Simulating zero emission vehicle adoption and economic impacts in Canada

Report prepared for the International Council on Clean Transportation

SUBMITTED TO

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About Us

Navius Research Inc. ("Navius") is a private consulting firm in Vancouver. Our consultants specialize in analysing government and corporate policies designed to meet environmental goals, with a focus on energy and greenhouse gas emission policy. They have been active in the energy and climate change field since 2004 and are recognized as some of Canada's leading experts in modeling the environmental and economic impacts of energy and climate policy initiatives. Navius is uniquely qualified to provide insightful and relevant analysis in this field because:

- We have a broad understanding of energy and environmental issues both within and outside of Canada.
- We use unique in-house models of the energy-economy system as our principal analysis tools.
- We have a strong network of experts in related fields with whom we work to produce detailed and integrated climate and energy analyses.
- We have gained national and international credibility for producing sound, unbiased analyses for clients from every sector, including all levels of government, industry, labour, the non-profit sector, and academia.

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Summary

The adoption of zero emission vehicles or ZEVs –including battery, plug-in hybrid and hydrogen fuel cell electric vehicles – is a key action for decarbonizing Canada's transport sector.

This report, commissioned by the International Council on Clean Transportation, simulates the adoption of ZEVs in Canada through 2040. It answers the following questions:

- What level of ZEV adoption and related economic activity is likely in Canada based on the declining cost of ZEVs, consumer preferences and current federal and provincial policies?
- What are the adoption and economic impacts of implementing stronger policies that (i) require greater adoption of ZEVs and (ii) provide support for Canadian ZEV manufacturing?

How is ZEV adoption forecasted?

Navius' **gTech** model was used to forecast the development of Canada's energy-economy, zeroing in on the adoption of ZEVs. gTech is the most comprehensive model available for forecasting the techno-economic impacts of climate policy in Canada.

It is ideally suited for this project because it includes:

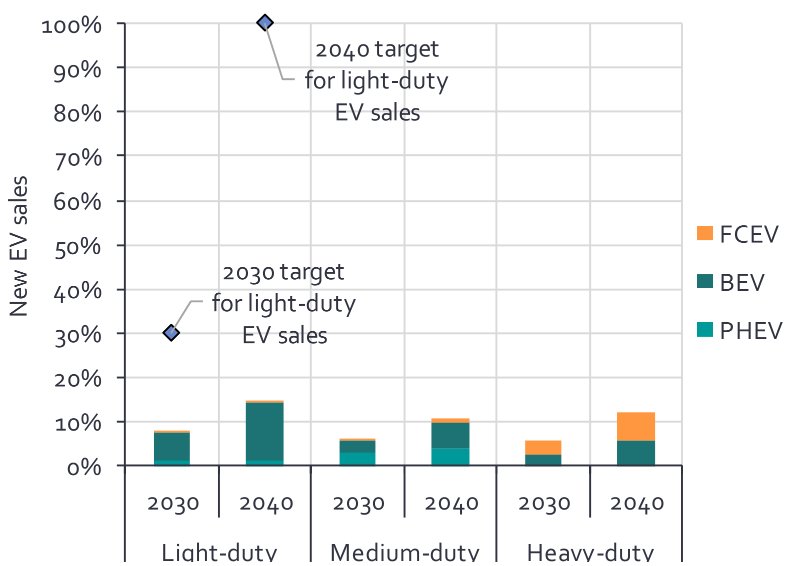
- Detailed characterization of ZEVs across all vehicle classes (i.e., light, medium and heavy-duty), including how their costs change over time.
- Realistic representation of how households and firms select among these technologies, including how preferences for vehicle technologies can change.
- Comprehensive accounting of economic activity, including vehicle manufacturing in particular and interaction between provinces and the rest of the world.
- Explicit representation of ZEV-supportive policies implemented in Canada and how they interact.

How is ZEV adoption likely to grow in the absence of new policy?

ZEV sales are expected to grow over time but fall short of Canada's targets for ZEV adoption. In response to current policy, ZEVs are projected to account for 14% of new light-duty vehicle sales, 11% of medium-duty sales and 13% of heavy-duty sales by 2040 (see Figure 1). These levels of adoption are below Canada's light-duty ZEV target of 30% by 2030 and 100% by 2040.

This projected growth in sales is driven by (1) declining battery costs and (2) existing ZEV-supportive policies. The strongest of these existing policies are in BC and Québec, which both require an increasing share of new light-duty vehicles be zero emission.

Figure 1: ZEV adoption in response to current policy



Note: FCEV = fuel cell electric vehicle, BEV = battery electric vehicle, and PHEV = plug-in hybrid electric vehicle.

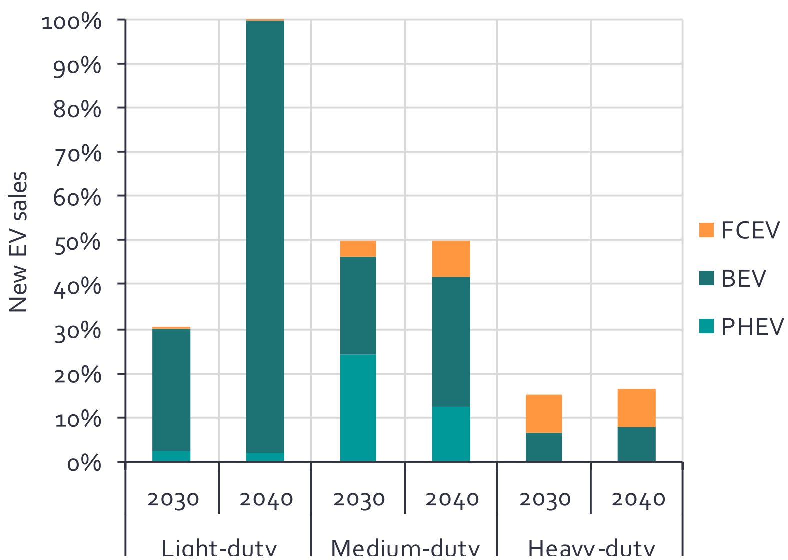
How could ZEV adoption grow under new policy to achieve Canada's ZEV targets?

A single policy – a strong zero emission vehicle mandate with national coverage – could achieve Canada's targets for ZEV adoption. Figure 2 shows the impact of such a policy, building on the regulation recently implemented in BC (for light-duty vehicles) and being developed in California (for medium and heavy-duty vehicles). By 2040, this simulated policy requires that ZEVs account for 100% of light duty vehicle sales, 50% of medium-duty sales and 15% of heavy-duty sales.

This type of ZEV mandate requires that an overall percentage of vehicle sales be ZEVs in a given year but provides flexibility in which types of ZEVs can be used to comply.

Based on current expectations about technology performance and cost, plug-in electric vehicles are likely to be the dominant choice for complying with the standard for light and medium duty vehicles, while hydrogen fuel cell vehicles are a stronger candidate for heavy duty vehicles.

Figure 2: ZEV adoption in response to a national ZEV mandate



Note: FCEV = fuel cell electric vehicle, BEV = battery electric vehicle, and PHEV = plug-in hybrid electric vehicle.

What are the economic impacts of ZEV adoption?

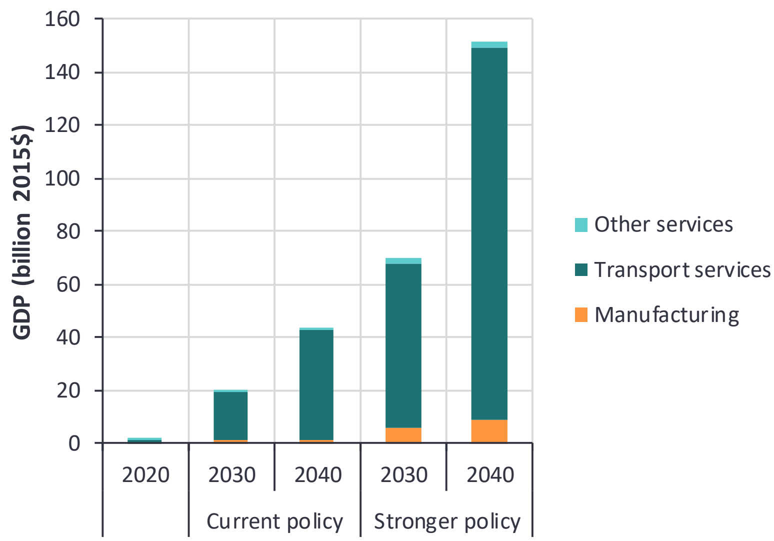
ZEV-related economic activity is expected to increase rapidly and could grow more quickly in response to strong ZEV-supportive policy. ZEVs contribute to the economy in several ways:

- **Vehicle manufacturing.** Manufacturing of ZEVs (or components of ZEVs) boosts Canadian GDP if it occurs domestically.
- **Transport services.** When purchased by businesses, electric vehicles are used to generate value-added by transporting freight and passengers. In other words, this category represents the share of total transport services that are electric.
- **Other services.** The purchase of electric vehicles supports a variety of other economic activities, such as retailing, maintenance and construction of charging infrastructure.

At present, Canada's ZEV economy accounts for about $1.1 billion of GDP (2015$) and employs around 10 thousand people (see Figure 3). In response to current policy, this economy is projected to grow to $43 billion of GDP and 342 thousand workers by 2040. It could grow further under stronger policy, to $152 billion and 1.1 million workers in 2040.

For context, the ZEV economy's GDP grows at an average annual rate of between 18% (current policy) and 24% (strong policy). By contrast, growth in the rest of the economy is in the range of 2%.

Figure 3: Growth in Canada's ZEV-economy in response to policy



What are key insights for policy makers?

1. Transitioning to zero emission vehicles is crucial for achieving Canada's emissions reduction targets. Plug-in electric and plug-in hybrid electric vehicles are currently the most promising ZEV technology for light-duty vehicles. Hydrogen fuel cell technology holds greater potential for heavy-duty vehicles in the longer term.
2. Despite many ZEV-supportive policies currently implemented across Canada, the country is not on track to achieve its 2030 and 2040 ZEV sales targets. In the absence of new policy, ZEV adoption is expected to reach 14% or less by 2040 across light, medium and heavy-duty vehicle classes.
3. A single policy – a strong ZEV mandate with broad coverage across the country – could achieve Canada's target for ZEV adoption of 30% light-duty sales by 2030 and 100% by 2040. This strength of policy is already being implemented in BC. ZEV

mandates for medium and heavy-duty vehicles could also be developed based on policy being designed in California.

4. Nationwide ZEV policy can help decarbonize Canada's transport sector while (1) contributing to global cost reductions of ZEVs and (2) boosting the ZEV economy by over $150 billion GDP and 1.1 million jobs by 2040. Compared to outcomes under in response to current policies, this more ambitious ZEV policy package represents $109 billion more GDP and 791 thousand more jobs. Most of the economic activity related to ZEVs will be their use to transport people and goods across the country, activity that otherwise would have involved conventional vehicles.
5. Growing demand for ZEVs represents an opportunity for ZEV manufacturing in Canada. Canada could consider policies to support domestic ZEV manufacturing, though the outcomes of such measures are uncertain. Raising revenue to pay for ZEV manufacturing incentives would impose costs on the broader economy.

Areas for additional research

This work involved a detailed technology review of ZEV technologies across all vehicle classes and their likely adoption in response to Canadian policy. Future research could build on this work by considering:

- The impact of uncertainty in technological change, consumer preferences and other factors on ZEV adoption.
- Regional variation in ZEV adoption trends.
- The potential to further strengthen ZEV policy in the medium and heavy-duty vehicle segments.
- The extent to which ZEV policy can contribute to achieving Canada's greenhouse gas reduction targets.
- The relative impacts and interactions of different combinations of regulations that can induce ZEV sales, including a ZEV mandate, low carbon fuel standard and vehicle emissions standard.

Contents

1. Introduction

The adoption of electric vehicles or ZEVs – defined here as battery, plug-in hybrid and hydrogen fuel cell electric vehicles – is a key action for decarbonizing Canada's transport sector. Recognizing the importance of ZEVs for climate change mitigation, Canada has committed to a ZEV target of 30% of new light-duty vehicle sales by 2030 and 100% by 2040[1].

Despite this target, ZEV-supportive policy in Canada remains fragmented. Québec and BC have the strongest policies in place, both requiring that ZEVs account for a growing share of new sales. ZEV-supportive policy is much less developed in other provinces.

Interested in better understanding ZEV adoption in Canada, the International Council on Clean Transportation contracted Navius Research to simulate both ZEV adoption and ZEV-related economic activity through 2040.

The objective of this report is to answer the following questions:

1. What level of ZEV adoption and related economic activity is likely in Canada based on the declining cost of ZEVs, consumer preference and current federal and provincial policies?
2. What is the impact of implementing stronger policies that (i) require greater adoption of ZEVs and (ii) provide support for Canadian ZEV manufacturing?

The report is structured as follows: Chapter 2 describes how Navius uses gTech to simulate ZEV-related dynamics and policies. Chapter 3 presents several forecasts of ZEV adoption and economic activity to 2040. Chapter 4 summarizes key insights for policy makers. Appendices provide additional information about assumptions and results.

[1] Natural Resources Canada. 2019. *Zero-emission vehicle infrastructure program*. Available from: https://www.nrcan.gc.ca/zero-emission-vehicle-infrastructure-program/21876

2. Analytical approach

Navius' gTech model was used to forecast ZEV adoption and ZEV-related economic activity in Canada. This Chapter introduces energy-economy modeling (Section 2.1) and gTech (Section 2.2), reviews how key ZEV-related dynamics are included in the modeling (Section 2.3), and describes the ZEV-supportive policies that are considered (Section 2.4).

2.1. Introduction to energy-economy modeling

Canada's energy-economy is complex. Energy consumption, which is the main driver of anthropogenic greenhouse gas emissions, results from the decisions made by millions of Canadians. For example, households must choose what type of vehicles they will buy and how to heat their homes; industry must decide whether to install technologies that might cost more but consume less energy; municipalities must determine whether to expand transit service; and investors need to decide whether to invest their money in Canada or somewhere else.

