In Search of Politically Achievable Decarbonization Pathways for British Columbia

by

Emily Doan

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Declaration of Committee

Name:	**Emily Doan**
Degree:	**Master of Resource Management**
Thesis title:	**In Search of Politically Achievable Decarbonization Pathways for British Columbia**
Committee:	**Chair: Pascal Haegeli** Assistant Professor, Resource & Environmental Management
	Mark Jaccard Supervisor Professor, Resource & Environmental Management
	Bradford Griffin Committee Member University Research Associate, Resource & Environmental Management
	Merran Smith Examiner Executive Director Clean Energy Canada

Abstract

British Columbia's current policy package is insufficient to meet the province's 2030, 2040, or 2050 greenhouse gas emissions targets. To design and assess different policy pathways to close this emissions gap, I used the CIMS energy-economy model. The first target-achieving pathway emphasized the carbon tax due to its economic efficiency. The second pathway tightened existing regulations with flexible compliance options, including the low carbon fuel standard, the zero-emission vehicles mandate, the clean electricity standard and the clean gas standard. I found that meeting the targets with either policy pathway results in similar technology and energy-use outcomes. This suggests that B.C. can choose to emphasize either carbon pricing, or flexible regulations to close its emissions gap. This range of options enables B.C. policymakers to consider other criteria, notably the political acceptability of their climate policy alternatives.

Keywords: British Columbia; Climate policy; Energy-economy modeling; Low Carbon Fuel Standard; Zero-emission vehicles mandate; LNG

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List of Acronyms

B.C.	British Columbia
CAFÉ	Corporate Average Fuel Economy
CER	Canada Energy Regulator
CGE	Computer generated equilibrium
EITE	Emissions intensive trade exposed
GDP	Gross domestic product
GHG	Greenhouse gas
HDRD	Hydrogenation-derived renewable diesel
HVAC	Heating, ventilation, and air conditioning
LCFS	Low Carbon Fuel Standard
NEB	National Energy Board
NIR	National Inventory Report
OBPS	Output-Based Pricing System
RNG	Renewable natural gas
RPP	Refined petroleum products
RPS	Renewable Portfolio Standard
VES	Vehicle Emissions Standard
ZEV	Zero emission vehicle

Chapter 1.

Introduction

Since 1989, British Columbia has sought to establish itself as a climate policy leader. In 2007, it became one of few jurisdictions in North America to legislate an ambitious set of climate targets (Government of British Columbia, 2007): a 40% emissions reduction by 2030, 60% reduction by 2040, and 80% by 2050, all relative to 2007 levels. To meet these targets, the government implemented a series of compulsory emissions reductions policies between 2007 and 2008. This included a suite of regulations, notable among them the Clean Electricity Standard, the Low Carbon Fuel Standard (LCFS), tighter energy efficiency standards, and a mandatory carbon-neutral offset program for all emissions from the public sector. In addition, B.C. introduced a broad-based carbon tax. The Clean Electricity Standard and the carbon tax were the first policies of their kind in North America.

British Columbia’s compulsory policies succeeded in establishing it as a North American leader in climate policy alongside California (Jaccard, 2012). However, B.C. has yet to develop and implement policies that will achieve its GHG reduction targets. The government stabilized the stringencies of the existing policies between 2012 and 2018. In 2018, the government launched CleanBC, another commitment to reducing emissions. As part of this package, the government increased the stringencies of existing policies and added additional policies to the mix. Independent analysis of the current policy package (Navius Research, 2017) found that it will not meet the 2030, 2040, or 2050 emissions targets. Thus, the provincial government continues to assess options to further reduce emissions by increasing stringencies on existing policies and implementing new policies.

While none of B.C.’s climate plans since 1989 have been estimated to meet the intended emissions targets, there has been little academic work aimed at evaluating policy pathways that will. Past research exploring policy alternatives to meet emission reduction targets has been done at the national level (Christoph & Rutherford, 2012; Davis & Kumar, 2018; Jaccard et al., 2004; Vass, 2016), but research at a national level does not necessarily provide a regional government (with its own climate targets) clear paths for emissions reductions. B.C.'s climate policies are a popular case study for economists and climate policy analysts (Beck et al., 2015; Lacroix & Richards, 2015; Navius Research, 2016; Rhodes & Jaccard, 2013; Rivers & Jaccard, 2005a) but there are few studies that specifically investigate how these policy packages can be altered to achieve emissions targets. Such exploratory research has centered on individual sectors (Lepitzki & Axsen, 2018; Talebian et al., 2018), rather than on policy packages that could be applied to the entire B.C. economy.

I aim to fill this research gap by exploring pathways to meet British Columbia's GHG reduction targets for the key years of 2030, 2040, and 2050, using different assumptions of external demand for B.C.'s natural gas and the intensity of climate policies in other jurisdictions, notably those that comprise the province's major trading partners. To explore possible pathways for emissions reductions, I model a series of policy runs to examine how different combinations of policies would influence the economy from the present day until the year 2050. To model these policy runs I use CIMS, an energy-economy model that represents the capital stocks in an economy and simulates their turnover and competition with one another over time. CIMS features a high level of technological detail, allowing me to examine how climate policies might influence the market shares of specific technologies into the future. CIMS also features a parameter that allows the user to represent consumer values not included in capital and operating costs, such as convenience and reliability. This sets it apart from the many technology-rich models that do not take consumer preferences explicitly into account (Rivers & Jaccard, 2005b).

To provide further insight into the outcomes of a policy package that would achieve the climate targets, I explore alternative policy packages dominated by two different policy types. My first policy package retains the current set of policies but focuses on steadily increasing the carbon tax as the main policy going forward. The carbon tax places a uniform price on fossil fuel-originated CO_2 emissions in B.C. A carbon tax applied across the economy is theoretically one of the most economically efficient policies for reducing emissions, alongside cap-and-trade programs (Goulder & Parry, 2008). To offset the costs of the tax when it was first applied in the period 2008-2012, the B.C. government simultaneously cut income and corporate taxes by a near-equivalent amount to ensure government revenue-neutrality. This policy allowed taxpayers to reduce their overall tax burden by reducing their emissions relative to others by their technology choices for vehicles, furnaces and other end-use devices, and by substituting high-emissions goods and services for low-emission alternatives (i.e. using public transit as an alternative to driving) (Jaccard, 2012). The visible nature of carbon taxes and the strong opposition they provoke from some percentage of constituents (Rhodes et al., 2017; Rhodes & Jaccard, 2013) may be a factor in preventing policymakers from raising them to the level necessary to meet emissions targets. However, the economic efficiency of a carbon tax makes it a useful policy to model at a high stringency, as it can illustrate an economically efficient outcome given the current policy package.

My second alternative policy package keeps the current set of policies but focuses on a suite of regulations (of increasing stringency) to meet the climate targets. Evidence suggests that regulations have in the past encountered less public opposition than the carbon tax for an equivalent or greater amount of GHG reductions (Rhodes et al., 2017). For example, Rhodes and Jaccard (2013), found that The Clean Electricity Standard, which requires that a given percentage of new electricity is generated by zero-emission sources, resulted in far less public opposition despite a higher estimated cost per tonne of reductions. They suggest that the lack of public opposition may be due to the policy's low visibility, or low awareness by the public of the higher costs of regulation relative to the carbon tax.

The Clean Electricity Standard is a prominent example of a regulation that does not prescribe a specific technological outcome, thereby allowing electricity generators to decide the technology they will adopt to comply with the regulation. Throughout this thesis, I refer to the Clean Electricity Standard and other regulations that do not prescribe specific technologies as "flexible regulations." To meet the climate targets in this package, I emphasize the most "flexible" of the existing regulations and design additional regulations for sectors that are only covered by the carbon tax. While there is no guarantee that this package will not be met with political opposition, it presents an alternative decarbonization strategy for policymakers to consider.

In summary, I model four different runs:

1. Business-as-usual (BAU): All policies currently implemented at their 2020 stringencies.

2. Current and Announced Policies (CAP): All policies with quantified stringencies that have been implemented and announced by the B.C. government as of December 2018, the date when the government presented its most recent major climate plan, called CleanBC. Policies are modeled at their announced stringencies for the years 2020 to 2030 and assumed to remain constant after that, unless the government has specified otherwise.

3. Current and Announced Policies + Carbon Pricing (CAP + Carbon Pricing): All policies in the Current and Announced Policies run combined with a rising carbon tax whose trajectory is set to achieve the 2030, 2040, and 2050 emissions targets.

4. Current and Announced Policies + Flexible Regulations (CAP + Flexible Regulations): All policies in the Current and Announced Policies run, plus flexible regulations whose rising stringencies are set to ensure that the province achieves the 2030, 2040, and 2050 GHG targets.

I analyze the results of these scenarios by comparing the technological outcomes of each sector across scenarios. This includes examining how specific categories of technologies change over time, as well as how fuel use shifts to meet demand despite growing restrictions on carbon.

Due to the linear progression of the emissions targets, every run intended to meet the emissions targets in 2030 and 2050 meets or exceeds the 2040 targets. When discussing the results, I focus on B.C.'s 2030 and 2050 emissions targets. The reasons for this are twofold: (1) Exploring the technological outcomes for two target years instead of three removes redundancies from my discussion. (2) I suggest that it is reasonable to assume that B.C. will collaborate, to some extent, with the federal government on climate policy. Canada's federal government has climate targets for 2030 and 2050 and is implementing an overlapping policy package to achieve them. To provide analysis that is most useful for both a provincial and national context, I focus discussion on the targets that both jurisdictions have in common. I do not assume that B.C.'s targets will align precisely with the national targets. Although B.C. will be part of Canada's efforts to go net-zero in 2050, their targets may differ in the intervening years. Moreover, to achieve an economically efficient outcome in 2050 at the national level, B.C. may need to reduce more or less emissions relative to the rest of Canada.

To add further complexity to the task of meeting the emissions targets, B.C. is promoting the growth of its natural gas industry[1]. Favourable market conditions have motivated some energy companies to expand their activities in B.C., as natural gas can be cooled into liquid natural gas (LNG) and exported overseas. By 2015, companies had presented 18 proposals for LNG projects to export natural gas by tanker to Asian markets. Since then, momentum in the Canadian LNG industry has waned. A combination of falling natural gas prices in 2014, a surplus of LNG liquefaction capacity, and high transportation costs resulted in a poor economic case for most proposals (Gomes, 2015). As of 2020, one project is in development while three others remain in the proposal stage.

Successive provincial governments have voiced their support for the industry, citing economic benefits for the province including jobs and increased provincial revenue (Government of British Columbia, 2018). However, natural gas production and processing into transportable LNG can be an emissions-intensive process depending on the form of energy that is used to liquify the natural gas (Luke & Noble, 2019). Major LNG expansion without technologies to prevent or remove upstream emissions in the extraction, processing, transporting and liquefaction phases could contribute substantially to provincial emissions. To accommodate this uncertainty, I run each set of policies under two different scenarios which I call High LNG and Low LNG.

To this end, my goal is to assess how alternative policy packages can achieve B.C.'s climate targets, while also gauging how the expansion of LNG might impact B.C.'s ability to meet those targets. Thus, my thesis addresses the following three objectives:

1. Evaluate the emissions reductions and possible technological outcomes resulting from the implementation of the government's current policy package of 2018-2020 (which thus far is projected not to achieve the B.C. government's GHG emission targets).

[1] For a more in-depth description of global LNG markets up to the year 2018, see Winter et al. (2018). For a detailed description of the Canadian natural gas industry up to 2015, see Gomes (2015).

