3. GDP under the EV mandate relative to baseline, 2019—2050 assuming cost parity by year indicated.

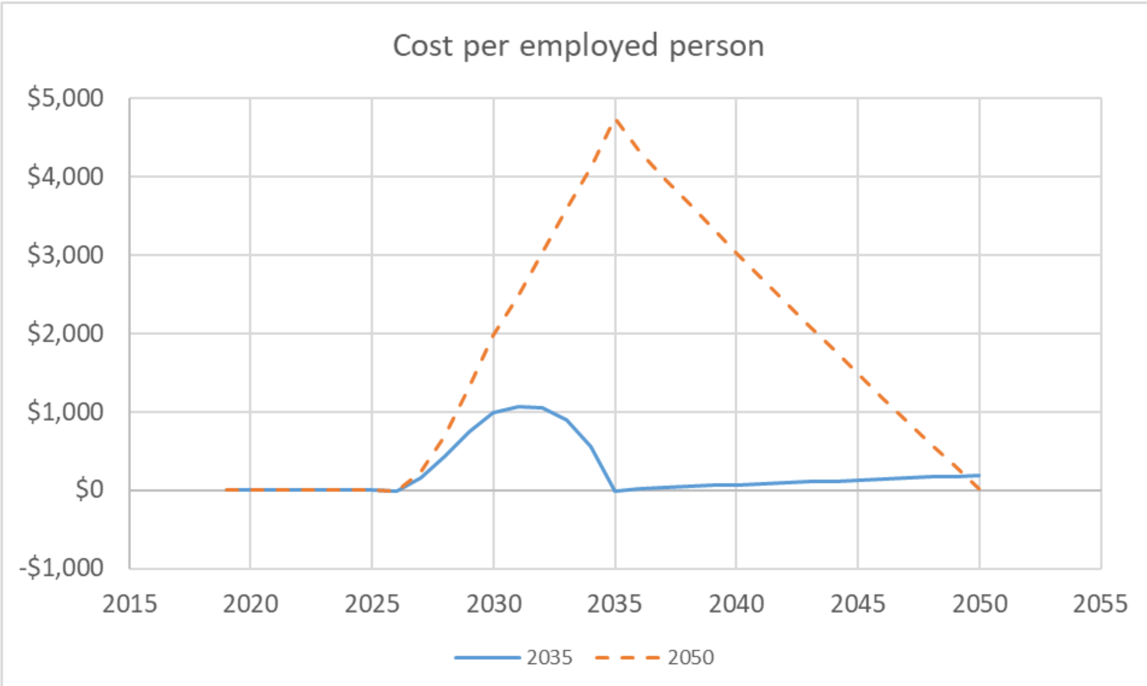

Figure 4. Cost (GDP change) per employed person (national, $CAD) of the EV mandate assuming cost parity by year indicated.