Existing policies and those required to achieve Canada's greenhouse gas reduction targets will have effects throughout the economy and interact with each other. For example, the federal vehicle emission standard and federal/provincial carbon pricing efforts seek to reduce greenhouse gas emissions from passenger vehicles, as do a variety of provincial policies (such as BC's low carbon fuel standard, the proposed federal clean fuel standard and zero-emission vehicle mandates in Québec and proposed in BC). The interactive effects among such policies can be complex. The economic effects of all federal and provincial climate initiatives implemented together are even more complex.

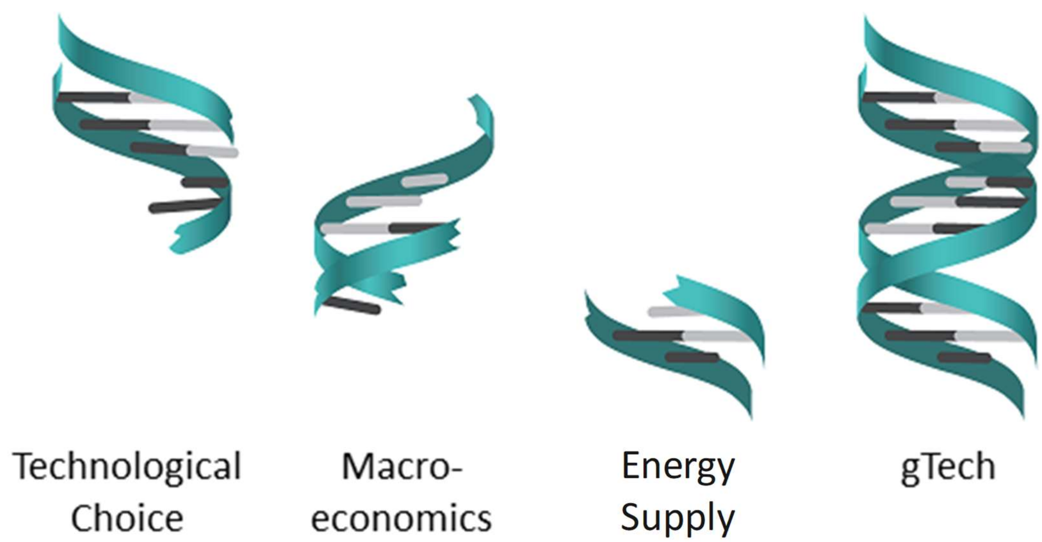
Estimating the greenhouse gas and economic impacts of Canadian climate policy therefore requires a modeling framework that captures much of the complexity of the energy-economic system as well as the range of policies implemented and proposed across the country.

2.2. The gTech model

gTech is unique among energy-economy models because it combines features that are typically only found in separate models (see Figure 4):

- A realistic representation of how households and firms select technologies and processes that affect their energy consumption and greenhouse gas emissions.
- An exhaustive accounting of the economy at large, including how provinces interact with each other and the rest of the world.
- A detailed representation of energy supply, including liquid fuel (crude oil and biofuel) and gaseous fuel (natural gas and renewable natural gas) supply chains, as well as the production of energy carriers such as electricity and hydrogen.

Figure 4: The gTech model



gTech builds on three of Navius' previous models (CIMS, GEEM and OILTRANS), combining their best elements into a comprehensive integrated framework.

Simulating technological choice

Technological choice is one of the most critical decisions that influence greenhouse gas emissions in Canada. For example, if a household chooses to purchase an electric vehicle over a gasoline car, that decision will reduce their emissions. Similarly, if a manufacturing facility chooses to electrify its operations, that decision reduces its emissions.

gTech provides a detailed accounting of the types of energy-related technologies available to households and businesses. In total, gTech includes 200 technologies across more than 50 end-uses (e.g., light-duty vehicle travel, residential space heating, industrial process heat, management of agricultural manure).

Naturally, technological choice is influenced by many factors. Table 1 summarizes key factors that influence technological choice and the extent to which these factors are included in gTech.

Table 1: Technological choice dynamics captured by gTech

Criteria	Description
Purchasing (capital) costs	Purchasing costs are simply the upfront cost of purchasing a technology. Every technology in gTech has a unique capital cost that is based on research conducted by Navius. Everything else being equal (which is rarely the case), households and firms prefer technologies with a lower purchasing cost.
Energy costs	Energy costs are a function of two factors: (1) the price for energy (e.g., cents per litre of gasoline) and (2) the energy requirements of an individual technology (e.g., a vehicle’s fuel economy, measured in litres per 100 km). In gTech, the energy requirements for a given technology are fixed, but the price for energy is determined by the model. The method of “solving” for energy prices is discussed in more detail below.

Criteria	Description
Time preference of capital	Most technologies have both a purchasing cost as well as an energy cost. Households and businesses must generally incur a technology's purchasing cost before they incur the energy costs. In other words, a household will buy a vehicle before it needs to be fueled. As such, there is a tradeoff between near-term capital costs and long-term energy costs. gTech represents this tradeoff using a "discount rate". Discount rates are analogous to the interest rate used for a loan. The question then becomes: is a household willing to incur greater upfront costs to enable energy or emissions savings in the future? Many energy modelers use a "financial" discount rate (commonly between 5% and 10%). However, given the objective of forecasting how households and firms are likely to respond to climate policy, gTech employs "behaviourally" realistic discount rates of between 8% and 25% to simulate technological choice. Research consistently shows that households and firms do not make decisions using a financial discount rate, but rather use significantly higher rates.[2] The implication is that using a financial discount rate would overvalue future savings relative to revealed behavior and provide a poor forecast of household and firm decisions.
Technology specific preferences	In addition to preferences around near-term and long-term costs, households (and even firms) exhibit "preferences" towards certain types of technologies. These preferences are often so strong that they can overwhelm most other factors (including financial ones). For example, buyers of passenger vehicles can be concerned about the driving range and available charging infrastructure of vehicles, some may worry about the risk of buying new technology, and some may see the vehicle as a "status symbol" that they value[3]. gTech quantifies these technology-specific preferences as "non-financial" costs, which are added to the technology choice algorithm. As detailed below, these non-financial preferences are also dynamic, where consumers generally increase their valuation of new technologies as they gain more prominence in the market.
The diverse nature of Canadians	Canadians are not a homogenous group. Individuals are unique and will weigh factors differently when choosing what type of technology to purchase. For example, one household may purchase a Toyota Prius while one neighbour purchases an SUV and another takes transit. gTech uses a "market share" equation in which technologies with the lowest net costs (including all the cost dynamics described above) achieve the greatest market share, but technologies with higher net costs may still capture some market share[4]. As a technology becomes increasingly costly relative to its alternatives, that technology earns less market share.

[2] For example, see: Rivers, N., & Jaccard, M. (2006). Useful models for simulating policies to induce technological change. *Energy policy*, *34*(15), 2038-2047; Axsen, J., Mountain, D.C., Jaccard, M., 2009. Combining stated and revealed choice research to simulate the neighbor effect: The case of hybrid-electric vehicles. Resource and Energy Economics 31, 221-238.

[3] Kormos, C., Axsen, J., Long, Z., Goldberg, S., 2019. Latent demand for zero-emissions vehicles in Canada (Part 2): Insights from a stated choice experiment. Transportation Research Part D: Transport and Environment 67, 685-702.

[4] Rivers, N., & Jaccard, M. (2006). Useful models for simulating policies to induce technological change. *Energy policy*, *34*(15), 2038-2047.

Criteria	Description
Changing costs over time	Costs for technologies are not fixed over time. For example, the cost of electric vehicles has come down significantly over the past couple of years, and costs are expected to continue declining in the future[5]. Similarly, costs for many other energy efficient devices and emissions-reducing technologies have declined and are expected to continue declining. gTech accounts for whether and how costs for technologies are projected to decline over time and/or in response to cumulative production of that technology.
Policy	One of the most important drivers of technological choice is government policy. Current federal and provincial initiatives in Canada are already altering the technological choices households and firms make through various policies: (1) incentive programs, which pay for a portion of the purchasing cost of a given technology; (2) regulations, which either require a group of technologies to be purchased or prevent another group of technologies from being purchased; (3) carbon pricing, which increases fuel costs in proportion to their carbon content; (4) variations in other tax policy (e.g., whether or not to charge GST on a given technology); and (5) flexible regulations, like BC's low-carbon fuel standard which creates a market for compliance credits. gTech simulates the combined effects of all these policies implemented together. Policies included in the forecasting are described in Section 2.4.

Understanding the macroeconomic impacts of policy

As a full macroeconomic model (specifically, a "general equilibrium model"), gTech provides insight about how policies affect the economy at large. The key macroeconomic dynamics captured by gTech are summarised in Table 2.

[5] Nykvist, B., Sprei, F., & Nilsson, M. (2019). Assessing the progress toward lower priced long range battery electric vehicles. *Energy Policy*, 124, 144-155.

Table 2: Macroeconomic dynamics captured by gTech

Dynamic	Description
Comprehensive coverage of economic activity	gTech accounts for all economic activity in Canada as measured by Statistics Canada national accounts[6]. Specifically, it captures all sector activity, all gross domestic product, all trade of goods and services and a large number of transactions that occur between households, firms and government. As such, the model provides a forecast of how government policy affects many different economic indicators, including gross domestic product, investment, household income, etc.
Full equilibrium dynamics	gTech ensures that all markets in the model return to equilibrium (i.e., that the supply for a good or service is equal to its demand). This means that a decision made in one sector is likely to have ripple effects throughout the entire economy. For example, greater demand for electricity requires greater electricity production. In turn, greater production necessitates greater investment and demand for goods and services from the electricity sector, increasing demand for labor in construction services and finally leading to higher wages. The model also accounts for price effects. For example, the electricity sector can pass policy compliance costs on to households, who may alter their demand for electricity and other goods and services (e.g. by switching to technologies that consume other fuels and/or reducing consumption of other goods and services).
Sector detail	gTech provides a detailed accounting of sectors in Canada. In total, gTech simulates how policies affect over 80 sectors of the economy. Each of these sectors produces a unique good or service (e.g., the natural gas sector produces natural gas, while the trucking sector produces transport services) and requires specific inputs into production.
Labor and capital markets	Labor and capital markets must also achieve equilibrium in the model. The availability of labor can change with the "real" wage rate (i.e., the wage rate relative to the consumption level). If the real wage increases, the availability of labor increases. The model also accounts for "equilibrium unemployment". Capital markets are introduced in more detail below.
Interactions between regions	Economic activity in Canada is highly influenced by interactions among provinces and with the United States and countries outside of North America. Each province in the model interacts with other regions via (1) the trade of goods and services, (2) capital movements, (3) government taxation and (4) various types of "transfers" between regions (e.g., the federal government provides transfers to provincial governments). The version of gTech used for this project accounts for 10 Canadian provinces, the three territories in an aggregated region and the United States. The model simulates each of the interactions described above, and how interactions may change in response to policy. In other words, the model can forecast how a policy may affect the trade of natural gas between Canada and the United States; or whether a policy would affect how corporations invest in Canada.

[6] Statistics Canada. Supply and Use Tables. Available from: www150.statcan.gc.ca/n1/en/catalogue/15-602-X

Dynamic	Description
Households	On one hand, households earn income from the economy at large. On the other, households use this income to consume different goods and services. gTech accounts for each of these dynamics, and how either changes with policy.

Understanding energy supply markets

gTech accounts for all major energy supply markets, such as electricity, refined petroleum products and natural gas. Each market is characterized by resource availability and production costs by province, as well as costs and constraints (e.g. pipeline capacity) of transporting energy between regions.

Low carbon energy sources can be introduced within each fuel stream in response to policy, including renewable electricity, bioenergy and hydrogen. The model accounts for the availability and cost of bioenergy feedstocks, allowing it to provide insight about the economic effects of emission reduction policy, biofuels policy and the approval of pipelines.

gTech: The benefits of merging macroeconomics with technological detail

By merging the three features described above (technological detail, macroeconomic dynamics, and energy supply dynamics), gTech can provide extensive insight into the effect of climate and energy policy.

First, gTech can provide insights that would typically be provided by a technologically explicit model. These include answering questions such as:

- How do policies affect technological adoption (e.g. how many electric vehicles are likely to be on the road in 2030)?
- How does technological adoption affect greenhouse gas emissions and energy consumption?

Second, gTech can further provide insights associated with macroeconomic models (in this case “computable general equilibrium” models) by answering questions such as:

- How do policies affect provincial gross domestic product?
- How do policies affect individual sectors of the economy?
- Are households affected by the policy?

- Does the policy affect energy prices or any other price in the model (e.g., food prices)?

Third, gTech answers questions related to its energy supply modules:

- Will a policy generate more supply of renewable fuels?
- Does policy affect the cost of transporting natural gas, and therefore the price for natural gas in Canada?

Finally, gTech expands our insights into areas where there is overlap between its various features:

- What is the effect of investing carbon revenue into low- and zero-carbon technologies? This answer can only be answered with a model such as gTech.
- What are the macroeconomic impacts of technology-focused policies (e.g. how might a zero-emissions vehicle standard impact GDP)?
- Do biofuels focused policies affect (1) technological choice and (2) the macroeconomy?

This modeling toolkit allows for a comprehensive examination of the impacts of policies to boost ZEV adoption in Canada.

2.3. Simulating ZEV-related dynamics

As part of this project, we conducted a literature review to determine how best to characterize several ZEV dynamics, including the mechanisms behind declining capital costs and changing consumer preferences for ZEVs. Based on our review, we added endogenous declining capital cost and declining intangible cost functions to the model, which are described below.

2.3.1. Declining capital costs

The cost of a technology may decline as a function of cumulative production experience with that technology, known as “learning by doing”. This dynamic has been observed in a wide variety of contexts, such as aircraft manufacturing, chemical processing, agricultural technology, shipbuilding and automobile manufacturing[7].

[7] Bollinger, B., & Gillingham, K. (2014). Learning-by-doing in solar photovoltaic installations. Available at SSRN 2342406.