2. Compare outcomes when B.C.’s climate policy package is made more stringent to meet the emission targets, first, with an emphasis on increased carbon pricing and, second, with an emphasis on flexible regulations.
3. Explore the implications for achieving emission targets from greater or lesser provincial production of natural gas for export in the form of LNG.

In Chapter 2 I provide further background into types of policy, policy evaluation criteria, and B.C.’s climate policy context. In Chapter 3 I provide an overview of the model I used to conduct this research. In Chapter 4 I detail my key assumptions for representing B.C.’s economy and for each policy package. I present and discuss the results of my modeling exercise in Chapter 5. Finally, I summarize my findings in Chapter 6.

Chapter 2. Background

To provide some context to the methodology I used for this study, I provide background information in the following three sections. In section 2.1, I give an overview of the types of climate policy and discuss policy evaluation criteria. In section 2.2., I offer a brief summary of how the B.C. government uses these policies in its climate plans. Finally, in section 2.3., I describe energy-economy models, their advantages and disadvantages, and how they can be used to provide insight for policymakers by simulating alternative policy packages.

2.1. Types of climate change policy

GHG reduction policies can be characterized in terms of their degree of "compulsoriness" (Jaccard & Bataille, 2002). Firms and households subject to compulsory policies are obligated to pay financial charges for their carbon emissions or pay financial penalties for non-compliance with regulations requiring technology, energy or emission outcomes. Compulsory policies can vary in scope. Carbon pricing policies, for example, will typically apply to the entire economy's GHG emissions unless full or partial exemptions are granted for specific sectors. As mentioned previously, carbon pricing places a specific price on GHG emissions (usually $/tonne CO2 equivalent), thereby disincentivizing high-emission activities. Carbon pricing can take the form of a carbon tax, which applies a price on emissions, or a cap-and-trade system, which caps emissions and subsequently allows firms to trade permits for allowable emissions, the price of which has the same effect as a carbon tax in incentivizing decarbonization.

While the carbon price is shown by economists to be the most economically efficient method of reducing emissions, researchers also determined that the price would need to be at least $150/tonne CO2e for Canada to achieve its 2030 emissions target (Carbon Pricing Leadership Coalition, 2017; World Bank Group, 2019). Without the rest of Canada collaborating to reduce emissions to the same degree, the carbon price necessary to meet B.C.'s emissions targets is likely to be even higher, given that BC's hydropower-dominated electricity system is already decarbonized, thereby reducing the opportunities for high percentage reductions. Furthermore, a unified, global carbon price is important for the economic survival of emissions-intensive, trade-exposed (EITE) industries (Bumpus, 2015). Otherwise, EITE industries that incur increased costs due to one jurisdiction's climate policies are at a competitive disadvantage relative to their unregulated counterparts in some other jurisdictions. Conscious of this vulnerability, jurisdictions around the world have applied separate or modified policies to EITE industries in an effort to induce some emissions reductions while at the same time alleviating the effect of climate policies on the production costs of these firms (Dobson & Winter, 2018).

Regulations are another compulsory policy option. Prescriptive, or "command-and-control," regulations stipulate a specific action that must be taken by each firm or household. Policymakers have used regulations to address other environmental issues, such as water and air pollution (Huffman, 1994). For instance, a regulation might specify that a polluting industrial facility install scrubbers in its chimneys. Command-and-control regulations are a common policy for environmental protection because they allow policymakers to target easily identifiable damaging actions and technologies. However, economists generally consider prescriptive regulations to be inefficient. Prescribing a specific compliance mechanism disregards the heterogeneous costs of firms resulting from the age of their equipment, locational advantages and technology differences. This results in a higher overall cost to society, wasting resources that could have been used in other, more beneficial ways. Additionally, prescriptive regulations do not incentivize firms to perform beyond what is mandated by the regulation (Goulder & Parry, 2008).

To mitigate some of these economic inefficiencies, policymakers in recent decades have increasingly tried, where possible, to implement "flexible" regulations. B.C.'s Clean Electricity Standard, as mentioned earlier, is one such regulation, currently requiring that 93% of new electricity generation be from zero-emissions sources (B.C. Hydro, B.C.'s utility, currently exceeds this objective, sourcing 98% of generation from renewable resources). The prescription of "zero-emissions" rather than "renewable" allows electricity suppliers to choose from a larger range of options in addition to renewable sources of electricity – such as nuclear power or coal-fired power plants with carbon capture and storage – while still complying with the regulation. California was the first North American jurisdiction to adopt a similar regulation for fuels, what it called the Low Carbon Fuel Standard.

At the other end of the spectrum are non-compulsory or voluntary policies. While non-compulsory policies such as subsidies are known to increase purchases of otherwise unaffordable buildings and equipment, they require a high level of government expenditure (Axsen & Wolinetz, 2018; Jaccard et al., 2003; Morrow et al., 2010). Moreover, they can be taken advantage of by firms and households who intended to invest in these changes anyway, thereby undermining the effectiveness of the policy. This is referred to as free-ridership. Thus, policymakers intending to induce large reductions in GHG emissions must implement compulsory policies, although this does not exclude the use of non-compulsory policies as part of a policy package.

2.1.1. Policy evaluation criteria

Researchers and policymakers often turn to multiple evaluation criteria to assess policies. These criteria assess the economic efficiency, environmental effectiveness, administrative feasibility and likely political acceptability of policies to facilitate choosing among them and determining their design.

My first criterion, economic efficiency, is the cost-effectiveness of the policy in reducing emissions. Unnecessarily high costs may undermine public support for emissions reduction policies, and, more importantly, unnecessarily absorb societal resources that could be allocated to health, education and other welfare programs. Economists have long advocated for climate policies that satisfy the equi-marginal principle, which states that policies must achieve the same marginal emissions abatement cost across all sectors to minimize the total cost of emissions reductions. In practice, this principle dictates that emissions reductions policies should allow actors to choose all options available to them when they are required to restrict their GHG emissions (Baumol & Oates, 1971). Carbon pricing systems, such as a carbon tax or cap-and-trade program, can satisfy this requirement if they apply a single carbon price across the economy. Command-and-control regulations are generally considered economically inefficient, as they typically require adoption of a specific technology even though this technology might not be the lowest-cost option for GHG abatement for all firms and actors. Subsidies may also be economically inefficient if they induce GHG reduction investments that would not have occurred under a single economy-wide carbon price because of their high cost (Jaccard & Bataille, 2002).

My second criterion is environmental effectiveness. This is the ability of a policy to achieve the intended emissions reductions. Compulsory policies can be environmentally effective if designed properly. In an ex ante simulation study, Rhodes and Jaccard (2013) estimated that the Clean Electricity Standard would decrease B.C.'s GHG emissions by 12-17Mt CO_2e by 2020 relative to a scenario without the policy. In an ex post econometric study, Murray and Rivers (2015) estimated that the carbon tax had reduced B.C.'s GHG emissions by 5-15% between its 2008 implementation and 2014. At higher levels, the carbon tax could cause large shifts in low-emission technology uptake and decrease emissions substantially as a result. Aside from carbon pricing, regulations have historically been the policy instrument of choice when governments have aimed to improve the environment (Huffman, 1994). Many climate policies satisfy this criterion to some degree.

My third criterion is administrative feasibility. Certain policies will be simpler than others to implement. A carbon pricing system, for example, is simple because energy consumption is already taxed, so the carbon tax only changes the tax rate of taxes for which a collection system already exists. A cap-and-trade system, on the other hand, requires policymakers to allocate permits to firms, establish a permit trading market, and monitor firm reporting. Flexible regulations like the Low Carbon Fuel Standard have credit trading systems that require government resources to set up and maintain.

My fourth criterion is political acceptability. Policies that receive less opposition from important segments of the public are more likely to be implemented. Policymakers aim to create policies that minimize political risk to maximize their chances of being re-elected. Political acceptability of climate policies depends in part on the perceptions of influential individuals or groups. Notably, policy researchers have found that policy can be influenced by small groups of strongly opinionated constituents who wield influence or who will experience large real or perceived costs (Galbraith, 1952). Researchers have further theorized that self-serving biases makes such parties sensitive to salient, highly visible policies that they perceive as disadvantageous to themselves. Less salient policies do not tend to garner the same level of opposition (Chetty et al., 2009). Furthermore, a review conducted by Klenert et al. (2018) found that high trust in government has been correlated with successful implementation of the more visible policies set at higher stringencies. They note that public trust in government in North America is relatively low compared to trust in countries known to be climate leaders, such as Finland, Denmark, Norway, and Sweden. This suggests an additional challenge in North America in terms of needing to minimize opposition by any potentially powerful interest group or group of voters.

Carbon pricing has been especially challenging for policymakers. In 2008, the Liberal government of B.C. introduced a broad-based carbon tax, covering approximately 70% of the economy. The Liberal government is considered centre-right and implemented the carbon tax due to its theoretical economic efficiency. Although the government reduced corporate and personal income taxes simultaneously to keep the policy revenue-neutral, the visible impacts of the carbon tax were exploited by opponents of the government and opponents of effective climate policy. B.C.'s New Democratic Party (NDP) actively campaigned against the carbon tax between its inception in 2008 and the provincial election of 2009. While a global economic recession may have distracted opponents of the carbon tax and allowed it to survive the election cycle (Jaccard, 2012), the subsequent Liberal government froze the carbon tax at \$30/tonne CO_2e until 2018. Carbon pricing was also a key election issue in the 2019 federal election; the Conservative Party of Canada emphasized the visible increases in gasoline prices at the pump and framed the policy as an attack on the middle class, just as it had successfully done in the 2008 federal election.

Regulations for GHG emissions reduction may encounter less opposition. Rhodes, Axsen, and Jaccard (2017) determined that strong opposition among respondents in B.C. was much higher for the carbon tax than for the other four main compulsory climate policies, all of which were regulations (the Clean Electricity Standard, the Low Carbon Fuel Standard, tighter energy efficiency standards, and the carbon-neutral government mandate). 24% of respondents strongly opposed the carbon pricing policy, while less than 3-9% strongly opposed the other compulsory climate policies. Given that such regulations can satisfy the other three criteria if designed properly, researchers may help policymakers through evaluating the use of alternative policy packages that focus on either carbon pricing or flexible regulations.

2.2. Climate policy in British Columbia

British Columbia has had some form of climate policies in place since 1989. As in many other countries, the government's earliest policy packages relied on relatively ineffective information and subsidy programs. Between 2007-08, the B.C. government shifted its strategy and implemented its Climate Action Plan that introduced several compulsory policies. The current policy package, introduced in December 2018, added additional compulsory policies to the mix. In the following section, I briefly describe the climate policies currently in place and discuss their performance against the four policy evaluation criteria.

Compulsory policies

The current policy package makes use of a carbon tax as well as some regulations and voluntary policies. In 2018, the government lifted the freeze on the carbon tax that had been in place since 2012. As mentioned in the introduction, revenues from this tax were made neutral to the government's budget with the introduction of offsetting income tax reductions. The carbon tax is slated to rise to $50/tonne CO2e by 2021, in line with the expectations of the Pan Canadian Framework, negotiated in 2016 between the federal and provincial governments. Industrial revenue collected by carbon taxes above the $30/tonne CO2e level will be channeled into two different incentive programs, titled the Industrial Incentive and the Clean Industry Fund. The industrial incentive reduces carbon taxes for facilities meeting specified carbon intensity benchmarks, while the Clean Industry Fund provides funding for specific industry emissions reductions projects, for which industries must apply. The current policy package does not raise the carbon tax to the level estimated by most experts to cause large emissions reductions (Carbon Pricing Leadership Coalition, 2017; World Bank Group, 2019). The carbon tax does not apply to emissions from planes and ships that are traveling to and from B.C., nor from forestry, waste, agriculture, and process emissions (released from the raw materials during processing) from industry.