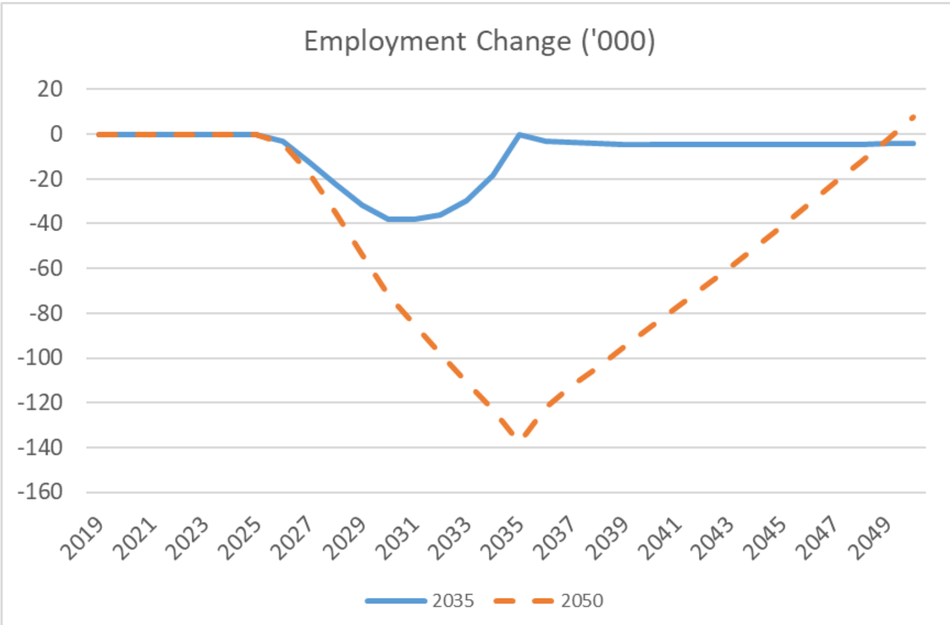

Figure 5. Change in total employment nationally under the EV mandate assuming cost parity by year indicated.

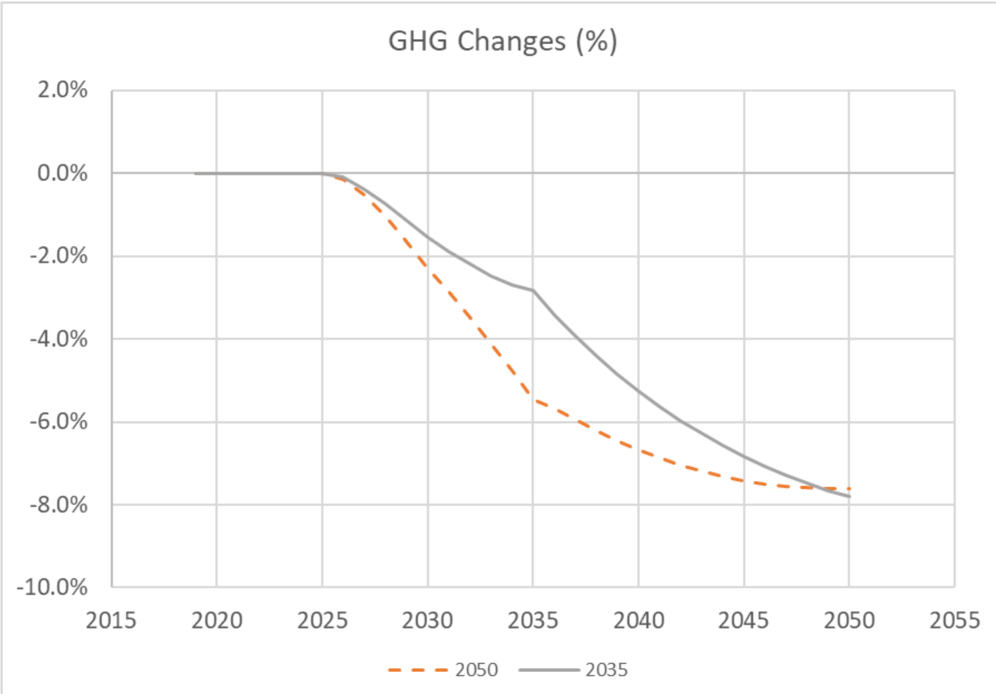

Figure 6. Percent change in national GHG emissions under the EV mandate assuming cost parity by year indicated.