Learning by doing is a common lens through which to examine the cost of new energy technologies and how they might change in the future, including ZEVs. It can be formalized using the declining capital cost function, which has been incorporated into gTech:

$$CC_j(t) = CC_j(t_0)\left(\frac{N_j(t)}{N_j(t_0)}\right)^{log_2 PR_j}$$

Where each emerging technology's capital cost (CC_j) declines based on its progress ratio (PR_j) until the technology reaches maturity (defined by a capital cost floor), $N_j(t)$ is the cumulative production at time (t) and $N_j(t_0)$ is the base stock, or cumulative production in the model's base year[8].

Normally, this function is specified at a global level, considering cumulative production across all countries. Our function differentiates between Canadian ZEV production and rest-of-world ZEV production. Including this dynamic in the forecasting allows us to represent the extent to which Canadian policy can accelerate cost reductions (i.e., if it results in greater production of ZEVs).

Battery cost assumptions

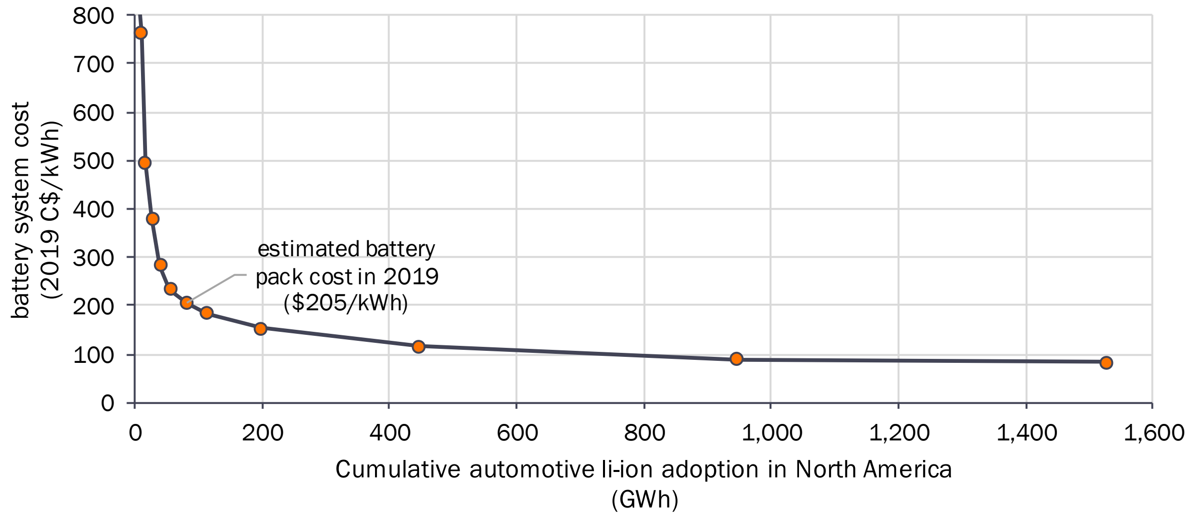
Anticipated global cumulative adoption is inferred from Bloomberg's 2019 Electric Vehicle Outlook[9] and the corresponding battery cost forecasts are also sourced from Bloomberg[10]. Canada and the US are assumed to represent 20% of that adoption, in line with data from recent years. Figure 5 shows the battery cost decline that is parametrized in the model (in Canadian dollars).

[8] Jaccard, M., 2009. Combining top down and bottom up in energy economy models. In: Evans, J., Hunt, L.C. (Eds.), International Handbook on the Economics of Energy. Edward Elgar, Northampton, pp. 311–331.

[9] Bloomberg New Energy Finance. (2019). *Electric Vehicle Outlook 2019*. Retrieved on 11/8/2019 from: https://about.bnef.com/electric-vehicle-outlook/

[10] Goldie-Scot, L. (2019). *A Behind the Scenes Take on Lithium-ion Battery Prices.* Retrieved on 11/8/2019 from: https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

Figure 5: Battery pack cost decline as a function of cumulative adoption (in Canadian dollars)



Note: Graph edited to only show costs below $800/kWh. Data starts at $1,530/kWh.

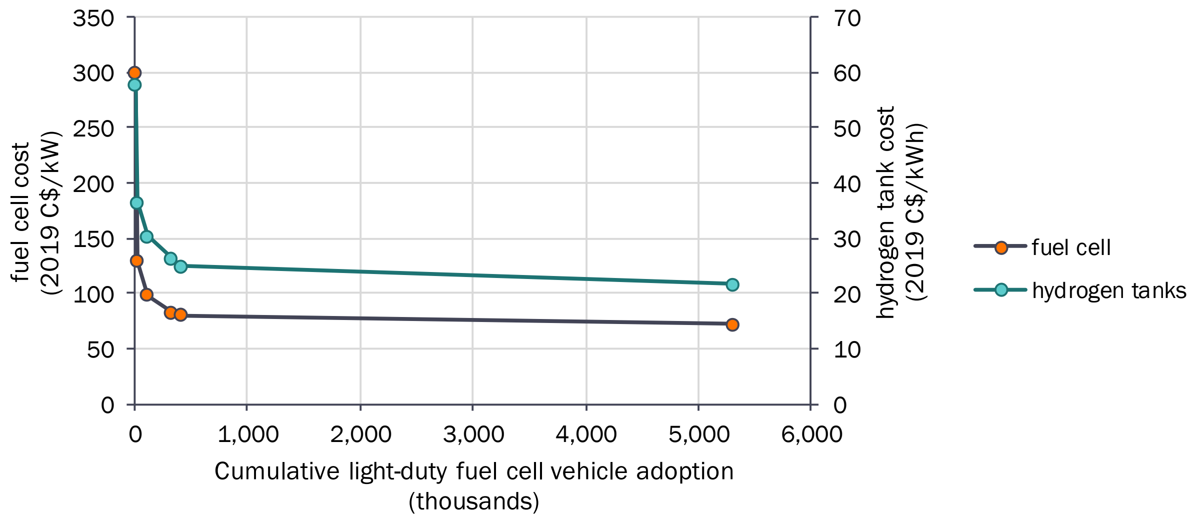
Fuel cell cost assumptions

Fuel cell vehicle cost components are collected from Strategic Analysis Consultants' work for the U.S. Department of Energy[11]. Figure 6 shows how the cost of light-duty vehicle fuel cell components decline as a function of light-duty fuel cell vehicle adoption. This trend is based on fuel cell drivetrains with a fuel cell stack output of 80 kW_{net} and a 185-kWh storage (the tank holds roughly 4.75 kg of hydrogen).

Note that this vehicle specification differs somewhat from the archetypal light-duty fuel cell vehicle included in the model. Heavy-duty vehicle fuel cell components are more expensive per unit output but follow a similar cost trajectory. The model accounts for the varying sizes of vehicles when considering deployment. For example, a heavy-duty fuel cell truck contributes 2.3 times more to the cumulative fuel cell system deployment and 2.6 times more to the storage tank deployment than a light-duty fuel cell vehicle.

[11] Strategic Analysis Consultants. (2017). *Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2016 Update. Available from:* *https://www.energy.gov/sites/prod/files/2017/06/f34/fcto_sa_2016_pemfc_transportation_cost_analysis.pdf; James, B.D.. (2019). 2019 DOE Hydrogen and Fuel Cells Program Review Presentation*. Available from: https://www.hydrogen.energy.gov/pdfs/review19/fc163_james_2019_o.pdf

Figure 6: Light-duty fuel cell system cost decline as a function of cumulative adoption



Since fuel cell drivetrain costs are modelled with two components, the combined rate of decline varies by vehicle category. For example, the fuel cell component represents 87% of the overall fuel cell system cost for heavy-duty vehicles. Therefore, a heavy-duty fuel cell vehicle's overall cost will decline at a rate that is more similar to the fuel cell component than to the fuel tank component.

2.3.2. Consumer preferences

As noted in Table 1 above, a wide range of financial and non-financial factors influence decisions regarding the purchase and use of vehicles. For example, consumers and firms may not view a ZEV as being a perfect substitute for a conventional vehicle because of real or perceived risk of failure, higher upfront costs or a lack of information. Accounting for these factors (and how they may change) is important for developing a plausible forecast of ZEV adoption.

gTech simulates consumer purchase decisions using the following market competition algorithm:

$$MS_j = \frac{LCC_j^{\ -v}}{\sum_{k=1}^{K}\{LCC_K^{\ -v}\}}$$

Where new vehicle market share is allocated based on each technology's lifecycle costs (LCC_j) compared to the lifecycle costs of all available technologies (LCC_K). The definition of lifecycle costs includes both conventional financial factors (e.g. capital, maintenance and energy costs) as well as parameters that represent consumer preferences and other "non-financial cost differences".

These factors include:

- **Revealed discount rate.** A discount rate represents how car buyers weigh upfront capital costs compared to ongoing annual operating and energy costs. A discount rate can also be thought of as representing the time value of money, or the opportunity cost of capital. Financial discount rates are interest rates used by banks; that is, they're the return on investment that would be required to make a capital stock investment. However, sales data suggests that consumers often apply implicit discount rates that are higher than financial discount rates. For example, buyers of passenger vehicles are found to be fairly short-sighted, requiring a payback period of 3-4 years for an investment in a more fuel-efficient vehicle, which translates to a discount rate of up to 25% (our assumption in gTech)[12]. These discount rates take into account the general tendency for people to place more value on present costs than the future savings, as well as perceptions of uncertainty in future fuel savings.

- **Intangible costs.** Intangible costs are a way to represent all the non-financial factors that influence car buyers, such as perceived risk of ZEVs, lack of model variety and availability, lack of consumer awareness and other perceptions (e.g. safety and aesthetics). Some intangible costs may remain relatively constant over time (for example, some people may always consider it less convenient to take public transit than drive a car). However, other intangible costs may decline as a technology gains broader market share (for example, if electric vehicles become widespread and fast charging stations are broadly deployed, concerns about running out of a battery charge would decline). We discuss intangible cost assumptions below.

- **Market heterogeneity.** This parameter (v in the above equation) accounts for how not all consumers are identical or face identical circumstances. First, consumers may face different financial factors. For example, driving patterns will influence the cost of owning an electric vehicle, whereby a more intensely used vehicle will help offset the high capital cost with lower operating costs. The availability of technologies may also differ among regions. For example, vehicle retailers in one region may have more ZEV models available than in another region[13]. Lastly, consumers may differ in terms of their perceptions of risk, their perceptions of

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[12] Mau, P., J. Eyzaguirre, et al. (2008). "The `neighbor effect': Simulating dynamics in consumer preferences for new vehicle technologies." Ecological Economics 68(1-2): 504-516; Axsen, J., D. C. Mountain, et al. (2009). "Combining stated and revealed choice research to simulate the neighbor effect: The case of hybrid-electric vehicles." Resource and Energy Economics 31(3): 221-238.

[13] Lutsey, N. and S. Slowik (2018). The Continued Transition to Electric Vehicles in U.S. Cities. San Francisco, USA, The International Council on Clean Transportation (ICCT).

quality, their willingness to incur high upfront costs, and the information available to them[14]. In line with previous studies, we use a value of 10 for this parameter[15].

How are dynamic consumer preferences included in gTech?

Recent research suggests that intangible costs (i_j) include a fixed portion that does not change (i_{Fj}) and a variable portion (i_{Vj}) that declines as a technology gains market share[16]. Fixed intangible costs represent patterns in consumer preferences that are assumed to be stable (e.g. North American preferences for larger vehicles). Variable intangible costs decline according to the following formula in gTech:

$$i_{Vj}(t) = \frac{i_{Vj}(t_0)}{1 + Ae^{k*MS_j(t-1)}}$$

Where the variable intangible cost (i_{Vj}) of a given technology in time (t) depends on its initial variable intangible cost (i_{Vj} in time t_0), its market share in the previous period (MS_j in time $t-1$) and two constants (A and k) that define the shape of the intangible cost curve and the rate at which intangible costs decline from an increase in market share.

Intangible cost assumptions: Initial values

The intangible costs in the model apply to the following technology and energy-end use groups:

- Light-duty plug-in electric vehicles
- Light-duty hydrogen fuel cell electric vehicles
- Medium and heavy-duty plug-in electric vehicles (including buses)
- Medium and heavy-duty hydrogen fuel cell electric vehicles (including buses)
- Medium and heavy-duty natural-gas fuelled vehicles (including buses)

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14 Axsen, J., J. Bailey, et al. (2015). "Preference and lifestyle heterogeneity among potential plug-in electric vehicle buyers." Energy Economics 50: 190-201.

15 Rivers, N., & Jaccard, M. (2005). Combining top-down and bottom-up approaches to energy-economy modeling using discrete choice methods. The Energy Journal, 83-106.

16 For example, see: Sykes, M., & Axsen, J. (2017). No free ride to zero-emissions: Simulating a region's need to implement its own zero-emissions vehicle (ZEV) mandate to achieve 2050 GHG targets. Energy Policy, 110, 447-460.

The intangible costs for light-duty vehicles were selected to make a gTech simulation emulate the results of the REspondent-based Preferences and Constraints (REPAC) model. REPAC is a detailed forecasting model that simulates the extent to which consumers may adopt alternative fuel vehicles subject to their own valuation of the attributes of those vehicles (e.g. cost, range, powertrain type etc.). REPAC accounts for the barriers to adoption that they experience, namely a lack of knowledge about those vehicles, a lack of choice or availability and a lack of recharge access. It is parameterized using survey data from over 1,500 participating new car buyers in Canada.[17] The intangible costs applied to medium and heavy-duty vehicles are taken from Hammond et. al (2020)[18], expressed as a proportion of the full vehicle capital costs (e.g. capital cost for a vehicle glider and powertrain). The intangible costs applied to each technology archetype are noted with other technology parameters (see the Appendix).

Declining intangible cost assumptions

The intangible costs that apply to alternative fuel vehicles decline as a function of new market share (i.e. % of annual sales). The decline follows a logistic curve where increasing sales correspond to reduced intangible costs. In other words, as an emerging technology transitions to become a niche technology and then a mainstream technology, the associated intangible costs are reduced and then eliminated.