While the carbon tax applies to fossil fuels, transportation remains one of the largest sources of emissions in B.C. To further decarbonize this sector, the government implemented the Low Carbon Fuel Standard (LCFS) in 2010. The LCFS mandates a 10% decrease in liquid fuel emission intensity by 2020. The government has announced its intention to raise the LCFS stringency to a 20% reduction of transportation carbon intensity by 2030. Petroleum product suppliers generally comply with the LCFS by blending biofuels into gasoline and diesel. However, as a flexible regulation, the LCFS allows suppliers to trade credits amongst themselves. Firms that find emission intensity reductions to be cheaper than the credit price may over-comply and sell their surplus credits to firms that under-comply. To further increase flexibility, the LCFS also allows for the creation of Part 3 Agreements, which grants credits to projects that might facilitate the decarbonization of transportation, but don't directly cause creditable reductions. The credits granted to Part 3 Agreement holders and suppliers who over-comply have the effect of subsidizing low-carbon fuels, reducing the economic efficiency of the policy (Holland et al., 2009). However, the LCFS has seen relatively little opposition, likely due to its low visibility (Rhodes et al., 2017). Alongside the LCFS, B.C. has a Renewable Fuel Standard (RFS) in place, which requires a minimum renewable fuel content in gasoline and diesel. Given that the policy mandates a specific type of decarbonization mechanism (biofuels), in a specific quantity, it is considerably less flexible than the LCFS.

To specifically target the technological evolution of personal vehicles, the government introduced the Zero-Emission Vehicle (ZEV) mandate in 2018. It specifies that a minimum percentage of new vehicles sold in B.C. must be classified as zero-emissions. Vehicles that can run at least part-time without producing any emissions, such as plug-in hybrid vehicles, qualify as partial ZEVs under this policy. The policy requires ZEVs to achieve 10% of vehicle sales by 2025, 30% by 2030, and 100% by 2040. The policy was introduced in May 2019, and regulations are likely to be finalized by the end of 2020.

There are additional transportation policies at the federal level. There are vehicle emissions standards for passenger vehicles, light trucks, and heavy-duty vehicles. The federal Passenger Automobile and Light Truck Greenhouse Gas Emissions Regulations specify fuel economies for new vehicles. Until very recently, this regulation was aligned with the corporate average fuel economy (CAFE) standards in the United States. For heavy-duty freight vehicles there are the Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations, which mandate a declining emission intensity per short-ton mile.

In many jurisdictions, electricity generation contributes substantial emissions alongside transportation. As mentioned previously, B.C.'s most significant policy from an emissions-reductions perspective is the Clean Electricity Standard. Much of the existing electricity generation (90%) in B.C. before 2007 was from large hydropower facilities.

Many proposed large hydropower projects have since become politically unacceptable due to their local social and environmental impacts (Jaccard, 2012; Trussart et al., 2002). To prevent B.C.'s electricity system from shifting to cheaper fossil fuel generation, the Clean Electricity Standard requires that 93% of new electricity generation be from zero-emission sources. Once the government implemented the Clean Electricity Standard, BC Hydro was forced to abandon two contracts for coal-fired power plants and its own plan to build a natural gas-fired plant. Not only did the regulation result in immediate avoided emissions, but it prevented the province from developing an increasing dependency on fossil fuels (Jaccard, 2012).

In 2018, the government committed to expanding high-voltage transmission lines into natural gas producing areas in northeastern British Columbia, the goal being to encourage natural gas producers to switch from natural gas to electricity in production processes and pumping. This is expected to reduce the life cycle emissions of extracting, processing, transporting, liquifying and consuming natural gas. The government stated that investments will be made to incentivize this fuel switch, although no monetary amounts have to date been specified. To further decrease natural gas production emissions, the government requires that methane emissions from natural gas production are to be reduced by 45% by 2025. This regulation does not specify a compliance pathway, which allows producers to choose the method best suited to their circumstances (although this is typically achieved by improving leak detection and pipeline repair programs).

To reduce within-province natural gas combustion emissions, the government in 2018 mandated a minimum biomethane content in the natural gas supply. For the remainder of this study, I refer to this policy as the Renewable Natural Gas (RNG) mandate. This policy requires a 15% minimum biomethane content in the natural gas stream supplied to the residential, commercial, and industrial sectors by 2030. Unlike natural gas, biomethane has very low life cycle emissions because its feedstock is derived from organic matter (Argonne National Laboratory, 2011). Biomethane is substantially more expensive to produce than natural gas (Electrigaz, 2008; International Energy Agency, 2020), and consequently will increase the price of the final blended natural gas product. Many natural gas-powered technologies have electric alternatives that can be used if natural gas prices increase too drastically. As an example, residential consumers can switch to electric heat pumps if natural gas costs become too high.

While a stringent RNG mandate would incentivize consumers to switch fuels, the provincial government is also working towards decarbonizing buildings through increasing the energy and emissions stringency of the building code for the construction of new buildings. It released the BC Energy Step Code in 2017. The code sets out several energy efficiency and emission levels, or “steps,” that municipalities can require or incentivize in place of the BC Building Code. Currently, only the lower levels of the steps can be required by municipalities. The provincial government claims that in 2032 the higher steps (3, 4, and 5) of the BC Energy Step Code will be in force, although a government in 2017 has no control over the policies of a government 15 years in the future.

Non-compulsory policies

To encourage further uptake of ZEVs, the government made ZEV subsidies available for consumers wishing to purchase a new vehicle. There are additional subsidies for those who trade in an existing internal combustion engine (ICE) vehicle. These subsidies, when combined with the federal ZEV subsidy introduced in 2019, results in subsidies of up to $8,000 for vehicles under $45,000. A limited amount of funds are set aside each year to fund these subsidies on a first-come-first-served basis. To motivate fuel switching from natural gas to electricity, the government is also offering a similar $2,000 subsidy for residential heat pumps.

The provincial government committed to several different actions designed to decarbonize smaller segments of the economy. These actions include support for off-grid communities, the development of vocational programs, and the electrification of government facilities. Many of these policies fall under the “voluntary” category, as they do not require any party (including the government) to make the changes.

2.3. Types of energy-economy models

I use an energy-economy model to simulate the environmental and economic impacts of the climate policies described above. In this section, I provide some background into the features of energy-economy models to contextualize my choice of model[2].

Energy-economy models, broadly speaking, are mathematical representations of an economy that can be used as tools to examine the environmental and economic impact of climate policies. Models can be designed to provide a variety of information. To meet my research objectives, I specifically required a simulation model. Simulation models create projections based on trends from historical data and research that reveal the current and likely future preferences of firms and households under changing incentives. The researcher can change these projections by simulating incentive-changing policies in the model. Generally, models can be differentiated by their performance along the following attributes:

1. Technological explicitness: the degree to which technology is represented in detail. This includes the technology's cost and its physical potential (energy use, service output). Ideally, the model should be able to represent how costs decline as the production and diffusion of a new technology increases.

2. Behavioral realism: representation of the key factors affecting technology and energy choices made by firms and households.

3. Macro-economic feedbacks: the model's ability to reflect how changes in production costs and technology choices will change the structure of the economy, total output, government revenues, government expenditures, trade, investment, jobs, and monetary value.

Models with a high degree of technological explicitness have historically been referred to as "bottom-up". These represent a broad set of technologies in detail and model how these technologies compete to meet service demands. Building a model to track technology stocks allows the modeler to see changes in technology choices over time as compulsory policies influence financial costs and other factors. This can be very useful to policymakers who seek to influence technology choices to reduce emissions. However, most conventional bottom-up models lack behavioral realism. Older bottom-up

[2] For an in-depth overview of the history, attributes, and applications of energy-economy models, see Jaccard (2009).

models treat competing technologies as perfect substitutes even though the non-financial preferences of firms and households can play a huge role in technology uptake. For example, a bicycle is a much cheaper mode of transportation than a personal vehicle. However, cyclists experience some degree of discomfort relative to a car in the form of exertion, occasional poor weather, increased safety risks, and a lengthier travel time. These are factors that are not included in the financial cost of a bicycle but will be considered by the purchaser. Modelers refer to such welfare costs as “intangible costs.” Many early bottom-up models also lacked macro-economic feedbacks and thus were unable to estimate the change in output that would result from climate policies. However, as I discuss later in this section, complete equilibrium macro-economic feedbacks are not always necessary for modeling the key effects of climate and energy policies.

As described by Jaccard (2009), models that estimate the aggregate relationships between the relative costs and market shares of inputs to the economy and its outputs are referred to as top-down models. Because top-down models estimate these relationships from real-world market data, they are thought to incorporate a high degree of behavioral realism – economists refer to these as revealed preferences. Top-down models make use of elasticity of substitution parameters to represent substitution between competing inputs in the economy. Elasticity of substitution parameters dictate the ease with which a climate policy can induce a shift from high-emission inputs to low-emission inputs (Ramskov & Munksgaard, 2001). It is not always possible to obtain adequate historical records to estimate statistically significant parameters. Where elasticity of substitution parameters cannot be estimated, the modeler makes judgement calls on the appropriate value, which introduces the risk of inaccuracy and bias. An additional weakness of typical top-down models is that their parameters represent responses with past technologies to cost changing policies whereas emerging technologies may trigger significantly different responses. For example, the response to a carbon tax that increases gasoline prices may be greater once electric vehicles are a more viable alternative. Likewise, it can be difficult to simulate policies that target a specific new technology, such as a purchase subsidy for electric or hydrogen fuel cell vehicles.

Models can be further categorized as partial or full equilibrium. This characteristic describes the degree to which the model represents all the feedback effects in the economy. A partial equilibrium model will represent sections of the economy, finding an equilibrium amongst these represented sections. To increase realism, the model may also equilibrate with the economy "outside" what is represented in the model. Partial equilibrium models are generally less computationally taxing to run, as they will not need to equilibrate a full economy nor any external economies outside of the one the researcher chooses to represent. Because they are less complex, it is easier for researchers and policymakers to understand the model's results (Pfenninger, 2017; Pindyck, 2018). Unfortunately, their incomplete representation of economic impacts means that important policy implications may be underrepresented. Modelers can help policymakers decide if these implications are significant and potentially adjust their results to compensate for the lack of general equilibrium feedbacks in the model.

Full (or general) equilibrium models must equate the inputs and outputs of an entire economy (the boundary of which is still defined by the modeler). Full equilibrium models begin under an assumed equilibrium, which is then disrupted by climate policies. The model calculates a new set of prices based on elasticity of substitution parameters and finds a new level of consumption and production based on supply and demand functions (Bergman and Henrekson, 2003). Full equilibrium models that link macroeconomic feedbacks are referred to as Computable General Equilibrium (CGE) models. Policymakers may find it convenient to rely on full-equilibrium models given that they can be used to estimate changes in GDP, employment, and trade with external economies. These estimates are useful for assessing the fullest possible economic impacts of high-stringency policies seeking to almost completely decarbonize the energy-economy system.

Depending on what the researcher chooses to analyse, both partial and full equilibrium models can be useful. GTech, the model used by Navius Research for their 2018 government-commissioned evaluation of CleanBC, is a model built on macroeconomic relationships that also incorporates a high degree of technological explicitness. Classic "bottom-up" models such as MARKAL have been expanded into families of models that integrate technological explicitness and macroeconomic feedbacks to increase their utility (Loulou et al., 2004). A variety of energy-economy models are used to advise all levels of government, from spatial and technology-focused models at the municipal level to large-scale economy-climate models at the international level that require teams of researchers to maintain. The model I use for this study, CIMS, has been applied in Canada and other countries since the early 1990s, modified to suit investigations at the urban, regional, and national levels and to incorporate new evidence and techniques over the last two decades. I discuss CIMS in more detail in the methodology section.