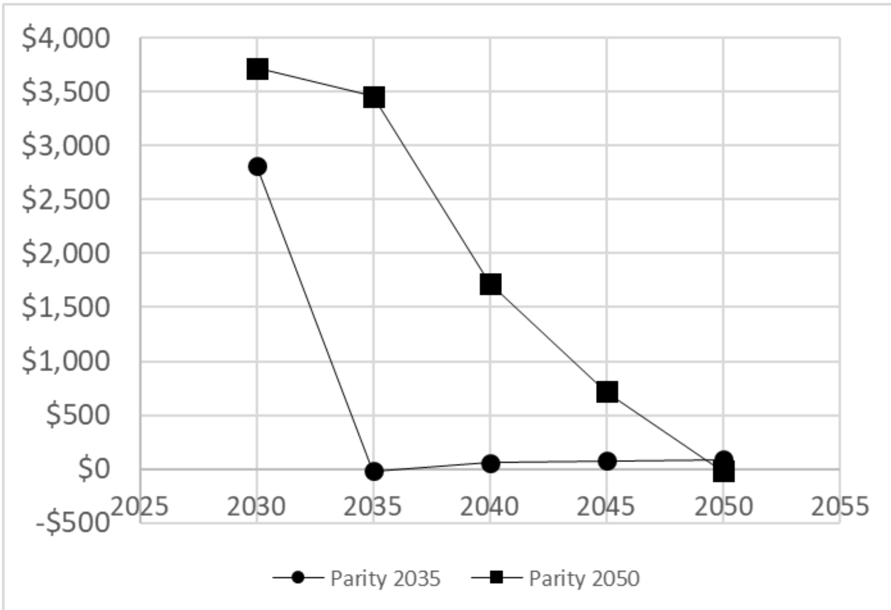

Figure 7: Cost per tonne of emission abatement (CAD$2019) based on year of cost parity.

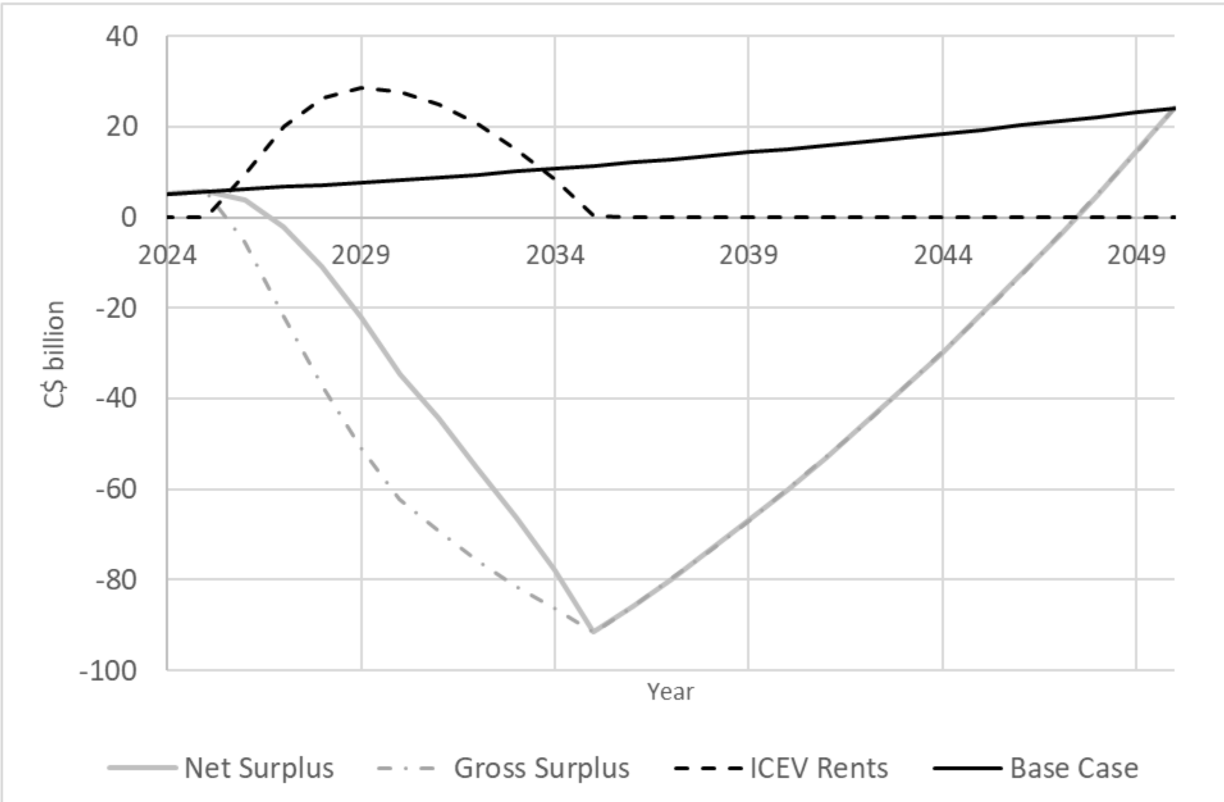

Figure 8: Base case earnings and earnings paths under EV mandate 2024-2050 assuming cost parity by 2050.