Our assumption for the rate of decline corresponds to an intangible cost that reaches roughly 50% of its starting value when a technology accounts for 12% of new market share, and 5% of its starting value at 20% new market share (Figure 7). This rate of decline is consistent with the values used in other technology adoption studies that account for these intangible costs, e.g. Hammond et al. (2020)[19] and Sykes and Axsen (2017)[20].

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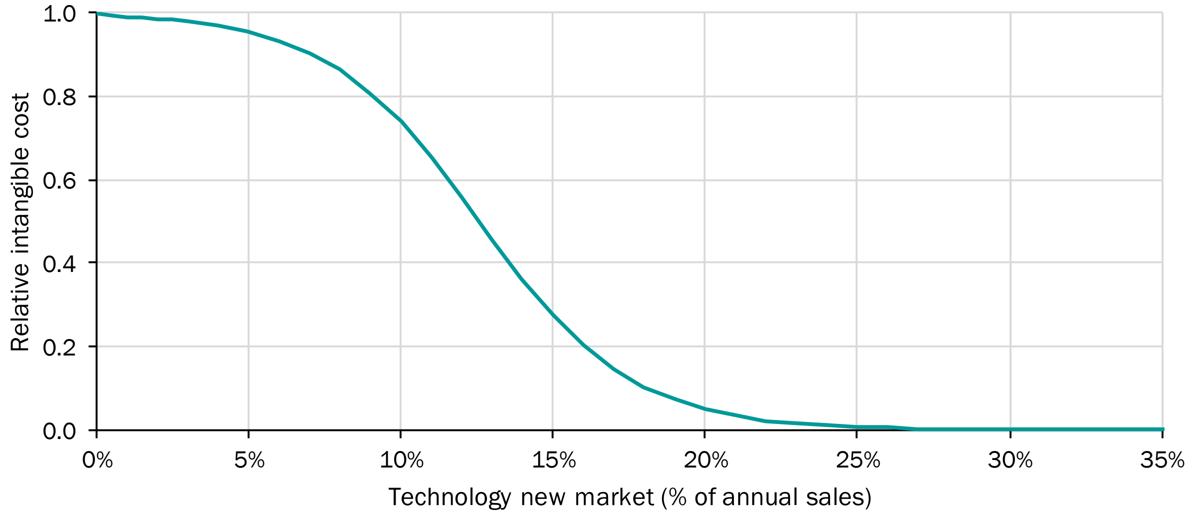
[17] Wolinetz, M., Axsen, J. (2018). Reaching 30% plug-in vehicle sales by 2030: Modeling incentive and sales mandate strategies in Canada. Transportation Research Part D, 65, 596-617. https://doi.org/10.1016/j.trd.2018.09.012

[18] Hammond, W., Axsen, J., Kjeang, E., 2020. How to slash greenhouse gas emissions in the freight sector: Policy insights from a technology-adoption model of Canada. *Energy Policy 137*, 111093. https://doi.org/10.1016/j.enpol.2019.111093

[19] Ibid.

[20] Sykes, M., Axsen, J. (2017). *No free ride to zero-emissions: Simulating a region's need to implement its own zero-emissions vehicle (ZEV) mandate to achieve 2050 GHG targets.* Energy Policy, 110, 447-460. http://dx.doi.org/10.1016/j.enpol.2017.08.031

Figure 7: Declining intangible cost trends



A technology's intangible cost is affected by both provincial new market share (i.e. "regional") and North American new market share (i.e. "global"). Sykes and Axsen (2017) conceptualized "regional" effects relating to access to refueling/recharging infrastructure, availability of vehicles in a regional market, perceptions amongst peers and access to information through social networks. "Global" effects might relate to the real or perceived performance of new technologies and the perception of the risk of technology failure[21]. Half of the intangible cost in this analysis is subject to "regional" market share, while the other half is affected by "global" market share, consistent with Sykes and Axsen's baseline assumption.

Finally, intangible costs decline across the six technology groups listed in the previous section rather than only for a single technology archetype. For example, if a light-duty battery-electric vehicles gain market share, the intangible cost of light-duty plug-in hybrids also declines. However, that does not affect the intangible cost applied to fuel cell vehicles or medium and heavy-duty vehicles.

[21] Ibid

2.4. Policies to support ZEV adoption

We develop several forecasts of ZEV adoption, reflecting the impact of both current ZEV-supportive policies implemented in Canada and potential stronger policy options.

2.4.1. Current ZEV-supportive policies

The following ZEV-supportive policies are included in the current policy forecast.

- **Federal policies**
  - **Federal ZEV purchase incentives.** Between $2,500 and $5,000 for new battery electric and plug-in hybrid electric vehicles (depending on their electric range) from the federal government[22]. We assume the government to phase out the program when it depletes its $300 million in funds, which is anticipated to be by 2021.
  - **Regulations Amending the Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations[23].** New passenger vehicles and light-commercial vehicles/light trucks sold in Canada must meet fleet-wide greenhouse gas emission standards. The combined requirement for cars and light trucks in 2025 is 119 g CO_2/km, about 30% below the current required fleet average. Although this policy doesn't directly require the deployment of zero emission vehicles, selling such vehicles helps manufacturers comply with the policy.
  - **Carbon Pollution Pricing System[24].** The carbon levy reaches $50 per tonne CO_2e by 2022 and is constant thereafter in nominal terms. The carbon price increases the cost of fossil fuels relative to low-carbon electricity, increasing the fuel-cost savings associated with operating an electric vehicle.

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[22] Transport Canada. 2019. *Zero-emission vehicles*. Available from: www.tc.gc.ca/en/services/road/innovative-technologies/zero-emission-vehicles.html

[23] Government of Canada. 2018. *Regulations Amending the Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations*. Available from: www.gazette.gc.ca/rp-pr/p2/2014/2014-10-08/html/sor-dors207-eng.html

[24] Government of Canada. 2019. *Pricing pollution: how it will work*. Available from: www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work.html

- **Provincial policies**

  - **Québec Zero Emission Vehicle Standard[25].** Automakers that sell over 4,500 vehicles in the province are required to meet a minimum zero-emission vehicle credit quota. The credit requirement is set to rise from 3.5% in 2018 to 22% of non-ZEV sales by 2025. The government's own impact assessment estimates that the policy will result in zero-emission vehicles accounting for 9.9% of new sales in 2025.

  - **British Columbia's Zero Emission Vehicle Standard[26].** British Columbia is set to introduce a Zero Emission Vehicle standard similar to the one implemented in Québec. The standard will require that zero-emission vehicles make up 10% of light-duty vehicle sales by 2025, 30% by 2030, and 100% by 2040.

  - **Provincial ZEV purchase incentives.** Incentives between $500 and $14,000 in British Columbia, Ontario, and Québec[27]. Ontario's incentives were phased out in 2018.

  - **British Columbia's Renewable and Low Carbon Fuel Requirement Regulation[28].** British Columbia introduced this policy in 2008. It includes two components: 1) a minimum renewable fuel content for gasoline (5% by volume) and diesel (4% by volume); and 2) a decrease in average carbon intensity of fuels by 10% by 2020 relative to 2010. Fuel suppliers can meet the second requirement by acquiring credits generated from fuelling electric vehicles.

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25 Gouvernement du Québec. 2017. *Analyse d'impact réglementaire du règlement d'application de la Loi visant l'augmentation du nombre de véhicules automobiles zéro émission au Québec afin de réduire les émissions de gaz à effet de serre et autres polluants*. Available from: http://www.environnement.gouv.qc.ca/changementsclimatiques/vze/AIR-reglement201712.pdf

26 Government of British Columbia. 2019. *Zero Emission Vehicle Legislation*. Available from: https://engage.gov.bc.ca/govtogetherbc/consultation/zero-emission-vehicle-legislation/

27 Ontario Ministry of Transportation. 2017. *Eligible Electric Vehicles Under the Electric Vehicle Incentive Program and Electric Vehicle Incentives*. Accessed on 10/26/2017 at: http://www.mto.gov.on.ca/english/vehicles/electric/electric-vehicle-rebate.shtml; Government of British Columbia. 2019. *CEVforBC™ Vehicle Incentive Program*. https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/clean-transportation-policies-programs/clean-energy-vehicle-program/cev-for-bc; Gouvernement du Québec. 2019. *Discover Electric Vehicles*. https://vehiculeselectriques.gouv.qc.ca/english/

28 Government of British Columbia. 2019. *Renewable and Low Carbon Fuel Requirements Regulation Summary: 2010-2017*. Available from: https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/rlcf007_-_2017_summary_2010-17v2.pdf

- **Amendment to British Columbia's Renewable and Low Carbon Fuel Requirement Regulation[29].** The province has announced its intention to extend its carbon intensity requirement. Suppliers will have to achieve a 20% reduction in their fuel carbon intensity by 2030 relative to 2010.

2.4.2. Stronger ZEV-supportive policies

We examine the impact of several national policies that increase support for both ZEV adoption and ZEV manufacturing. These policies are summarized in Table 3 and include:

- **National ZEV mandates** for different types of road vehicles:
  - Light-duty ZEV mandate. This policy requires that all new light-duty vehicles sold in Canada be ZEVs by 2040. It is based on BC's policy.
  - Medium-duty ZEV mandate. This policy requires that half of all new medium-duty vehicles sold in Canada be ZEVs by 2030, based on California's proposed Advanced Clean Trucks Regulation[30].
  - Heavy-duty ZEV mandate. This policy requires that 15% of new heavy-duty vehicles sold in Canada be ZEVs by 2030, also based on California's proposed policy.
- **A ZEV production incentive** provided to domestic manufacturers. This subsidy covers 10% of the cost of ZEVs manufactured in Canada and is analogous to a tax incentive.

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[29] Government of British Columbia. 2018. *CleanBC plan to reduce climate pollution, build a low-carbon economy*. Available from: https://news.gov.bc.ca/releases/2018PREM0088-002338

[30] California Air Sources Board. 2019. Advanced Clean Trucks Fact Sheet. https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-trucks-act-fact-sheet

Table 3: Summary of stronger ZEV-supportive policies

Policy	*Unit*	2025	2030	2035	2040
Light-duty ZEV mandate	*% of new vehicle sales*	10%	30%	65%	100%*
Medium-duty ZEV mandate	*% of new vehicle sales*	9%	50%	50%	50%
Heavy-duty ZEV mandate	*% of new vehicle sales*	5%	15%	15%	15%
ZEV production incentive	*% of ZEV costs*	10%	10%	10%	10%

* For computational reasons, this policy is simulated as 95% rather than 100%.

2.4.3. Policy in the US

We examine how the level of ZEV policy implemented in the US (modeled with a national ZEV mandate) may affect ZEV costs, ZEV demand and ZEV manufacturing in Canada. In particular, we explore the impact of a scenario in which the US implements a national ZEV mandate that achieves equivalent outcomes as the strong Canadian policies described above (i.e., 100% light-duty ZEV sales by 2040). This policy will result in greater ZEV manufacturing, and hence lower the costs of ZEVs in Canada.

2.5. Uncertainty

Despite using the best available forecasting methods and assumptions, the evolution of our energy economy is uncertain. In particular, forecasting technological change is subject to two main types of uncertainty.

First, all models are simplified representations of reality. Navius' gTech model is, effectively, a series of mathematical equations that are intended to forecast the future. This raises key questions: "are the equations selected a good representation of reality?" and "do the equations selected overlook important factors that may influence the future?"

The use of computable general equilibrium models (gTech) is well founded in the academic literature. In addition, Navius undertakes significant efforts to calibrate and back-cast the model to ensure that it captures key dynamics in the energy-economic system.

Nevertheless, Navius' tools do not account for every dynamic that will influence technological change. For example, household and firm decisions are influenced by many factors, which cannot be fully captured by even the most sophisticated model.

The inherent limitation of energy-economic forecasting is that virtually all projections of the future will differ, to some extent, from what ultimately transpires.

Second, the assumptions used to parameterize the models are subject to uncertainty. These assumptions include, but are not limited to, oil prices, improvements in labor productivity and the rate of improvement in battery technologies. If any of the assumptions used prove incorrect, the resulting forecast could be affected.

Nevertheless, gTech is the most comprehensive model available for forecasting the techno-economic impacts of climate policy in Canada. Its representation of technological change, macroeconomic dynamics and fuels markets (as described above) mean that it is ideally positioned to forecast how the broad range of policies implemented in Canada will affect technological change, energy consumption, greenhouse gas emissions, the economy and a large array of other indicators.

3. Simulating ZEV adoption and economic activity to 2040

How is ZEV adoption likely to evolve in Canada? This Chapter presents several forecasts of ZEV adoption in response to both current and stronger ZEV-supportive policies. It also quantifies the extent to which ZEVs could contribute to Canada's economy in the future.

3.1. What is the impact of current policies on ZEV adoption and economic activity?

3.1.1. ZEV sales

ZEV sales are likely to continue to grow in Canada in response to declining battery costs and current ZEV-supportive policies (described in Sections 2.3 and 2.4). By 2040, ZEVs are projected to account for 14% of new light-duty vehicle sales, 11% of medium-duty vehicle sales, 13% of heavy-duty vehicle sales, and 26% of bus sales (see Figure 8 through Figure 11). This level of adoption is below Canada's light-duty ZEV target of 30% by 2030 and 100% by 2040[31].

This growth in electric vehicle adoption is driven by:

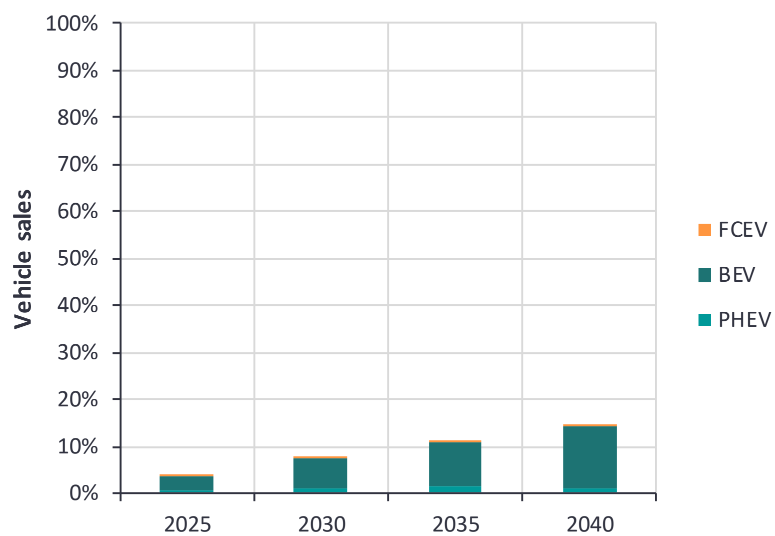
- Declining battery costs. Since 2010, battery system costs have declined from over $1,000/kWh to around $250/kWh in 2019 (in Canadian dollars). As described in Section 2.3.1, costs could fall below $100/kWh depending on the extent of growth in global battery production.
- Existing electric vehicle-supportive policies. Most notable of these policies are in BC and Québec, which both require that an increasing share of new light-duty vehicles are zero emission.