Chapter 3. Modeling Methodology

CIMS is a partial-equilibrium energy-economy simulation model that includes technological explicitness, behavioral realism, and, to some extent, macroeconomic feedbacks. CIMS tracks the technology capital stocks as they age and are replaced over time. It has a long record of being used for provincial and national-level analysis (Jaccard et al., 2003). In section 3.1., I give an overview of CIMS's structure and the market-share equation. In section 3.2, I discuss the specific settings I used for this study. In section 3.3., I review the modeling assumptions I use that apply to all policy runs. Finally, in section 3.4, I briefly address CIMS's limitations.

3.1. CIMS model overview

CIMS simulates the economy in 5-year intervals from the year 2000 through to 2050. In each time interval, the model runs through the following steps (Bataille, 2005; Rudd, 2012):

1. Demand assessment: The model assesses demand based on the forecasts provided by the user. Demand is represented by a unit of service provided, such as vehicle kilometers traveled, or unit of floorspace lit.

2. Retirement and retrofit: During each time period, some of the previous year's capital stock is retired. The service provided by the remaining stock is subtracted from the forecasted energy service demand. The difference between total demand and the available stock determines how much new stock should be purchased.

3. Competition for new stock: Technologies compete to fulfill the new stock requirements. The competition between these technologies is represented by the market share equation (Figure 1 CIMS market-share equation (Bataille et al., 2007), which I explain below.

4. Equilibrium of supply and demand: Once there is adequate stock to fulfill forecasted demand, the model iterates between energy supply and demand until it reaches an equilibrium set of energy prices and energy demand.

5. Output: The model uses its technology market shares to determine energy consumption, emissions, economic factor costs, and service output.

Competition for new market shares in CIMS is represented by the market share equation (Figure 1).

$$MS_j = \frac{\left[CC_j \cdot \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{k}\left\{\left[cc_k \cdot \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k\right]^{-v}\right\}}$$

Figure 1 CIMS market-share equation (Bataille et al., 2007)

This equation calculates market share for a technology by dividing the annualized costs of the technology (*j*) by the sum of the annualized costs of all other competing technologies (*k*) in a logistic function that includes all real and intangible costs that would be associated with purchasing and operating the technology. This includes the capital cost (CC), which is multiplied by the capital recovery factor to determine annualized capital cost, operation and maintenance costs (MC), and energy costs (EC).

The CIMS market share equation contains three behavioral parameters that distinguish it from traditional bottom-up technology-rich simulation models:

- *r* represents the revealed time preference (private discount rate) of the household or firm choosing between technologies. This value can vary across sectors because of the different decision-makers being simulated.

- *i* represents intangible costs, which are additional costs not reflected in the purchase price of technologies. These reflect non-financial factors in firm and household preferences when choosing between technologies.

- The heterogeneity parameter, *v*, indicates the circumstances different consumers face when making what is otherwise the same purchase decision. If the market were homogeneous, the apparent least-cost technology would always capture all the market. In reality, people and firms face heterogeneous costs and have different perceptions of costs and risks and are therefore likely to make different decisions based on their circumstances. A high *v* value causes the least-cost technology to receive most, if not all, of the market share, indicating that most technology acquirers are similar in a particular case. A low *v* value causes a greater diversity of technological adoption, indicating a greater heterogeneity of market conditions and consumer perceptions, even if the single least-cost choice appears obvious to the analyst (Bataille, 2007).

By modeling all the available technologies involved in an economy's production and consumption of energy, CIMS can track the flow of energy in the economy and how it evolves as firms and households are influenced by compulsory policies. Policies can provide certain technologies with cost advantages over others or even specify minimum or maximum market shares so that the model outcomes match regulatory requirements. B.C.'s Zero-Emission Vehicle (ZEV) mandate, for example, requires a minimum new market share of zero-emission vehicles, which can be set explicitly in CIMS. As CIMS can simulate competitions between technologies for nearly every aspect of the economy, it is a suitable model for energy and climate policy analysis.

Aside from its market-share equation, CIMS incorporates a suite of other functions designed to characterize microeconomic effects and behavioral realism. The Declining Capital Cost (DCC) function characterizes the rate at which capital costs fall as a result of learning-by-doing and economies-of-scale with greater adoption of new and emerging technologies. This function allows the capital costs of technologies to fall as a function of cumulative adoption of the technology in the model. Capital cost is also impacted by an exogenous rate of decline if there is a rising global production of the new technology. The declining intangible cost function captures how the perceived risk of a new technology falls as its market share increases, also known as the "neighbour effect" (Jaccard, 2009). Together, these functions represent both the economic and the behavioral effects that can reduce the real and perceived costs of technologies in the market.

CIMS includes functions that represent some macroeconomic feedbacks such as changes in disposable income, reductions in service demands (like mobility) with rising costs, and Armington elasticities that reflect reductions in industrial output (of emission-intensive, trade-exposed industries) with rising costs relative to competitors (Bataille, 2007). Industrial output in CIMS is initially set exogenously and thus does not change unless the user chooses to activate Armington elasticities as an optional macroeconomic feedback function[3].

3.2. CIMS settings and sector calibration

3.2.1. Model settings

CIMS includes several settings that the analyst can adjust to suit their research. These settings dictate which variables will be calculated endogenously and which must be set exogenously. The scope of the modeling exercise may dictate which variables are endogenous or exogenous. Research at the urban level, for example, can be conducted with a minimal level of endogenous calculation, as an urban economy will be largely influenced by provincial, national, and global markets. A national-level analysis may have more influence on energy prices and technology economies-of-scale. Even at a national level, the user might choose to model certain parameters exogenously, if the country is considered a price-taker in global markets. Thus, CIMS is very flexible for modeling runs at many regional scales. I summarize my economy-wide settings in Table 1.

[3] For the purposes of this study, I assume that the rest of the world works towards similarly stringent climate policies, which would cause imported goods to rise in cost at the approximately the same rate as domestic goods. I explain this assumption further in Chapter 4.

Table 1 CIMS settings for this study.

CIMS Setting	Setting for this study
Energy supply and demand	On
Fuel production	
Crude Oil	Exogenous
Natural gas	Exogenous
Coal	Exogenous
Refined petroleum products	Exogenous
Fuel Pricing	
Crude oil	Exogenous
Natural gas	Endogenous
Refined petroleum products	Exogenous
Electricity	Endogenous
Biofuels	Endogenous
Macro feedbacks	Off
Energy trade	Off
GHG pre-cognition	Average (begins in 2020)
Revenue recycling	On

For my research, I set energy supply and demand to equilibrate. I also specify which energy supplies would follow a fixed exogenous production and price trajectory versus a trajectory calculated endogenously to meet demand within the model. As B.C. is a price taker in the context of global markets, most energy price trajectories can be set as exogenous to the model. In this study, I allow crude oil, coal, and refined petroleum products to follow exogenous production and price forecasts, which were obtained from the Canadian Energy Regulator's (CER) Energy Futures Report 2016[4]. I rely on the 2016 report rather than more recent reports due its High and Low LNG scenarios, which are relevant to the LNG scenario analysis I conduct for this study. To stay consistent, I use the 2016 report for conventional fuel prices as well.

B.C.'s electricity market is mostly self-contained, relying on hydropower with minimal imports from Alberta and exports to the United States. Therefore, I set electricity production as endogenous. Although B.C. is currently a price taker in the global natural

[4] As of 2019, the National Energy Board has been replaced by the Canadian Energy Regulator. Therefore, I credit all work I reference by the National Energy Board to the CER.

gas market, the government's RNG mandate is set to push B.C.'s domestic natural gas consumption towards biomethane. In anticipation of a shift in B.C.'s consumption and production of natural gas, I set domestic natural gas pricing as endogenous. I set the level of natural gas production in B.C. exogenously, dependent as it is on the gas trading prices resulting from the interaction of global demand and supply through pipeline and LNG trading.

For larger-scale studies, researchers using CIMS can make use of the aforementioned Armington elasticities, which alter domestic production based on relative production cost changes. While these elasticities can be useful for approximating national-level interactions with global markets, I chose to turn them off for this study. As discussed previously, a jurisdiction as small as B.C. is unlikely to pursue stringent climate policies independently of other jurisdictions.

CIMS has a "GHG-precognition" feature, which allows the researcher to set consumer anticipation of an emissions pricing policy. The government could announce a base level for a pricing scheme and specify its increasing stringency over time. This was the case for the government of B.C. with its scheduled rising carbon tax over the period 2008 to 2012, and more recently the federal government, with its carbon price on a scheduled increase between 2018 and 2022. Transparency in pricing allows firms and households to respond to the change in price when it is convenient. For example, a firm with technology stock that needs to be retired could switch to a less emissions-intensive, but more expensive technology if it knew that a future increase in the carbon price would result in the life-cycle costs of the high-emissions alternative exceeding that of the low-emissions technology. In CIMS, GHG-precognition can be set one of three ways: "current," which only accounts for the emissions prices during the iteration period, "average," which accounts for the tax over the lifetime of the technology, and "discount," which accounts for the tax over the lifetime of the technology using discounted future emission charges. I set GHG-precognition to average, in line with similar studies previously conducted with CIMS. Firms and households will be able to anticipate future changes in emissions prices but are unlikely to conduct a formal economic calculation that discounts future increases in emissions prices back to present values.

CIMS can include the return of revenue from emissions prices directly back to the sector where it was collected. Until 2018, this option was reflective of B.C.'s carbon pricing policy. B.C. collected tax revenue from carbon pricing, but reduced corporate and personal income taxes by an approximately equal amount (Murray & Rivers, 2015). With the introduction of the current policy package, the provincial government announced that it would earmark revenue from industrial carbon pricing over $30/tonne CO2e into several industrial decarbonization incentives. Given that all revenues collected for these incentives will eventually be reinvested back into the industrial sectors, I continue to assume full revenue recycling for industry and all other sectors.

3.2.2. Calibration of the model to historical emissions

All models, to some extent, are calibrated to past data on the energy-economy system to ensure that the model adequately represents the static condition of that system in the current period and to also, hopefully, capture dynamics of that system. For this study, I calibrate my representation of B.C. in CIMS to the federal government's National Inventory Report (NIR). The NIR comprises data collected from industry, modeled estimates, as well as an array of emissions and other data. At the time of calibration, the most recent report was from 2018. I calibrate to historical emissions for the 2005, 2010, and 2015 timesteps.

To calibrate the emissions by sector, I adjust the exogenous demand forecasts. These forecasts specify the service demands for each sector that the model must use technology stocks to meet. I adjust demand forecasts over other parameters because increasing demand preserves the relationship between represented technologies and their associated fuel use, process emissions (such as those released in concrete production), and combustion emissions. Given that the policies I model, such as the carbon tax, impact technology uptake according to associated fuel use and emissions, I concluded that changing demand forecasting is the least disruptive way of calibrating CIMS. I adjust the forecast for each sector until emissions in CIMS were within a 10% threshold of the equivalent NIR sector (Table 2). I focus on the industrial sectors, as the demand forecasting for the residential, commercial, electricity, and transportation sectors are based on exogenous projections from other researchers.

Table 2 Calculated differences between CIMS output emissions and NIR emissions. Emissions are shown in MtCO2e.