[31] Natural Resources Canada. 2019. *Zero-emission vehicle infrastructure program*. Available from: https://www.nrcan.gc.ca/zero-emission-vehicle-infrastructure-program/21876

- Changing consumer preferences. For example, as electric vehicles become widespread and fast charging stations are broadly deployed, concerns about running out of a battery charge decline.

Plug-in electric vehicles, including battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs), are the ZEV technology of choice across most vehicle types as shown in the figures below. An exception is in heavy-duty vehicles, where hydrogen fuel cell technology accounts for about half of ZEV sales in that class. The use of batteries in heavy-duty vehicles, particularly long-haul trucking, is challenging due to battery weight and range. Cold temperature impacts on battery performance are also expected to be an important limiting factor for battery electric trucks in Canada[32]. Conversely, fuel cell vehicles may become more competitive with diesel trucks if they are produced at scale and powered by low cost hydrogen.

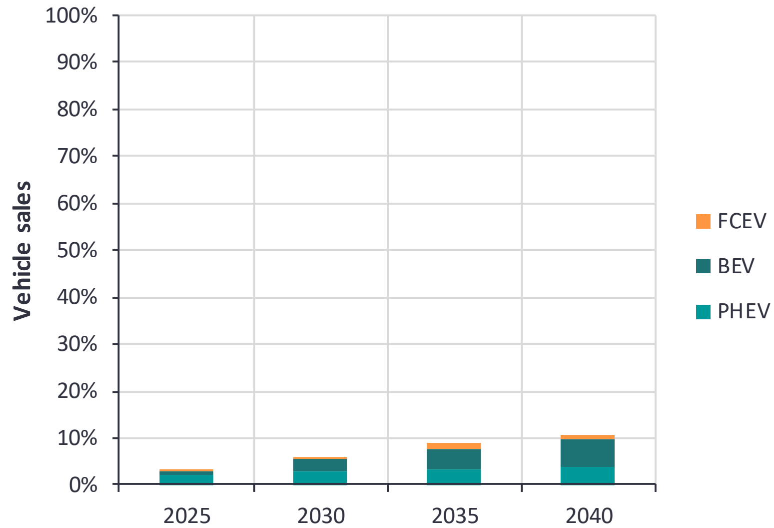
Figure 8: Light-duty vehicle sales under current policy



Note: FCEV = fuel cell electric vehicle, BEV = battery electric vehicle, and PHEV = plug-in hybrid electric vehicle.

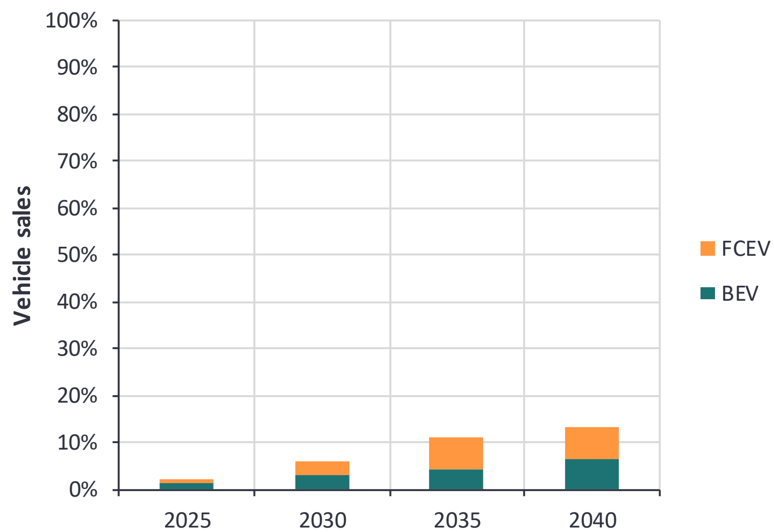
[32] Sharpe. B. 2019. Zero emission tractor-trailers in Canada. The International Council on Clean Transportation. Available from: https://theicct.org/sites/default/files/publications/ZETractorTrailers%20Working%20Paper042019.pdf

Figure 9: Medium-duty vehicle sales under current policy



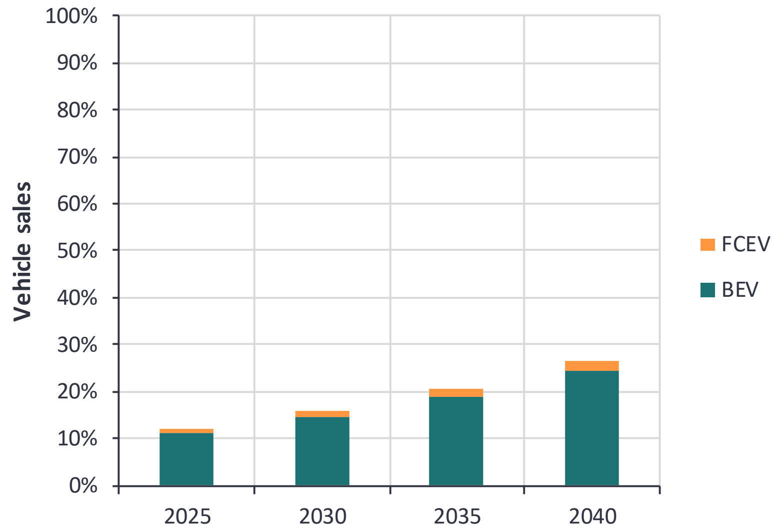
Note: FCEV = fuel cell electric vehicle, BEV = battery electric vehicle, and PHEV = plug-in hybrid electric vehicle.

Figure 10: Heavy-duty vehicle sales under current policy



Note: FCEV = fuel cell electric vehicle and BEV = battery electric vehicle.

Figure 11: Bus sales under current policy

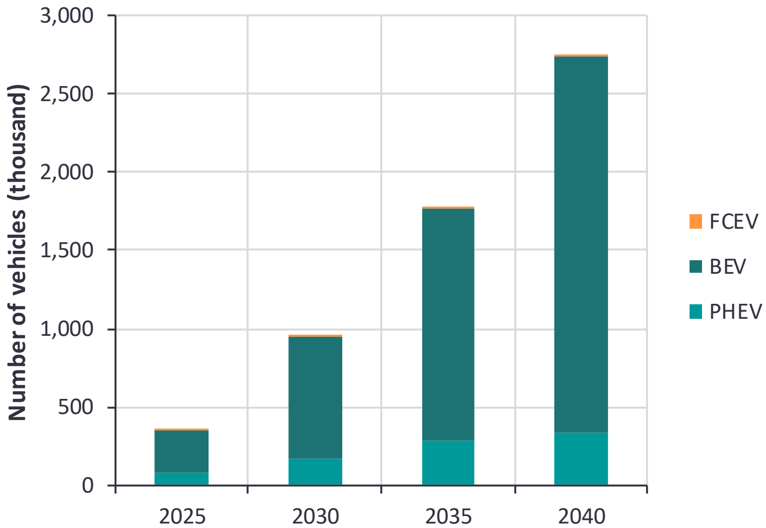


Note: FCEV = fuel cell electric vehicle and BEV = battery electric vehicle.

3.1.2. Number of ZEVs on the road

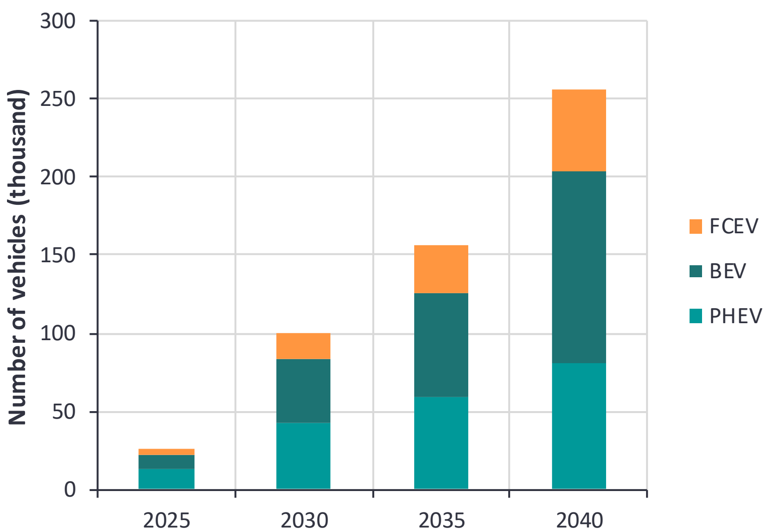
As ZEV sales increase, so will the number of electric vehicles on Canadian roads. By 2040, 2.7 million light-duty vehicles and 257 thousand medium and heavy-duty vehicles are expected to be electric (see Figure 12 and Figure 13). This number of vehicles equates to 10% of all light-duty vehicles on the road and 9% of all medium and heavy-duty vehicles. Of these, virtually all light-duty vehicles are plug-in electric, whereas over 20% of medium and heavy-duty vehicles are powered by hydrogen.

Figure 12: Light-duty ZEVs on the road under current policy



Note: FCEV = fuel cell electric vehicle, BEV = battery electric vehicle, and PHEV = plug-in hybrid electric vehicle.

Figure 13: Medium & heavy-duty ZEVs on the road under current policy



Note: FCEV = fuel cell electric vehicle, BEV = battery electric vehicle, and PHEV = plug-in hybrid electric vehicle.

3.1.3. ZEV economy

Building on earlier work that explored the contribution of clean energy to Canada's economy[33], we quantify the following ways that electric vehicles contribute to economic activity:

- **Vehicle manufacturing.** Electric vehicles currently manufactured in Canada include the plug-in hybrid Chrysler Pacifica minivan, the New Flyer Xcelsior® CHARGE™ transit bus, the Nova Bus LFSe transit bus and The Lion Electric Co school bus[34].
- **Transport services.** When purchased by businesses, electric vehicles are used to generate value-added by transporting freight and passengers. In other words, this category represents the share of total transport services that are electric. Most electric vehicle adoption in Canada to date has been by households (whose use doesn't directly contribute to GDP), although this is likely to change in the future.
- **Other services.** The purchase of electric vehicles supports a variety of other economic activities, such as retailing, maintenance and construction of charging infrastructure.

The contribution of ZEVs to Canada's economy is quantified in Figure 14 and Figure 15, which show a rapid increase in GDP and jobs associated with the ZEV economy. GDP grows from $1.1 billion (2015$) in 2020 to $43 billion in 2040. At the same time, the number of jobs increases from 11 thousand in 2020 to 342 thousand in 2040.

For context, the ZEV economy's GDP grows at an average annual rate of 18%, whereas growth in the rest of the economy is in the range of 2%, in response to current policies.

Most ZEV-related economic activity (about 92%) comes from providing transport services (i.e., transporting people and goods in electric vehicles). Economic growth from transport services is rapid over this timeframe because it is based on the total number of ZEVs on the road (i.e., cumulative sales). Other activities contribute to the ZEV economy to a lesser degree, including domestic vehicle manufacturing (6%) and other services (2%).

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[33] Building on work Navius Research. 2019. Quantifying Canada's Clean Energy Economy. Prepared for Clean Energy Canada. https://cleanenergycanada.org/report/the-fast-lane-tracking-the-energy-revolution-2019/

[34] Fiat Chrysler Automobiles. (2016). *Windsor Assembly Plant Launches Production of Industry's First-ever Hybrid Minivan*. Available from: https://media.fcanorthamerica.com/newsrelease.do?id=18026; New Flyer. 2018. *All New Flyer facilities now capable of manufacturing Xcelsior CHARGE™ battery-electric buses*; Nova Bus. 2017. *Nova Bus announces increase in production*. Available from: http://novabus.com/nova-bus-announces-increase-production/; School Bus Fleet. 2018. *Lion Delivers 13 Electric School Buses for Ontario Pilot Project*. Available from: https://www.schoolbusfleet.com/news/729700/lion-delivers-13-electric-school-buses-for-ontario-pilot-project

Note that estimates of future ZEV manufacturing in Canada are uncertain. This forecast assumes that an increase in electric vehicle demand translates into increased vehicle manufacturing in Canada based on historical relationships between auto demand, imports and relative costs of production. While this approach is reasonable, it is important to note that decisions to invest in domestic manufacturing are uncertain and likely depend on factors beyond those considered in this forecasting.