	2005			2010			2015		
Sector	**CIMS**	**NIR**	**Diff**	**CIMS**	**NIR**	**Diff**	**CIMS**	**NIR**	**Diff**
Chemical Products	0.97	0.89	-9.2%	0.43	0.44	2.4%	0.38	0.35	-7.3%
Industrial Minerals	2.51	2.33	-7.8%	1.77	1.67	-6.2%	2.23	2.22	-0.3%
Metal Smelting	1.60	1.73	7.6%	1.28	1.43	10.4%	0.92	0.93	1.2%
Mineral Mining	0.29	0.30	2.0%	0.25	0.23	-6.6%	0.31	0.32	3.4%
Paper Manufacturing	1.71	1.85	7.3%	2.11	1.95	-8.3%	1.83	1.87	1.9%
Other Manufacturing	4.31	4.28	-0.9%	2.51	2.26	-10.9%	2.48	2.35	-5.5%
Agriculture	3.09	3.07	-0.5%	2.39	2.66	10.1%	3.03	2.86	-6.0%
Waste	4.22	4.15	-1.6%	4.10	4.02	-2.1%	3.71	3.69	-0.6%
Oil & Gas	12.08	12.50	3.3%	13.62	13.43	-1.4%	14.32	13.84	-3.5%
Coal Mining	1.56	1.70	8.0%	1.92	1.88	-2.6%	1.46	1.63	10.2%

The NIR sectors do not equate exactly with the sectors in CIMS. The differences in categorization mean that some discrepancies occur between sectoral emissions in the NIR and CIMS.

3.2.3. Sector activity levels, energy production, and energy price projections

To set exogenous demand forecasts for industrial production and non-industrial energy service demands after 2015, I rely on historical production data from Statistics Canada and used various sources for setting growth rates out to 2050. The annual growth rate for each sector is listed in Table 3. For natural gas forecasting, I use forecasts from the CER’s Energy Futures report. To determine growth in demand, I average the percentage change in GDP over 5-year intervals from the earliest available year (either 1997 or 1990) in each sector until the latest available year, 2018. If there are any unusual spikes in GDP, I judge on a case-by-case basis on whether to include them. I then apply this average percentage change to the demand forecast extending to 2050.

Table 3 Annual change in activity in CIMS, by sector

Sector	Annual Growth Rate
Residential	1.0%
Commercial	1.8%
Transportation Personal	1.4%
Transportation Freight	0.8%
Chemical Products	1.3%
Industrial Minerals	1.5%
Metal Smelting	1.4%
Mineral Mining	0.5%
Paper Manufacturing	-0.6%
Other Manufacturing	2.1%
Agriculture	0.5%
Waste	4.1%
Electricity	1.3%
Petroleum Refining	2.4%
Petroleum Crude Extraction	2.5%
Natural Gas Extraction	0.7% Low, 1.8% High
Coal Mining	-0.4%

I do not make changes to the demand forecasts of other sectors. The personal and freight transportation sectors were calibrated by previous researchers in the Energy and Materials Research Group (EMRG) to match modeled data from Natural Resources Canada's Comprehensive Energy Use Database. Past EMRG researchers also compiled population projection data for the province, as well as commercial floorspace projection data. These drive demand for the residential and commercial sectors. Since the projections for these sectors match the NIR's emissions projections relatively closely, I do not alter them.

3.2.4. LNG production uncertainty

The natural gas production forecast was set separately from the other sectors. I focus on natural gas production due to uncertainty surrounding LNG development projects. Increased natural gas exports will cause significant increases in industrial energy demand and could cause a substantial increase in industrial GHG emissions, depending on the type of energy used to liquify the gas for export by tanker. To characterize the changes to provincial emissions this uncertainty would cause, I duplicate the policy runs under two scenarios: High LNG and Low LNG. This allows me to examine changes to capital stocks and fuel use that will occur under different energy demands from the natural gas extraction sector. To set the exogenous production forecasts for these scenarios, I use the CER's 2016 Energy Futures Report, which specifically explores High LNG and Low LNG scenarios. The Energy Futures Report projects to 2040. I extend the 2040 projection to 2045 and 2050. I set the sector's production rate and export rate to match the report.

3.3. New CIMS sector assumptions

Natural Gas Extraction

For this study, I update the way biomethane is produced and used in the CIMS model from previous studies. The Renewable Natural Gas mandate requires that the natural gas supply contain a minimum of 15% biomethane content by 2030. This policy includes the residential, commercial, and industrial sectors. Previously, biomethane had only been available in CIMS as a fuel alternative for industrial boiler technologies. A separate version of CIMS scaled down to the urban level also simulated competition between natural gas and biomethane in the residential and commercial sectors. Both competitions were modeled by creating methane fuel service that contained biomethane and conventional natural gas production technologies. Biomethane pricing was set exogenously, with costs rising proportionally to the price changes of natural gas (also exogenous at the time).

I alter these in-sector competitions slightly. On the demand side, I keep the competitions between biomethane and natural gas. On the supply side, I add biomethane production technologies to the natural gas supply sector. Adding representative biomethane technologies on the supply side and in end-use demand sectors allows me to model an increase in proportional biomethane supply as well as any potential fuel switching as a response to this shift. To determine the costs for these technologies, I rely on a 2008 report conducted by Electrigaz Consulting and a follow-up 2017 report by Hallbar Consulting on biomethane production feasibility in B.C. Electrigaz and Hallbar calculated a conservative retail cost of approximately $28/GJ of biomethane produced. This is significantly higher than the cost of natural gas. I anticipate that the biomethane blending mandates will increase the cost of blended natural gas, which in the CIMS policy simulations should lead to a growing substitution of natural gas for electricity in building services and potentially other end-uses. Due to the anticipated decrease in domestic demand for blended natural gas that would result from this policy, I assume that B.C. will be able to support enough domestic biomethane production to meet demand. Costs on the production side were calculated from the capital, operational, and energy costs estimated by Electrigaz.

Personal Transportation

To model B.C.'s personal vehicle policies more accurately, I altered the vehicle motor competition in CIMS. Normally, vehicle motors are modeled in a competition separate from the rest of the vehicle body. Vehicle body costs are assumed to be similar regardless of the motor that drives the vehicle. To force a minimum market share of zero-emissions vehicles for the ZEV mandate, I separated the competition of internal combustion engine (ICE) vehicles from the general vehicle motor competition. A variety of ICE vehicle motors now compete to fulfill a general demand for "ICE services," the market share of which declines at a rate determined by the stringency of the ZEV policy. The general ICE technology that demands "ICE services" competes with a variety of ZEVs.

Biofuel assumptions

Suppliers have lowered the carbon intensity of gasoline and diesel by blending ethanol and biodiesel as required by renewable fuel mandates. The content of ethanol in gasoline and biodiesel in diesel has an upper limit known as the "blend wall." Currently, the blend wall for conventional ethanol in gasoline is about 10% ethanol, while for conventional biodiesel the content is limited to 20% of the diesel blend. These maximum blends for biofuels will remain a limitation in transportation decarbonization until fully blendable fuels are commercialized and affordable. For this study I assume a blend wall of 10% ethanol in 2020, rising to 15% in 2030 as manufacturers develop the capacity to burn higher ethanol blends. The biodiesel blend wall in CIMS does not rise beyond 20%, but diesel can be substituted entirely by hydrogenation-derived renewable diesel (HDRD). HDRD is derived from the same feedstocks as conventional biodiesel, but undergoes more complex processing and is costlier as a result (Natural Resources Canada, 2012). I make HDRD available in the model to compete with the diesel blend in 2015. However, I place limit on the proportion of HDRD that can enter the market in early years to prevent a sudden uptake that does not reflect short-term availability.

Biofuel consumption is also constrained by feedstock availability. Conventional ethanol is produced from corn, sugarcane, and wheat. Researchers have noted that the demand for food crops for biofuels may create competition for arable land and spur an increase in food prices (Fischer et al., 2010). This is detrimental to both food security and cost-effective biofuel production. To mitigate reliance on food crops, among other reasons, scientists developed advanced (also known as second-generation) biofuels to use non-food feedstocks, such as woody biomass and other cellulosic feedstocks (Evans, 2007; Robertson et al., 2008). Biomass used in the production of second-generation biofuels can be grown on lower-quality land that is not used for food production (Gelfand et al., 2013).

The Global Energy Assessment (2012) estimates that, by using a wide range of potential feedstocks, Canada can produce enough biomass to maintain a 1.7 EJ/year production capacity by 2050, without encroaching on prime agricultural land. Given that B.C. currently consumes approximately 0.45EJ of RPP annually, I assume there will be adequate biofuel production within B.C. to meet the demand simulated by my application of CIMS to the year 2050. In its most recent climate plan, the provincial government discussed establishing a renewable fuel industry, increasing domestic production to supply 8% of B.C.'s road transportation fuel needs by 2030. I assume that this industry will able to grow sufficiently to meet domestic demand for biofuels. If provincial production does not grow adequately, I assume that B.C. will also be able to import fuel or biomass.

Biomethane assumptions

As with biofuels, I assume that there is adequate feedstock in B.C. to meet biomethane demand. Recent technological innovations have made it feasible to create biomethane out of woody biomass, further extending the feasible production quantity within B.C. Currently, most of the wood residue produced in B.C. is left onsite or burned as a waste product (Hoberg et al., 2016). Aside from biomethane, woody biomass has been targeted by biofuel production companies, researchers, and consultants as a potential feedstock for other biofuels as well. While there is potential for competition for woody biomass as a feedstock, a fall in domestic demand for natural gas may render this concern as moot. Although it is theoretically possible to produce enough biomethane to meet demand in end-use sectors, its cost is likely to fluctuate according to demand

and feedstock availability. To accommodate this likelihood, I set the pricing for biomethane conservatively high.

In this study, I assume that biomethane production is the dominant pathway towards decarbonizing the natural gas blend, but this is not necessarily the case. Further innovations in hydrogen production may allow it to become a viable alternative to natural gas. Using CCS may prove to be the more cost-effective option for low-emission natural gas production should biomethane feedstock prove limited. However, it is more important for these alternatives to be competitive with electricity; hydrogen and natural gas with CCS are not currently competitive with electricity for most energy end-uses. Unless the costs fall substantially, B.C.'s residential, commercial, and industrial sectors are more likely to electrify as depicted in this study.

3.3.2. Limitations

As noted, CIMS is a partial-equilibrium model with some of the corresponding limitations of such models. General equilibrium models incorporate a utility function for firms and households which simulates how they substitute between non-energy intermediate and final goods. To illustrate, wood and concrete can be used as substitutes in building construction to some degree. In reality, if the price of concrete were to rise high enough, firms would substitute more wood in buildings. Since CIMS does not represent this substitution potential between non-energy intermediate and final products, this lack could result in an overestimation of the costs of climate policies. As one sector's production costs rise relative to another's, a general equilibrium model can simulate how substitution might occur between products to lower the cost of responding to the climate policy, thus showing a lower cost of society achieving ambitious decarbonization targets. At the same time, however, governments design their climate policies to minimize structural change, by reducing for example the effect of climate policies on the production costs of different sectors. This suggests that a general equilibrium model may not always be necessary.

My representation of B.C. in CIMS as a stand-alone economy is also a limitation. Modeling B.C. alone, without macroeconomic feedbacks, is likely to underrepresent the adjustments in trade between B.C.'s economy and external economies. It could be more accurate to have other provinces and the United States, Canada's largest trading partner, explicitly represented within the model. Previous national-level studies using CIMS have represented all of Canada's provinces and territories. However, updating these provinces with the current and more stringent policies to match my target-achieving packages was deemed outside the scope of this study.