Figure 14: ZEV-related GDP under current policy

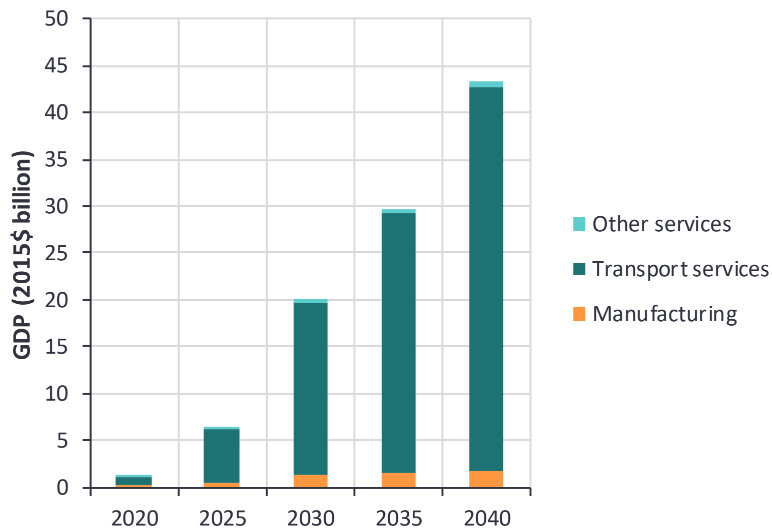
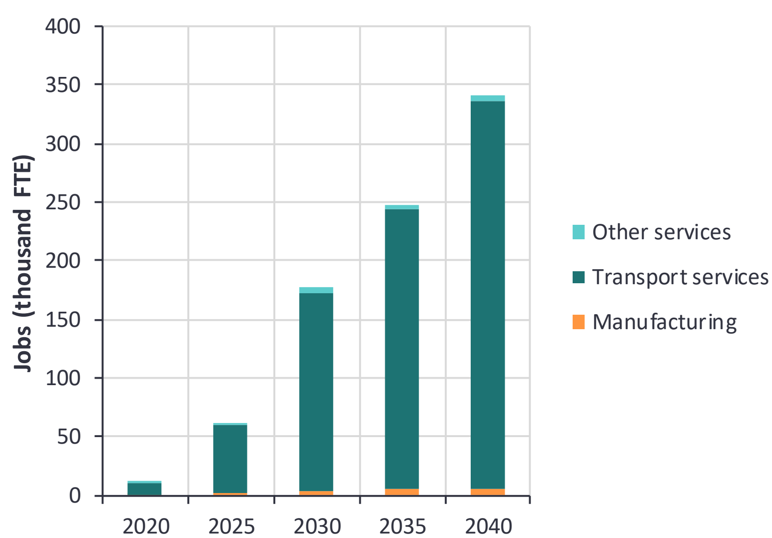


Figure 15: ZEV-related jobs under current policy



3.2. What is the impact of stronger policy to support ZEV adoption?

The forecasts above demonstrate that Canada is unlikely to achieve its ZEV target (30% of new light-duty vehicle sales by 2030 and 100% by 2040) without the introduction of new policies or the strengthening of existing policies. This section quantifies the impact of a national policy approach that increases support for both ZEV adoption and domestic ZEV manufacturing. This policy approach includes a national ZEV mandate for light, medium and heavy-duty vehicles, as well as a ZEV production incentive for domestic manufacturers. These policies are described in Section 2.4.

3.2.1. ZEV sales

A single policy – a strong zero emission vehicle mandate with national coverage – could achieve Canada's targets for ZEV adoption. Figure 16 through Figure 18 show the impacts of such a policy, based on regulations implemented in BC[35] (for light-duty vehicles) and being developed in California[36] (for medium and heavy-duty vehicles). This policy requires that zero emission vehicles account for 100% of light duty vehicle sales, 50% of medium-duty sales and 15% of heavy-duty sales by 2040.

While the ZEV mandate requires that an overall percentage of sales be ZEVs, it provides flexibility in which types of ZEVs can be used to comply. Based on current expectations about technology performance and costs, plug-in electric vehicles are likely to be the dominant choice for complying with the standard for light and medium-duty vehicles, while hydrogen fuel cell vehicles are a stronger candidate for heavy-duty vehicles.

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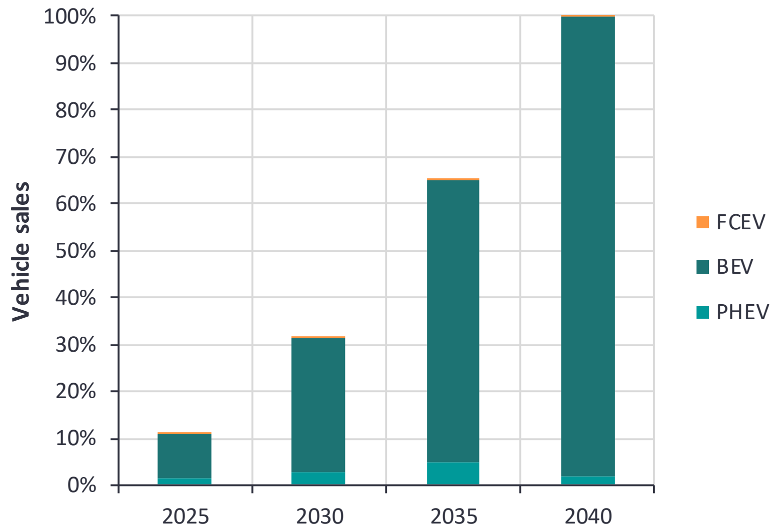
[35] Government of British Columbia. 2019. *Zero Emission Vehicle Legislation*. Available from: https://engage.gov.bc.ca/govtogetherbc/consultation/zero-emission-vehicle-legislation/

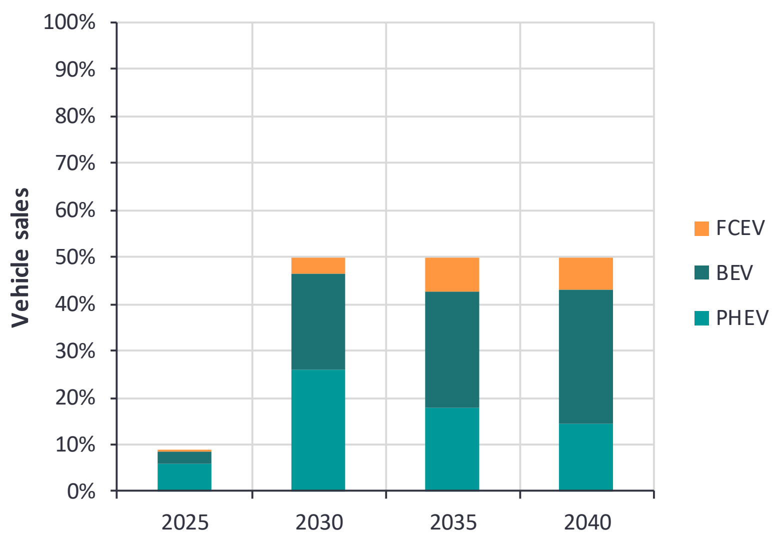
[36] California Air Sources Board. 2019. Advanced Clean Trucks Fact Sheet. https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-trucks-act-fact-sheet

Figure 16: Light-duty vehicle sales in response to a national ZEV mandate



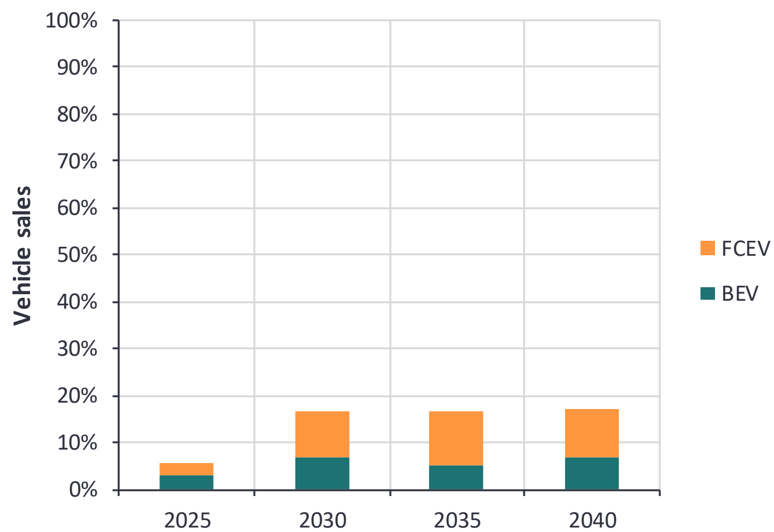
Note: FCEV = fuel cell electric vehicle, BEV = battery electric vehicle, and PHEV = plug-in hybrid electric vehicle.

Figure 17: Medium-duty vehicle sales in response to a national ZEV mandate



Note: FCEV = fuel cell electric vehicle, BEV = battery electric vehicle, and PHEV = plug-in hybrid electric vehicle.

Figure 18: Heavy-duty vehicle sales in response to a national ZEV mandate

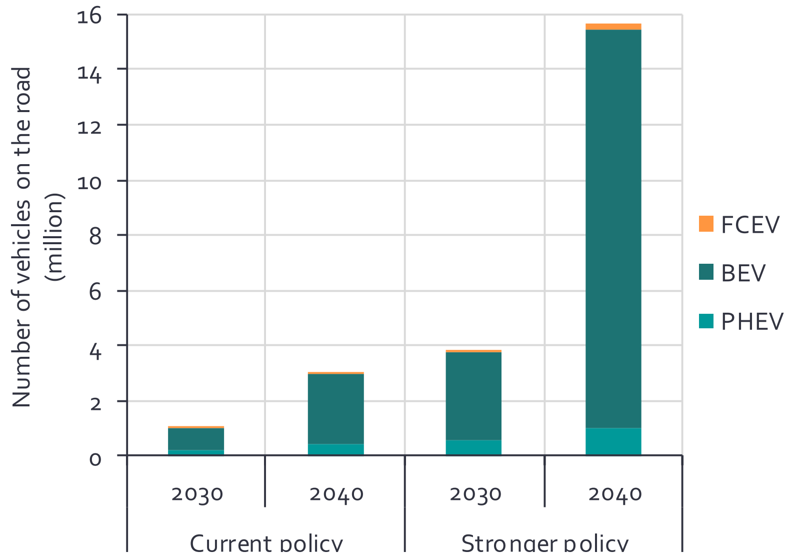


Note: FCEV = fuel cell electric vehicle and BEV = battery electric vehicle.

3.2.2. Number of ZEVs on the road

A strong national ZEV-supportive policy could lead to significantly more ZEVs on Canadian roads. By 2040, 15.6 million ZEVs could be on the road, up from 3 million as expected under current policy. This number of vehicles corresponds to 56% of all light-duty vehicles, 44% of all medium-duty vehicles and 15% of all medium and heavy-duty vehicles on the road by 2040. Most of these vehicles (14.4 million) are light-duty vehicles, in part because the ZEV mandate is strongest for these vehicles and in part because the market for light-duty vehicles (measured in number of vehicles) is much larger than that of medium and heavy-duty vehicles.

Figure 19: Number of ZEVs on the road in response to a national ZEV mandate



Note: FCEV = fuel cell electric vehicle, BEV = battery electric vehicle, and PHEV = plug-in hybrid electric vehicle.

3.2.3. Battery and fuel cell costs

Battery and fuel cell costs are expected to continue to decline (see Figure 20 and Figure 21). Over the next two decades, battery pack and hydrogen fuel cell costs are expected to decrease by more than half. By requiring automakers to accumulate more ZEV production experience, strong Canadian ZEV-supportive policy has the potential to contribute to further cost reductions.

Battery and fuel cell costs will be dominated by the level of ZEV production globally, and hence the level of ZEV-supportive policy implemented in other countries. For example, implementation of strong policy in the US (comparable to that modeled for Canada) could greatly accelerate battery and fuel cell cost reductions due to the size of the US market. This dynamic points to a benefit of coordinated global ZEV policy.

Figure 20: ZEV battery cost forecast

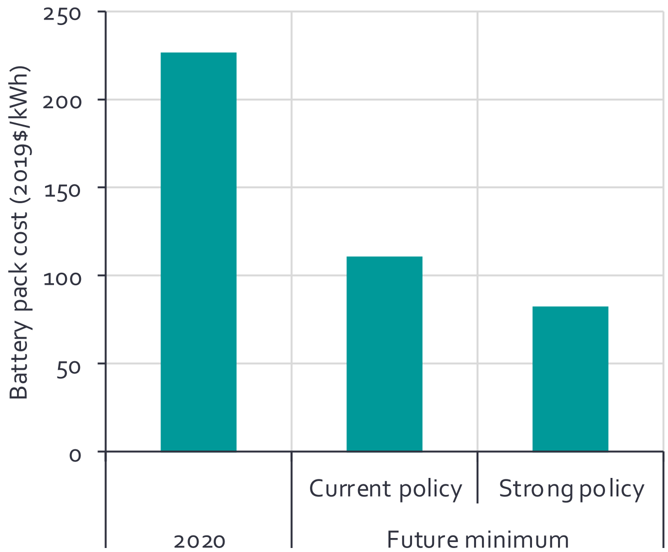
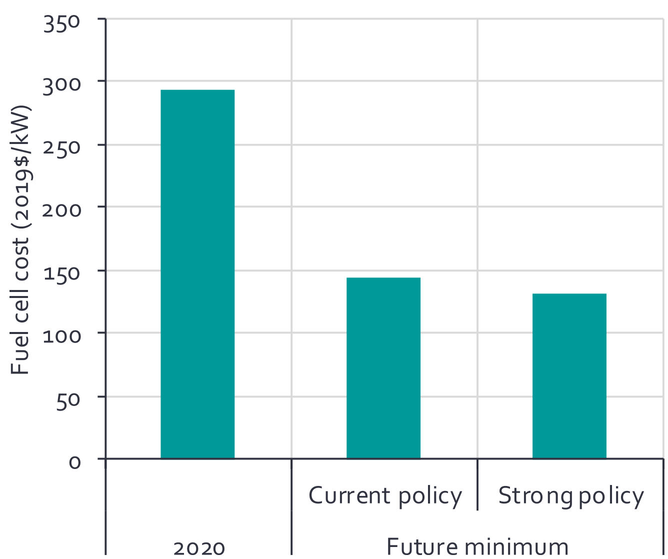


Figure 21: Hydrogen fuel cell cost forecast



3.2.4. ZEV economy

ZEV-related economic activity is expected to increase rapidly under current policy (See Section 3.1.3). As shown in Figure 22 and Figure 23, the ZEV economy could grow even more in response to stronger ZEV-supportive policy. By 2040, ZEV-related GDP could reach $152 billion (2015$), up from $43 billion under current policy. Likewise, ZEV-related jobs could reach 1.1 million, up from 342 thousand in the current policy forecast.

For context, the ZEV economy's GDP grows at an average annual rate of between 18% (current policy) and 24% (strong policy). By contrast, growth in the rest of the economy is in the range of 2%.

Figure 22: ZEV-related GDP in response to stronger ZEV-supportive policy

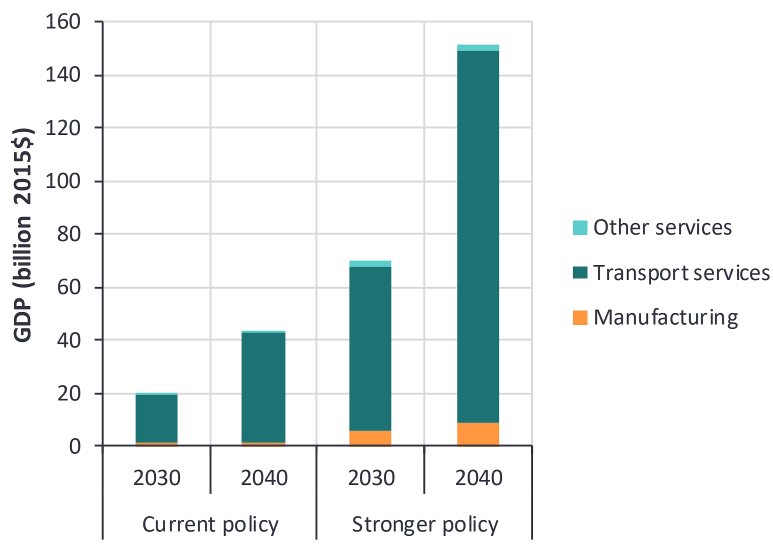
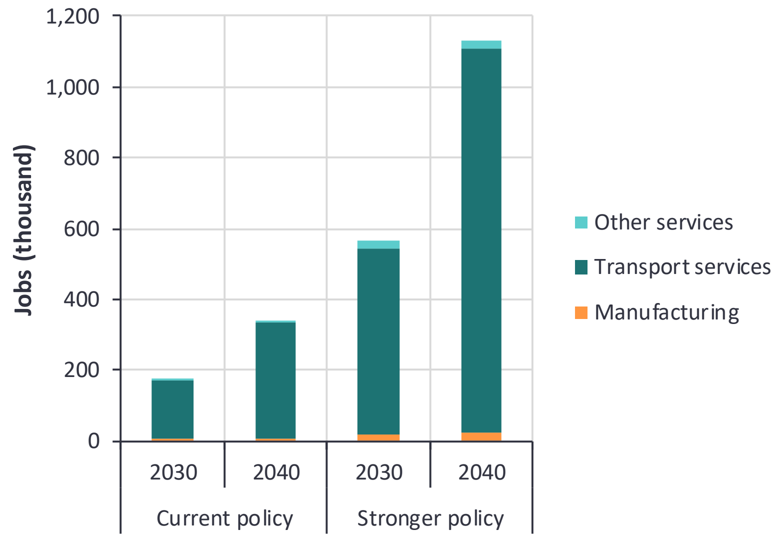


Figure 23: ZEV-related jobs in response to stronger ZEV-supportive policy



4. Key insights for policy makers

This research reveals several key insights for policy makers:

1. Transitioning to zero emission vehicles is crucial for achieving Canada's emissions reduction targets. Plug-in electric and plug-in hybrid electric vehicles are currently the most promising ZEV technology for light-duty vehicles. Hydrogen fuel cell technology holds greater potential for heavy-duty vehicles in the longer term.
2. Despite many ZEV-supportive policies currently implemented across Canada, the country is not on track to achieve its 2030 and 2040 ZEV sales targets. In the absence of new policy, ZEV adoption is expected to reach 14% or less by 2040 across light, medium and heavy-duty vehicle classes.
3. A single policy – a strong ZEV mandate with broad coverage across the country – could achieve Canada's target for ZEV adoption of 30% light-duty sales by 2030 and 100% by 2040. This policy is already being implemented in BC. ZEV mandates for medium and heavy-duty vehicles could also be developed based on policy being designed in California.
4. Nationwide ZEV policy can help decarbonize Canada's transport sector while (1) contributing to global cost reductions of ZEVs and (2) boosting the ZEV economy by over $150 billion GDP and 1.1 million jobs by 2040. Compared to outcomes under in response to current policies, this more ambitious ZEV policy package represents $109 billion more GDP and 791 thousand more jobs. Most of the economic activity related to ZEVs will be their use in the transportation of people and goods across the country, activity that otherwise would have involved conventional vehicles.
5. Growing demand for ZEVs represents an opportunity for ZEV manufacturing in Canada. Canada could consider policies to support domestic ZEV manufacturing, though the outcomes of such measures are uncertain. Raising revenue to pay for ZEV manufacturing incentives would impose costs on the broader economy.

Appendix A: Vehicle technology assumptions

Transportation technology cost inputs include vehicle drivetrain costs, which are defined as powertrain, transmission, motors, and fuel storage and supply. The remaining components are assumed to cost the same across technologies (e.g., seats, dashboard, vehicle chassis, wheels etc.). The data collected includes retail and manufacturer costs. A 30% gross profit margin is applied to manufacturer cost components.

The model represents declining capital costs for batteries, charging infrastructure, fuel cell systems and hydrogen fuel tanks. Batteries and fuel cell systems decline as a function of cumulative production, as described in Section 2.3.1.

The capital cost of charging infrastructure is constant for light and medium-duty vehicles and declines as a function of market share for heavy-duty vehicles and buses. The capital cost of hydrogen infrastructure is included in the cost of producing hydrogen through a dedicated “hydrogen for transport” sector.

The following sections provide a description of the technology assumptions across four road transport end-uses: light-duty vehicles, medium-duty vehicles, heavy-duty vehicles, and buses.

Light-duty vehicles

Table 4 summarizes the performance and cost assumptions of seven light-duty vehicle archetypes included in the modeling. The light-duty vehicle archetypes are based on a midsize passenger car with a 150-kW power output. As discussed in Section 2.3.2, an intangible cost is added to represent perceived cost due to range anxiety as well as the actual cost of renting an internal combustion engine (ICE) vehicle for trips longer than the electric vehicle’s assumed range.

The cost breakdown for the basic gasoline vehicle archetype is based on a 2015 Idaho National Laboratory report[37]. The Energy Information Administration’s National Energy Modeling System documentation was used to define the incremental cost and

[37] Idaho National Laboratory. (2015). *Vehicle Lightweighting: 40% and 45% weight savings*. Available from: https://inldigitallibrary.inl.gov/sites/sti/sti/6492855.pdf

efficiency improvement for the efficient gasoline vehicle archetypes[38]. The cost breakdown for battery electric vehicles was informed both from the UBS Bolt Teardown report and Bloomberg's battery cost assumptions[39]. The cost breakdown for hybrid and plug-in hybrid vehicle costs was calculated relative to ICE and electric vehicle costs using Argonne National Laboratory's 2016 Autonomie Model data[40]. The plug-in hybrid archetype in the modelling is based on Argonne's depiction of an extended range plug-in hybrid as opposed to a split drive plug-in hybrid. Fuel cell vehicle cost components are based on a Strategic Analysis Consultants report prepared for the U.S. Department of Energy[41].

Plug-in hybrid and battery electric vehicle energy intensities are based on the average combined fuel economy from Natural Resources Canada's 2019 Fuel Consumption Guide[42]. Fuel cell vehicle energy intensities are based on the EPA ratings found on the FuelEconomy.gov website[43].

We assume that 30% of battery electric vehicle owners install a $6,000 Level 2 charger when they purchase their vehicle. Fuel tank capacities are shown in kWh for gasoline and hydrogen vehicles to maintain unit consistency across technologies. The assumed energy intensity is 34.6 MJ/L for gasoline and 140 MJ/kg for hydrogen[44].

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[38] EIA. (2019). *Transportation Sector Demand Module of the National Energy Modeling System: Model Documentation*. Available from: https://www.eia.gov/outlooks/aeo/nems/documentation/transportation/pdf/m070(2018).pdf

[39] UBS. (2017). *Q-Series: UBS Evidence Lab Electric Car Teardown – Disruption Ahead*. Available from: https://neo.ubs.com/shared/d1wkuDlEbYPjF/

[40] Moawad A. et al. (2016). *Assessment of Vehicle Sizing, Energy Consumption and Cost through Large Scale Simulation of Advanced Vehicle Technologies*. Available from: https://www.autonomie.net/publications/fuel_economy_report.html

[41] Strategic Analysis Consultants. (2017). Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2016 Update. Available from: https://www.energy.gov/sites/prod/files/2017/06/f34/fcto_sa_2016_pemfc_transportation_cost_analysis.pdf

[42] Natural Resources Canada. (2019). *Battery-electric vehicles 2012-2019 & Plug-in hybrid electric vehicles 2012-2019*. Retrieved on 2019/11/12 from: https://open.canada.ca/data/en/dataset/98f1a129-f628-4ce4-b24d-6f16bf24dd64

[43] Fueleconomy.gov. (2019). *Compare Fuel Cell Vehicles*. Retrieved on 2019/11/12 from: https://www.fueleconomy.gov/feg/fcv_sbs.shtml

[44] We use the higher heating value for hydrogen because energy is converted through electro-chemical reaction as opposed to combustion.

Table 4: Light-duty vehicle technologies assumptions

Parameter	Units	2015	Future minimum
Gasoline new			
Engine size	kW	150	
Fuel storage size	kWh	575	
Drivetrain cost	2019$	9,225	
Maintenance cost	2019$/yr	930	
Energy consumption	MJ/vkm	2.40	
Gasoline efficient			
Engine size	kW	150	
Fuel storage size	kWh	575	
Drivetrain cost	2019$	10,780	
Maintenance cost	2019$/yr	930	
Energy consumption	MJ/vkm	1.77	
Hybrid			
Engine size	kW	75	
Generator size	kW	60	
Motor size	kW	75	
Fuel storage size	kWh	480	
Li-ion battery size	kWh	1.5	
Drivetrain cost	2019$	13,335	12,865
Intangible cost	2019$	2,700	0
Maintenance cost	2019$/yr	710	
Energy consumption	MJ/vkm	1.31	
Plug-in hybrid			
Engine size	kW	125	
Generator size	kW	125	
Motor size	kW	150	
Fuel storage size	kWh	340	
Li-ion battery size	kWh	20	
Drivetrain cost	2019$	28,600	18,460
Intangible cost	2019$	7,750	0
Maintenance cost	2019$/yr	710	
Charging infrastructure cost	2019$	1,800	
Energy consumption (gasoline)	MJ/vkm	0.47	

Parameter	Units	2015	Future minimum
Energy consumption (electric)	MJ/vkm	0.43	
Battery electric			
Motor size	kW	150	
Li-ion battery size	kWh	60	
Drivetrain cost	2019$	47,250	15,195
Intangible cost	2019$	8,225	0
Maintenance cost	2019$/yr	500	
Charging infrastructure cost	2019$	1,800	
Energy consumption	MJ/vkm	0.62	
Fuel cell electric			
Fuel cell size	kW	150	
Motor size	kW	150	
Fuel storage size	kWh	290	
Li-ion battery size	kWh	1.5	
Drivetrain cost	2019$	72,850	20,600
Intangible cost	2019$	12,340	0
Maintenance cost	2019$/year	600	
Energy consumption	MJ/vkm	1.27	

Medium-duty vehicles

Table 5 summarizes the performance and cost assumptions of the medium-duty vehicle archetypes included in the modeling. A survey and literature review conducted in 2019 shows that most medium-duty vehicles fit within the smaller weight classes (3 to 5), which are characterized by power outputs close to 170 kW. The daily driving range is sourced from the same survey[45].

Most medium-duty vehicle costs are based on the National Renewable Energy Laboratory (NREL) FASTSim model inputs with some adjustments to the battery cost

[45] Navius Research. (2019). *Medium- and heavy-duty vehicle characterization in British Columbia*. Report unavailable publicly.

and fuel cell drivetrain cost[46]. As discussed in Section 2.3.2, intangible costs are taken from Hammond et. al (2020)[47],

Larger commercial vehicles are expected to require more advanced charging infrastructure than their personal light-duty counterparts. Costs are based on charging infrastructure costs for local operations from a report prepared by the ICCT in 2019[48].

Medium-duty vehicle energy intensities are inferred from the energy intensities of heavy-duty vehicle technology archetypes. For example, if the heavy-duty fuel cell technology is 60% more efficient than the base heavy-duty diesel technology, then we applied the same relative energy intensity for the medium-duty fuel cell vehicle archetype.

The energy consumption of freight vehicles is shown in megajoules per tonne kilometre (MJ/tkm). The energy consumed per vehicle kilometre is calculated by multiplying MJ/tkm by the tonnes of freight moved per vehicle. We assume that medium-duty vehicles move 1.3 tonnes of freight on average each, consistent with NRCan data[49]. Therefore, a new diesel vehicle consumes 7.2 MJ/vkm (equivalent to around 19 L/100 km). The tables below only show diesel technology costs. Gasoline vehicles have similar parameters except for slightly higher energy consumption (5% more).