Chapter 4. Run Descriptions and Assumptions

To explore the changes in technological outcomes that result from different packages of decarbonization policies, I explore four different policy runs. In this section, I describe and list my assumptions for each run. *BAU* provides a reference point by depicting how emissions would increase without further increases in policy stringency. *Current and Announced Policies (CAP)* simulates the emissions trajectory with committed B.C. government policies as of 2020. *CAP + Carbon Pricing* models the current policy package along with a carbon price that rises sufficiently in a leading role to cause emissions to achieve the future targets. Finally, *CAP + Flexible Regulations* also models the current policy package but instead of a rising carbon price increases the stringencies of a set of flexible regulations sufficiently to achieve the climate targets. For details on how I modeled each policy in CIMS, see Appendix A.

4.1. Business as Usual (BAU)

This run represents B.C.'s climate policies as of 2020, with no additional increases in stringencies even if they have been announced to the public. *BAU* was used as a reference run for comparison with the other scenarios in this study. It could represent a scenario where a new government is elected and policies are either frozen at their current stringencies or repealed. Several Canadian political parties, such as the federal Conservative Party of Canada and the B.C. Liberals, have proposed such repeals as part of their election platforms.

- B.C.'s provincial carbon tax was introduced in 2008, at $10/tonne CO2e. The price rose by $5/tonne of CO2e per year until 2012, when it was frozen at $30/tonne CO2e until 2018. The provincial carbon tax is scheduled to rise $5/tonne of CO2e per year until it reaches $50/tonne CO2e in 2021. At the national level, the federal government implemented a backstop carbon price that rises to $50/tonne CO2e in 2022. For the *BAU* run, I keep the tax at its scheduled 2020 stringency of $45/tonne

CO2e[5]. Prices are entered into CIMS in 2005 dollars; I assume an inflation rate of 1.5%. The carbon tax is not indexed to inflation. As a result, the carbon tax declines slowly in real terms after it is frozen.

- I assume that the LCFS meets its target of a 10% carbon intensity reduction by 2020. I assume that the LCFS credit market clears in each of the model's timesteps.

- The Renewable Fuel Requirement requires a set proportion of renewable fuels per unit of fossil fuel. To model this policy in CIMS, I phase out unblended gasoline in 2010.

- To encourage adoption of zero-emission vehicles, both the provincial and federal governments currently have EV subsidies in place. Each government sets aside a specific budget amount for these and it fluctuates from year to year. It is difficult to anticipate how current and successive governments will alter EV subsidies beyond the current levels. For example, in 2019, the B.C. EV subsidy was reduced from $5000 per EV to $3000, without a change in government. The pricing scheme may or may not change following the 2020 provincial election. Leading up to the most recent federal election, The Conservative Party of Canada did not include any wording on vehicle subsidies or rebates in their climate plan. For the purposes of this study, I assume that EV subsidies in B.C. cease after CIMS's 2020 timestep.

- As of 2020, 98% of B.C.'s electricity is generated from renewable resources. The Clean Electricity Act was introduced by the B.C. Liberals (B.C.'s centre-right political party) in 2011 and no government has made significant moves to repeal it since. For this reason, I assume that the policy remains in place under a *BAU* scenario, although it does not rise in stringency.

[5] The scheduled increase in the carbon tax from $40/tonne CO2e to $45/tonne CO2e has been delayed due to the Covid-19 pandemic. Its scheduled increase will resume in April 2021. I have kept the tax rising according to its original schedule, as the pause will have a minimal impact over a multi-decade simulation.

- Finally, I include the federal vehicle emissions standards that separate personal and light-duty vehicles from heavy-duty vehicles. To model this policy, I assume that standard ICE vehicles become unavailable in 2020 and higher-efficiency ICE vehicles are sold instead.

4.2. Current and Announced Policies (CAP)

The *CAP* policy run is a representation of British Columbia's current and announced climate policies as of December 2018. It is difficult to anticipate how the government will implement climate policy beyond 2030 and the efforts of one government are not always sustained with a change of government – examples being the climate policy stagnation in B.C. from 2010 to 2015 with the government of Premier Christy Clark and federally in Canada from 2006 to 2015 with the government of Prime Minister Stephen Harper. Therefore, I assume that all policies remain frozen at their 2030 levels unless stated otherwise. *CAP* includes all policies from *BAU*, with the following changes:

- The carbon tax rises as part of the new policy package, from its frozen 2012 level of $30/tonne CO2e to $50/tonne CO2e by 2021. As there have been no announcements to increase the tax beyond this point, I hold the tax at $50/tonne CO2e from 2021 through until 2050. The current policy package changes the way revenue from the tax is distributed. All revenue from industries exceeding $30/tonne CO2e will be collected and redistributed through the Industrial Incentive and the Clean Industry Fund. To simplify this policy for modeling purposes, I assume that all revenue collected from industry is fully recycled back into its respective sectors.

- As with the LCFS, the ZEV mandate uses a credit trading mechanism. Automakers who exceed the minimum share of zero-emission vehicle sales are granted credits that can be traded with automakers who incur debits. I assume that the ZEV market clears in each timestep. To model the ZEV, I allot 10% of the new market share to ZEVs after 2025, rising to 30% in 2030, and 100% in 2040.

- Currently, municipalities have the option of adopting or ignoring lower stringencies of the Step Code. Higher levels of the Step Code will not become mandatory until 2032 when they will be instituted as a minimum requirement for the B.C. Building Code. To model the provincial building code with the introduction of the Step Code, I slowly phase out high-emission building technologies and prevent them from taking any market share after 2030.

- To model the RNG mandate, I assume that natural gas suppliers can source enough biomethane to meet their 15% target by 2030 in their natural gas stream. Biogas processed into biomethane is chemically nearly identical to conventional natural gas. Thus, I assume that there is no blend wall between the two fuel types.

- To further reduce emissions associated with natural gas extraction, production and transport, the government committed to a 45% reduction of methane emissions in the industry by 2025. I assume that natural gas industries will begin to phase out high-emission technologies and replace them with the least-cost low-methane alternative. I assume that the sector will move towards leak detection and repair technologies to reduce methane leakage, with more effective technologies becoming available over time. I phase out gas production pathways in CIMS that do not include leak detection and repair programs and prevent them from taking any new market share by 2020.

- The provincial government has also committed to provide subsidies for home appliance upgrades and retrofits. The government currently offers residents a $1200 rebate for converting their electric resistance heating system to an electric heat pump and $2000 for converting their oil, propane, and natural gas furnace heating systems to an electric heat pump. For simplicity, I assume a subsidy of $2000 for all new electric heat pumps.

There are several action items in the current policy package that are not detailed enough to be executed in CIMS. For example, the government aims to provide a regulatory framework for carbon capture and storage, including new direct air capture innovations. It does not specify any policies that require carbon capture and storage. However, policies that increase the costs of GHG-emitting technologies may induce increased carbon capture and storage as they become a viable solution in a stringent policy environment.

4.2.1. Current and Announced Policies + Carbon Pricing (CAP + Carbon Pricing)

To bridge the gap between the current policy package and the emissions target, I raise the carbon price from its announced level of $50/tonne CO2e by 2022 until B.C. meets its emissions reduction targets for both 2030 and 2050. In modeling policy runs that meet the emissions targets, I make implicit assumptions about jurisdictions outside of B.C. Decarbonizing the economy is likely to create a rise in production costs if emissions-intensive trade-exposed industries are subject to carbon pricing or regulations of rising stringency. Without carbon tariffs on imports and carbon subsidies to exports (called border carbon adjustments) to keep domestic and foreign goods at relatively the same cost, industrial output in B.C. is likely to fall. Thus, I assume that Canada and the rest of the world begin to pursue similarly ambitious climate targets, or that Canada implements policies that reduce the cost impacts for B.C. industries. These policies would keep the cost of foreign produced goods unchanged relative to domestic produced goods, thereby leaving domestic and export demand mostly unchanged.

4.2.2. Current and Announced Policies + Flexible Regulations (CAP + Flexible Regulations)

My final simulation also bridges the gap between the *CAP* policies and the 2030 and 2050 emissions targets. I adjust the stringencies of each regulation to approximate the GHG reductions in each sector that would occur under a single, economy-wide carbon price. My assumptions about the rest of the world's actions are identical to those I make in the *CAP + Carbon Pricing* scenario.

Some sectors are regulated by more than one policy. For example, the personal transportation sector experiences emissions reductions from both the ZEV mandate and the LCFS. Where there is policy overlap, I only change the stringency of the policy with more potential compliance pathways, or “flexibility.” For example, in the case of personal transportation, I increase the LCFS to meet emissions targets and leave the ZEV mandate as announced by the government. For the most part, I rely on regulations that already exist as part of B.C.’s current climate policy.

In summary, I make the following policy assumptions under this run:

- To decrease transportation emissions, I increase the LCFS beyond what was specified in the current policy package. To approximately match the carbon price scenario, I impose different percentage reduction rates for gasoline and diesel.

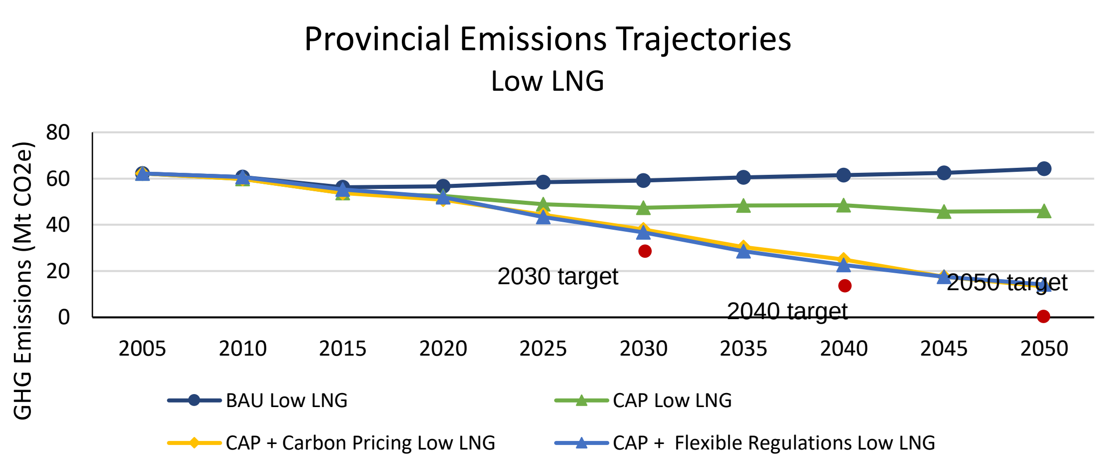
- To decrease the emissions of industrial sectors, I model industrial emission intensity standards, which require each industry to reduce its emission intensity until sectoral emissions match those of the *CAP + Carbon Pricing* run. To model the emission intensity standards, I assume that prices of high-emissions outputs rise as facilities with high abatement costs subsidize the production of facilities with low abatement costs by buying credits from them as necessary. I assume that the credit trading market for each industry clears in every timestep. These standards, when modeled, produce an outcome that is nearly identical to an Output-Based Pricing System (OBPS). The OBPS creates a price signal for emissions-intensive trade-exposed (EITE) industries by charging industries for emissions above an allowable amount. Each industry’s allowable emissions are determined using an output-based standard. Although the policies are not structured in exactly the same way, they create similar cost changes in the model and consequently similar outcomes.