Table 5: Medium-duty vehicle technologies assumptions

Parameter	Units	2015	Future minimum
Diesel new			
Engine size	kW	170	
Daily driving range	km/day	200	
Drivetrain cost	2019$	23,250	
Maintenance cost	2019$/yr	8,450	
Energy consumption	MJ/tkm	5.50	

[46] NREL. (2019). *Light Duty Hydrogen Infrastructure Analysis at NREL*. Available from: https://www.nrel.gov/docs/fy19osti/73944.pdf

[47] Hammond, W., Axsen, J., Kjeang, E., 2020. How to slash greenhouse gas emissions in the freight sector: Policy insights from a technology-adoption model of Canada. *Energy Policy 137*, 111093. https://doi.org/10.1016/j.enpol.2019.111093

[48] Hall D. and Lutsey N. (2019). *Estimating the infrastructure needs and costs for the launch of zero-emission trucks.* Available from: https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf

[49] Natural Resources Canada. (2019). *Comprehensive Energy Use Database*. Available from: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm

Parameter	Units	2015	Future minimum
Diesel efficient			
Engine size	kW	170	
Daily driving range	km/day	200	
Drivetrain cost	2019$	28,850	
Maintenance cost	2019$/yr	8,450	
Energy consumption	MJ/tkm	4.70	
Diesel very efficient			
Engine size	kW	170	
Daily driving range	km/day	200	
Drivetrain cost	2019$	30,650	
Maintenance cost	2019$/yr	8,450	
Energy consumption	MJ/tkm	4.21	
Compressed natural gas			
Engine size	kW	170	
Daily driving range	km/day	200	
Drivetrain cost	2019$	34,290	
Intangible cost	2019$	9,470	0
Fuelling infrastructure cost	2019$	21,650	
Maintenance cost	2019$/yr	8,450	
Energy consumption	MJ/tkm	5.56	
Hybrid			
Engine size	kW	85	
Generator size	kW	74	
Motor size	kW	85	
Daily driving range	km/day	200	
Drivetrain cost	2019$	42,330	41,260
Maintenance cost	2019$	6,340	
Energy intensity	MJ/tkm	3.76	
Plug-in hybrid			
Engine size	kW	140	
Generator size	kW	140	
Motor size	kW	170	
Daily driving range	km/day	200	
Drivetrain cost	2019$	76,560	43,490

Parameter	Units	2015	Future minimum
Intangible cost	2019$	15,150	0
Charging infrastructure cost	2019$	29,300	
Maintenance cost	2019$/yr	6,340	
Energy consumption (diesel)	MJ/tkm	1.33	
Energy consumption (electric)	MJ/tkm	0.90	
Battery electric			
Motor size	kW	170	
Daily driving range	km/day	200	
Drivetrain cost	2019$	139,000	36,500
Intangible cost	2019$	30,300	
Charging infrastructure cost	2019$	29,300	
Maintenance cost	2019$/yr	4,230	
Energy consumption	MJ/tkm	1.39	
Fuel cell electric			
Fuel cell size	kW	170	
Motor size	kW	170	
Daily driving range	km/day	200	
Drivetrain cost	2019$	124,450	46,850
Intangible cost	2019$	34,100	0
Maintenance cost	2019$/yr	8,450	
Energy consumption	MJ/tkm	2.49	

Heavy-duty vehicles

Table 6 summarizes the performance and cost assumptions of the heavy-duty vehicle archetypes included in the modeling. The model's heavy-duty vehicle archetypes are mostly based on a 2017 ICCT report[50]. The trucks are all assumed to have a 350-kW engine or motor. The daily driving range is inferred from the survey we conducted in 2019[51].

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[50] Moultak M. et al. (2017). *Transitioning to zero-emission heavy-duty freight vehicles*. Available from: https://theicct.org/sites/default/files/publications/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf

[51] Navius Research. (2019). *Medium- and heavy-duty vehicle characterization in British Columbia*. Report unavailable publicly.

The vehicle cost breakdowns are estimated both using the ICCT 2017 report and a 2017 paper written by Fries M. et al[52]. Battery costs and fuel cell system costs are based on Bloomberg and Strategic Analysis Consultants' work, respectively. As discussed in Section 2.3.2, intangible costs are taken from Hammond et. al (2020)[53],

The energy intensities for the heavy-duty vehicle technology archetypes shown below are all inferred from ICCT's 2017 report.

As with medium-duty vehicles, advanced charging infrastructure costs are also included for plug-in technologies. We assume that 30% of heavy-duty vehicles are used for long-haul transport and 70% for local operations. The ICCT finds that long-haul operation will likely require higher infrastructure costs, hence the higher estimate relative to the exclusively local operation-based medium-duty vehicle cost[54].

We estimate that a battery electric class 8 tractor weighs 11% more than a diesel tractor. Heavy-duty vehicles are restricted to a maximum weight for safety and infrastructure capacity limits, which means that any extra tractor weight reduces the hauling capacity. We therefore apply an 11% markup to the heavy-duty battery electric archetype to account for this disadvantage.

We use Natural Resources Canada's Comprehensive Energy Use Database and adjust it with the daily distance travelled estimated from our survey to infer that heavy-duty vehicles transport about 9.7 tonnes of freight on average each[55].

Table 6: Heavy-duty vehicle technologies assumptions

Parameters	Units	2015	Future minimum
Diesel new			
Engine size	kW	350	
Daily driving range	km/day	395	
Drivetrain cost	2019$	100,400	

52 Fries M. et al. (2017). *An overview of costs for vehicle components, fuels, greenhouse gas emissions and total cost of ownership update 2017*. Available from: https://steps.ucdavis.edu/wp-content/uploads/2018/02/FRIES-MICHAEL-An-Overview-of-Costs-for-Vehicle-Components-Fuels-Greenhouse-Gas-Emissions-and-Total-Cost-of-Ownership-Update-2017-.pdf

53 Hammond, W., Axsen, J., Kjeang, E., 2020. How to slash greenhouse gas emissions in the freight sector: Policy insights from a technology-adoption model of Canada. *Energy Policy 137*, 111093. https://doi.org/10.1016/j.enpol.2019.111093

54 Hall D. and Lutsey N. 2019. *Estimating the infrastructure needs and costs for the launch of zero-emission trucks.* Available from: https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf

55 Natural Resources Canada. (2019). *Comprehensive Energy Use Database*. Available from: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm

Parameters	Units	2015	Future minimum
Maintenance cost	2019$/yr	13,320	
Energy consumption	MJ/tkm	1.48	
Diesel efficient			
Engine size	kW	350	
Daily driving range	km/day	395	
Drivetrain cost	2019$	104,970	
Maintenance cost	2019$/yr	13,320	
Energy consumption	MJ/tkm	1.38	
Diesel very efficient			
Engine size	kW	350	
Daily driving range	km/day	395	
Drivetrain cost	2019$	112,750	
Maintenance cost	2019$/yr	16,120	
Energy consumption	MJ/tkm	1.06	
Liquid natural gas			
Engine size	kW	350	
Daily driving range	km/day	395	
Drivetrain cost	2019$	130,450	
Intangible cost	2019$	24,900	0
Fuelling infrastructure cost	2019$	30,490	
Maintenance cost	2019$/yr	16,850	
Energy consumption	MJ/tkm	1.48	
Battery electric			
Motor size	kW	350	
Daily driving range	km/day	395	
Drivetrain cost	2019$	482,420	102,680
Intangible cost	2019$	73,060	0
Charging infrastructure cost	2019$	149,245	63,020
Maintenance cost	2019$/yr	6,660	
Energy consumption	MJ/tkm	0.56	
Fuel cell electric			
Fuel cell size	kW	350	
Motor size	kW	350	
Daily driving range	km/day	395	

Parameters	Units	2015	Future minimum
Drivetrain cost	2019$	241,200	89,500
Intangible cost	2019$	109,600	0
Maintenance cost	2019$/yr	14,650	
Energy consumption	MJ/tkm	0.93	

Buses

Table 7 summarizes the performance and cost assumptions of the bus archetypes included in the modeling. There is little literature on bus cost component breakdown. The literature shows that buses' power output and driving range are on average 64% and 72% that of heavy-duty vehicle, respectively. We therefore scale the heavy-duty cost component breakdown by those factors for all the technologies.

Bus energy intensities are inferred from the energy intensities of heavy-duty vehicle technology archetypes. For example, if the heavy-duty battery electric technology is 60% more efficient than the base heavy-duty diesel technology then the battery electric bus technology is more efficient than the base diesel bus technology by the same amount.

For charging infrastructure, we use cost estimates from work prepared for Translink by M.J. Bradley & Associates (MJB&A) in 2018. We assume that 50% of buses charge on-route with the remaining 50% charging in-depot. ICCT anticipates heavy-duty vehicle charging infrastructure costs to decline with time. We apply that rate of decline to the estimates we infer from MJB&A.

We use Natural Resources Canada's Comprehensive Energy Use Database to estimate that each bus transports about 17.6 passengers on average[56].

Table 7: Bus technologies assumptions

Parameters	Units	2015	Future minimum
Diesel new			
Engine size	kW	225	
Daily driving range	km/day	210	
Drivetrain cost	2019$	64,200	
Maintenance cost	2019$/yr	49,200	

[56] Natural Resources Canada. (2019). *Comprehensive Energy Use Database*. Available from: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm

Parameters	Units	2015	Future minimum
Energy consumption	MJ/pkm	0.88	
Compressed natural gas			
Engine size	kW	225	
Daily driving range	km/day	210	
Drivetrain cost	2019$	92,750	
Fuelling infrastructure cost	2019$	30,490	
Intangible cost	2019$	15,930	0
Maintenance cost	2019$/yr	49,200	
Energy consumption	MJ/pkm	0.93	
Hybrid			
Engine size	kW	113	
Generator size	kW	113	
Motor size	kW	113	
Daily driving range	km/day	210	
Drivetrain cost	2019$	108,250	
Intangible cost	2019$	39,400	0
Maintenance cost	2019$/yr	0	
Energy consumption	MJ/pkm	0.60	
Battery electric			
Motor size	kW	225	
Daily driving range	km/day	210	
Drivetrain cost	2019$	189,470	55,890
Intangible cost	2019$	46,730	0
Charging infrastructure cost	2019$	149,250	63,020
Maintenance cost	2019$/yr	29,525	
Energy consumption	MJ/pkm	0.18	
Fuel cell electric			
Fuel cell size	kW	225	
Motor size	kW	225	
Daily driving range	km/day	210	
Drivetrain cost	2019$	160,200	52,960
Intangible cost	2019$	70,100	0
Energy consumption	MJ/pkm	0.55	

Appendix B: Cluster dynamics

As part of this project, we conducted a review of whether ZEV manufacturing may develop in geographically concentrated clusters and how such a dynamic could be modeled. Ultimately, we didn't attempt to represent such dynamics in the model, though we note such concentration may occur and can potentially be supported by policy.

Is ZEV manufacturing likely to cluster?

Many economic activities are geographically concentrated in "clusters". Some examples include financial services in London, film making in Los Angeles and auto manufacturing in Detroit.

Companies may cluster for a variety of reasons. For example:

- Industries with economies of scale benefit from shared infrastructure, labour pools and knowledge transfer.
- Industrial concentration supports a "thick" local labour market in which employees find it easier to find employers and vice versa.
- Industries benefit from external economies via information spillovers (i.e., the positive impact of knowledge sharing between individuals in different companies).

At the same time, a variety of factors may push companies to disperse. For example:

- Immobile factors (such as land, natural resources and in an international context, people) militate against concentration of production. Some production must go to where the workers are and some production will have an incentive to locate close to consumers.
- Concentrations of economic activity boost demand for local land, driving up land rents and providing a disincentive for further concentration.
- Concentration can result in external diseconomies such as congestion.

Ultimately, the concentration of economic activity depends on the outcome of these opposing forces and is the study of a field called "new economic geography"[57].

[57] Krugman, P. (1998). What's new about the new economic geography?. Oxford review of economic policy, 14(2), 7-17.

Auto making has traditionally clustered to some extent (in the North American context, think of Michigan and Ontario). According to at least one study, the ZEV manufacturing sector is also likely to cluster, due to factors such as economies of scale, tacit knowledge and transport costs[58].

Could Canadian policy create a ZEV cluster?

Could government policy influence clustering? Specifically, could Canadian policy help create a domestic ZEV cluster?

There are some examples of success when it comes to governments enabling the development of clusters. For example, a variety of policies played a role in the success of Korea's automobile industry since the 1970s, including tax and financial incentives, import protection and investments in research and development[59].

The Cluster Policies Whitebook[60], one of the more comprehensive summaries of cluster performance and policy, identifies a variety of policies to enable cluster formation, such as research and development funding, tax incentives and use of public procurement. The authors also suggest that policy interventions should be confined to revitalizing existing clusters with high growth potential, rather than trying to create clusters from scratch.

More recently, some researchers have called for government to implement policies to kick-start ZEV manufacturing clusters in California[61] and Michigan[62]. Recommended policies include tax credits for constructing manufacturing plants, developing partnerships between government, university and industry, developing local demand for ZEV products (e.g. through government procurement policies), and investing in science, mathematics and engineering education.

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58 Lyon, T. P., & Baruffi Jr, R. A. (2011). Creating a plug-in electric vehicle industry cluster in Michigan: Prospects and policy options. Mich. Telecomm. & Tech. L. Rev., 18, 303.

59 Lee, J. I., & Mah, J. S. (2017). The role of the government in the development of the automobile industry in Korea. Progress in Development Studies, 17(3), 229-244.

60 Andersson, T., Schwaag-Serger, S., Sörvik, J., & Wise, E. (2004). Cluster Policies Whitebook. IKED -International Organisation for Knowledge Economy and Enterprise Development.

61 Scott, A. J. (1995). The electric vehicle industry and local economic development: prospects and policies for Southern California. Environment and Planning A, 27(6), 863-875.

62 Lyon, T. P., & Baruffi Jr, R. A. (2011). Creating a plug-in electric vehicle industry cluster in Michigan: Prospects and policy options. Mich. Telecomm. & Tech. L. Rev., 18, 303.

These types of policies may have many benefits, both in terms of fostering clusters and boosting economic activity in general. Yet, they also present challenges in the context of energy-economy modeling.

In the 1990s, Paul Krugman proposed developing spatial computable general equilibrium models to predict the effects of policy on the economy's spatial structure, in the same way that computable general equilibrium models are used to predict the effects of changes in taxes and trade policy on the economy's industrial structure. Since then, researchers have had some success developing such models and applying them to examine the economic impact of transport infrastructure[63] and the asymmetric impacts of trade[64].

Such models face several limitations. First, they often lack a sound empirical foundation. Second, they can be unstable (i.e., fail to find a solution) because assumptions of increasing returns to scale (one of the underlying mechanisms by which clusters can be represented in general equilibrium models) result in the potential for multiple equilibria. Lastly, the outcomes of many of the cluster-promoting policies described above may be inherently uncertain and difficult to quantify.

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[63] For example, see: Tavasszy, L. A., Thissen, M. J. P. M., & Oosterhaven, J. (2011). Challenges in the application of spatial computable general equilibrium models for transport appraisal. Research in Transportation Economics, 31(1), 12-18.

[64] For example, see: Haddad, E. A., Bonet, J., Hewings, G. J., & Perobelli, F. S. (2009). Spatial aspects of trade liberalization in Colombia: A general equilibrium approach. Papers in Regional Science, 88(4), 699-732.

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