- To reduce emissions in the biofuel and hydrogen production sectors, I assume a phase-out of production technologies that consume fossil fuels and replace them with technologies that consume either electricity or biofuels. As I model relatively few biofuel production pathways, this could represent either an upstream performance standard or a more flexible emissions intensity standard.

Chapter 5. Results and Discussion

5.1. Provincial results

The provincial emissions targets specify a 40% reduction in GHG emissions by 2030, a 60% reduction by 2040, and an 80% reduction by 2050, relative to 2007 levels. This is equivalent to reducing emissions to 39Mt CO2e in 2030, 26Mt CO2e in 2040, and 14Mt CO2e in 2050. Absent the current policy package, emissions continue to rise (Figure 2 Provincial emissions trajectories by policy run. *CAP* + *Carbon Pricing* and *CAP* + *Flexible Regulations* meet the emissions targets.. The Low LNG scenario of *BAU* projects emissions rising to 64Mt CO2e by 2050, while the High LNG scenario projects emissions rising to 68Mt CO2e by 2050. Under *BAU*, a portion of natural gas extraction GHG emissions are captured and stored, which reflects acid gas disposal practices that currently occur throughout B.C. and includes some CO2 along with the targeted acid gases (B.C. Oil & Gas Commission, 2018). Without targeted carbon capture and storage, natural gas extraction contributes an additional 12MtCO2e under a Low LNG scenario, and 17MtCO2e under a High LNG scenario, which would more than double the sector's emissions. This demonstrates the importance of capturing emissions should the province proceed with LNG expansion. With the implementation of *CAP*, emissions in 2050 fall to 46Mt CO2e under a Low LNG scenario and to 48Mt CO2e under a High LNG scenario. By design, both *CAP* + *Carbon Pricing* and *CAP* + *Flexible Regulations* emissions meet the 2030, 2040, and 2050 climate targets.



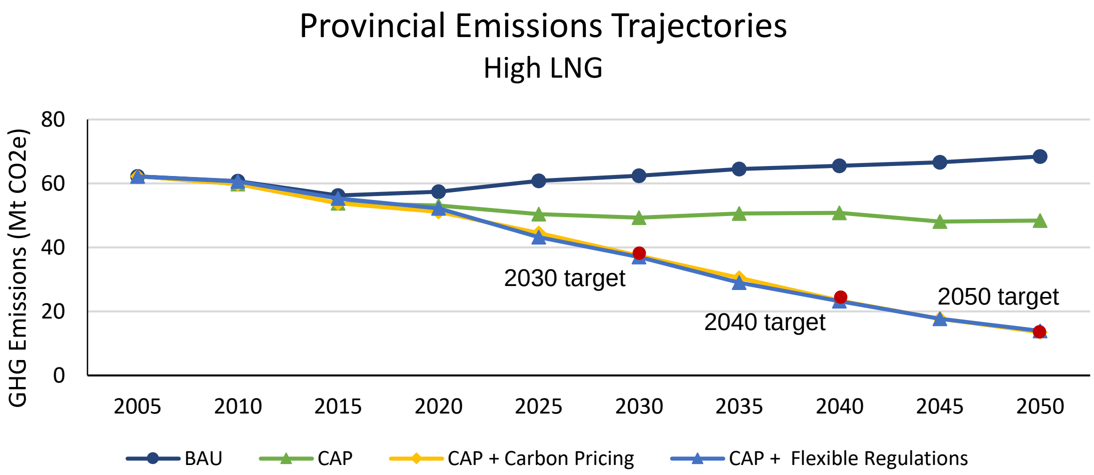


Figure 2 Provincial emissions trajectories by policy run. *CAP + Carbon Pricing* and *CAP + Flexible Regulations* meet the emissions targets.

In terms of emissions reductions, each *CAP + Flexible Regulation* run matches its corresponding carbon pricing run closely. It is possible to meet the emissions targets with every policy package intended to do so, indicating that policymakers in B.C. have multiple policy pathways to meet their goals.

5.1.1. Carbon pricing stringencies

With the addition of increased policy stringencies, it is possible to meet the emissions reductions targets in CIMS with either carbon pricing or flexible regulations regardless of whether there is a Low or High LNG scenario in place. Past EMRG researchers have postulated that CIMS overestimates the necessary carbon price due to its lack of complete macroeconomic equilibrium feedback. Vass (2016) estimated that the carbon price necessary to drive emissions reductions in CIMS is approximately 25% higher than the price necessary with the macroeconomic feedbacks included. With this adjustment, the carbon price (in 2020 dollars) in the Low LNG scenario must be driven to \$190/tonne CO2e to meet the 2030 emissions target and up to \$775/tonne CO2e to meet the 2050 target. To meet the 2030 and 2050 targets in the High LNG scenario, the carbon price must rise to \$260/tonne CO2e and \$775/tonne CO2e, respectively.

The natural gas sector is a key factor in setting the carbon price. The carbon price in 2030 varies between scenarios. A higher 2030 carbon price is necessary in the

High LNG scenario, owing to greater production of natural gas and liquefaction for export. By 2030, the sector is only partially decarbonized; a higher 2030 carbon price is necessary in the High LNG scenario to decarbonize the sector enough to meet the emissions target. As the price rises, the natural gas extraction sector decarbonizes its entire production cycle. By 2050, the carbon price approaches similar levels in the High LNG and Low LNG scenarios. Once the levelized costs of zero-emission technologies exceed those of high-emission technologies, the price does not have to rise beyond the rate necessary to combat inflation. I discuss the decarbonization of the natural gas extraction sector further in Section 5.4.

It is challenging to predict how the carbon price will rise beyond 2030, as society will likely develop alternative emissions reductions technologies in the intervening years. For example, Carbon Engineering has piloted direct air capture technology with estimated costs ranging from $93-232/tonne CO2 (Keith et al., 2018). If such a technology can be applied at a massive commercial scale this would reduce abatement costs substantially. I chose not to model such alternatives as their wide-scale deployment remains highly uncertain.

5.1.2. Flexible regulation stringencies

While a carbon tax is usually applied across the economy, the regulations in *CAP + Flexible Regulations* vary in application and stringency. In *CAP + Flexible Regulations,* the emissions intensity of fuels in 2030 must fall 13% lower than the level the government has proposed as part of its current policy package (Table 4). As mentioned earlier, blended diesel can result from substituting low-emission hydrogenation-derived renewable diesel (HDRD) for fossil fuel-based diesel without a blend limit, which facilitates emission intensity reduction in the diesel stream. The proportion of biofuels in blended diesel rises much more quickly but is limited by HDRD availability. The RNG mandate impacts every sector that makes use of natural gas. The current and perhaps future relatively high cost of producing biomethane incentivizes a switch to electricity in most sectors, probably negating the need for an RNG mandate that reaches 100% stringency.

Table 4 Stringencies for the LCFS and RNG mandate under CAP + Flexible Regulations. Stringencies are shown for both the High and Low LNG scenarios.

		CAP + Flexible Regulations Stringency (Low LNG)		*CAP + Flexible Regulations Stringency (High LNG)*	
Regulation	**Requirement**	**2030**	**2050**	**2030**	**2050**
LCFS gas	% intensity reduction	33%	72%	33%	73%
LCFS diesel	% intensity reduction	40%	95%	40%	90%
RNG Mandate	% biomethane minimum content	36%	82%	39%	87%

As natural gas is only a small portion of energy consumption in most industrial sectors, the emissions intensity standards do not vary between LNG scenarios (Table 5). As a reminder, I model the emissions intensity standards by increasing the cost of technologies proportional to their emissions per unit of output. I model a separate regulation for each industry. These standards produce an outcome similar to an OBPS in a scenario where the rest of the world undertakes strong climate action. Thus, the intensity standards that I provide below could represent the emissions benchmarks used in the OBPS in addition to industrial emissions standards.

Table 5 Industrial emission intensity standard stringencies for the *CAP + Flexible Regulations* policy runs.

	2030 intensity reduction	**2050 intensity reduction**
Industrial Minerals	21%	21%
Metal Smelting	46%	81%
Chemical Products	56%	77%
Pulp and Paper	11%	45%
Mining	67%	79%
Petroleum Refining	18%	70%
Other Manufacturing	9%	49%
Coal Mining	4%	9%
Petroleum Crude	32%	35%

While I created these emissions intensity standards as a regulation order to complete my *CAP + Flexible Regulations* package, the OBPS has already been introduced at the national level. Aside from a broad-based carbon price, B.C. has several options for inducing emissions reductions in industry, including intensity regulations and subsidies.

5.1.3. GHG emissions by sector

Emissions by sector were relatively similar across all policy packages that achieve the emissions targets (Figure 3), regardless of the LNG scenario. For this reason, I only display the Low LNG scenario in Figure 3. In general, there are few differences between *CAP* and the target-achieving runs leading up to 2030. The lack of variation between runs is indicative of how challenging it is to decarbonize an economy within a relatively short, 10-year timeframe. Many technologies have a lifespan longer than 10 years, which prevents rapid decarbonization via changes in capital stock. However, currently operating diesel freight trucks can easily switch to a diesel blend with greater HDRD content, allowing for some decarbonization without having to retire ICE trucks before the end of their lifespan. Thus, much of the difference between CAP and the target-achieving runs occurs in the freight transportation sector.

The additional two decades between 2030 and 2050 allows for greater turnover of capital stock as long-lived technologies retire, creating more opportunities for decarbonization. As a result, there is more variation in 2050 across all sectors when comparing *CAP* with target-achieving runs. Emissions are substantially lower than *CAP* under target-achieving runs in most sectors (the exceptions being agriculture and waste, which do not experience additional regulation in line with current exemptions in these sectors). Cumulative industrial emissions remain the highest of any sector due to their long-lived technologies and the high cost of low-emission alternatives.

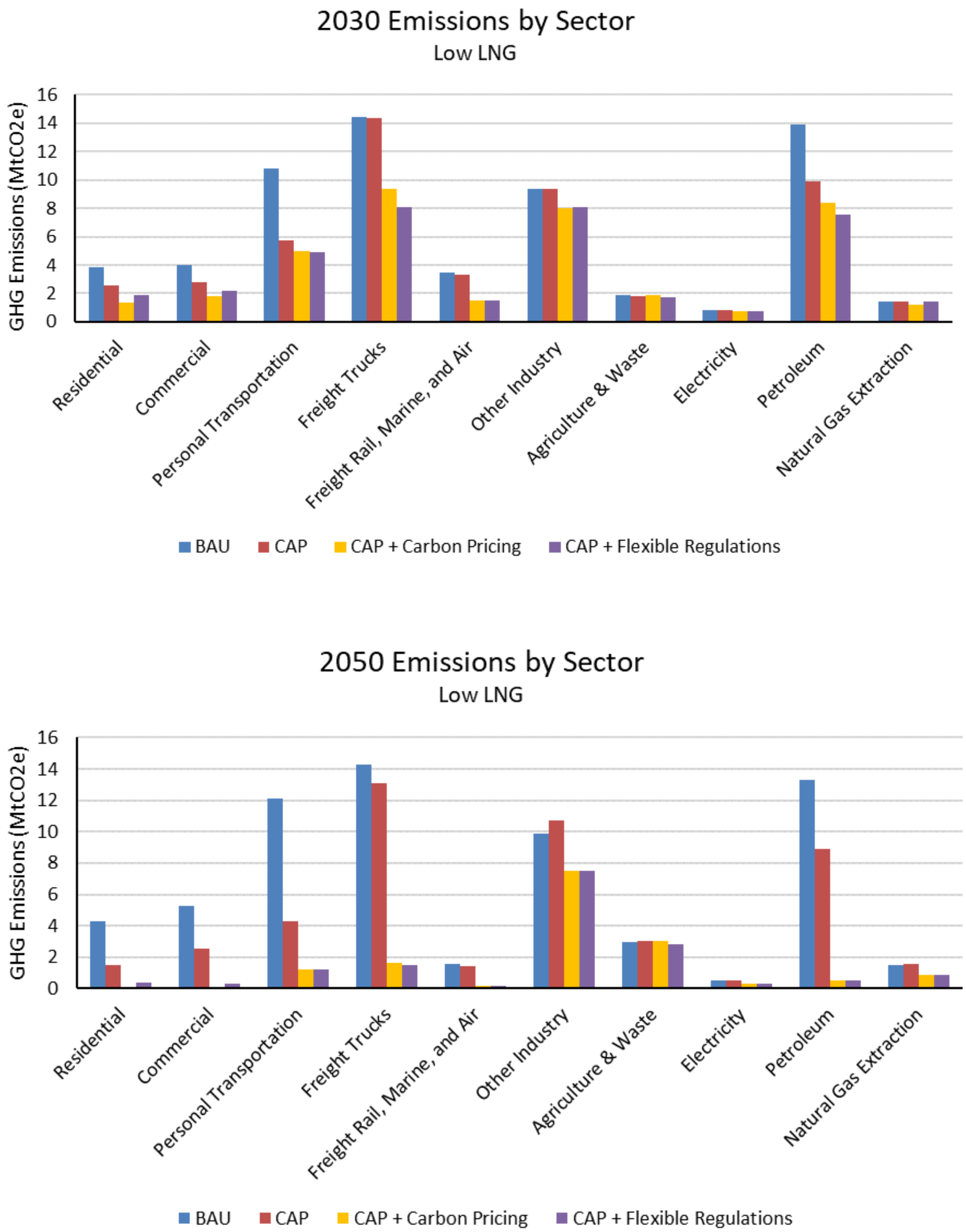


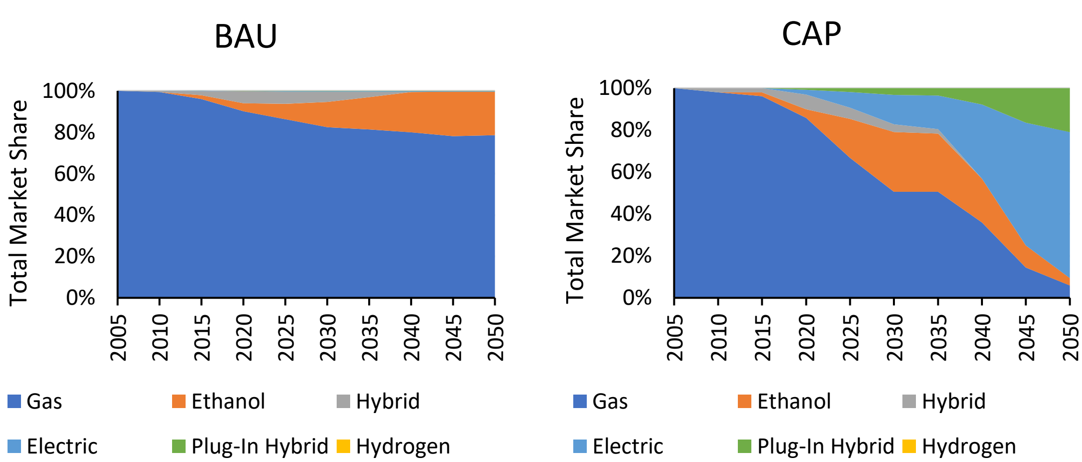
Figure 3 2030 emissions by sector for each policy run in a Low LNG scenario.

Transportation sector results

I separate my discussion of transportation into personal transportation and freight transportation. The additional natural gas demands of a High LNG scenario have little impact in these sectors in CIMS; the following results apply to both Low and High LNG scenarios unless otherwise noted. I present figures for the Low LNG scenario only.

5.1.4. Personal transportation sector

The personal transportation sector in *CAP* sees the largest drop in sector emissions relative to *BAU*. The emissions reductions in *CAP* are largely driven by a shift from ICE motors to EVs, PHEVs, and hydrogen vehicles (Figure 4). Emissions from personal transportation decrease 64% from 2005 levels with the implementation of the ZEV mandate and the LCFS. Personal vehicles transition largely from ICE motors to a combination of EVs and PHEVs by 2050. EVs dominate the personal vehicle market in 2050 in all runs. The remaining emissions from this sector come from ICE motors purchased before the ZEV mandate reaches its maximum stringency (100%) in 2040. Target-achieving runs create further emissions reductions in this sector. The carbon price in *CAP + Carbon Pricing* increases the levelized costs of ICE vehicles, reducing 2050 emissions by 88% relative to 2005 levels. *CAP + Flexible Regulations* has a similar effect on motors, reducing emissions by 79% in the same time period.



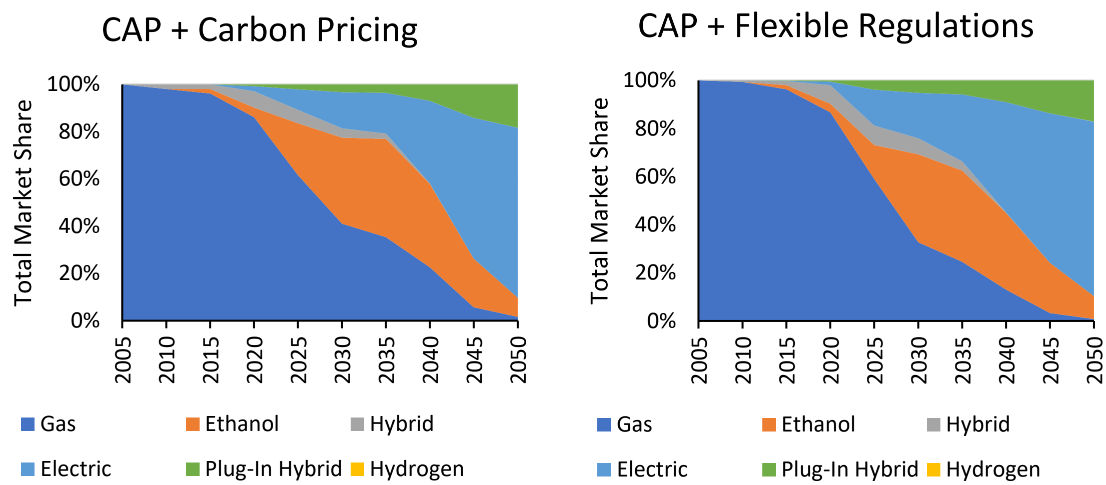


Figure 4 Total personal vehicle market share for each policy run. Note that "Ethanol" represents only E-85 motors that actually consume ethanol, as E-85 vehicles can consume both ethanol and gasoline. E-85 vehicles that consume gasoline are included under “Gas.”

The ZEV mandate, modeled in *CAP* as well as in the target-achieving runs, has a strong influence on which vehicles dominate the market. Most of the variation between runs occurs before the ZEV mandate stringency rises to 100% in 2040. As EVs, PHEVs, and hydrogen-powered vehicles have relatively high levelized costs, these vehicles generally do not take up more of the market than is mandated by the policy. E-85 motors, which do not count as a ZEV, also play a role in decarbonizing this sector. E-85 motors (commonly known as FlexFuel vehicles) can combust either gasoline or any blend between 0% and 85% ethanol. The capital costs of E-85 vehicles are very close to those of standard ICE vehicles and these vehicles are now available throughout North and South America (Posada & Facanha, 2015; U.S. Energy Information Administration, 2020). They become increasingly competitive in runs that push up the price of gasoline relative to other types of fuel. The LCFS and the carbon price do just that, spurring an increase in E-85 vehicles in the market that burn mostly ethanol. Under target-achieving runs, most of the market share that is not taken up by ZEV vehicles is taken up by E-85 vehicles. Under all runs save *BAU*, demand for ethanol peaks in 2035 before the ZEV mandate prevents the sale of new E-85 motors entirely in 2040.

EVs eventually come to dominate the market, overtaking PHEVs. Under the current legislation, plug-in hybrids (PHEVs) qualify as partial ZEVs while electric vehicle (EV) motors and hydrogen motors qualify as ZEV vehicles. Although ZEVs must receive a specific proportion of the new market share, they still compete amongst themselves. Plug-in hybrids have the advantage of being able to use solely electricity (thereby qualifying as a ZEV), or gasoline once its smaller battery has been depleted. They can have their gasoline tanks filled in minutes from well-established refueling infrastructure, mitigating some of the inconvenience associated with ZEVs. However, the LCFS will push up the price of gasoline, resulting in slightly higher levelized costs for PHEVs relative to the *BAU* run. Under *CAP*, the LCFS stringency does not increase after 2030. As a result, PHEVs have a total market share of 17% by 2050. The driving policies behind *CAP + Carbon Pricing* (the carbon tax) and *CAP + Flexible Regulations* (the LCFS) both increase the cost of gasoline, making PHEVs less cost-competitive over time. Target-achieving runs have a lower percentage of PHEV total market share (between 12% - 15%).

Although hydrogen motors qualify as ZEVs, there is little to no hydrogen uptake in any run. Hydrogen vehicles have the highest capital costs, even with technological developments, as well as added financial and convenience costs due to a lack of refueling infrastructure. The production and distribution of hydrogen is more expensive than that of electricity, although refueling a hydrogen motor is much faster than charging a battery. Indeed, intangible costs are a factor hindering the uptake of all ZEV vehicles, including hydrogen, and these account for the perceived risks associated with adopting new technology. Creating additional scenarios to factor in accelerated hydrogen innovations and direct government support of refueling infrastructure was deemed outside the scope of this research.

Fuel switching is not the only available decarbonization mechanism. Mode switching – changing the type of transportation – may also play a role in decarbonizing this sector. Under a high carbon price or a stringent flexible regulation, someone might choose to take transit or carpool instead of driving alone. My simulations did not show a dramatic shift away from personal vehicle use. Vehicles have many advantages in terms of trip flexibility and comfort and establishing effective non-vehicle transportation options in low-density areas is costly. Furthermore, any decrease in congestion because of mode shifting away from vehicles increases the attractiveness of vehicle use by lowering vehicle travel times, thus reducing the full effect of the shift (Coulombel et al., 2019; Hymel et al., 2010). For these reasons, personal vehicles continue to play a major role in CIMS's personal transportation sector out to 2050.

5.1.5. Freight transportation

I divide the discussion of freight decarbonization into two sections: truck and other types of transportation (rail, marine, and air).

Truck transportation

Truck transportation comprises the greatest portion of freight emissions. Without additional policies, decarbonization in this sector is less substantial than in the personal transportation sector. Emissions under the *CAP* run are 4% lower than those of the *BAU* run by 2050, as the LCFS forces a steady decrease in emission intensity before being frozen at its 2030 level. Target-achieving runs see a rapid increase in biofuel consumption that peaks in 2050 (Figure 5). *CAP + Carbon Pricing* increases the levelized cost of diesel, prompting an increase in conventional biodiesel blending and HDRD consumption. Under *CAP + Flexible Regulations*, the price of blended diesel increases as suppliers spend resources to either decarbonize their fuels, resulting in a very similar composition of fuels across runs that achieve the targets. This suggests that the LCFS, when designed carefully, is a reasonably economically efficient policy for reducing freight transportation emissions.

Truck freight transportation is mainly decarbonized through a transition to biofuels (Figure 5). Under target-achieving runs, conventional biodiesel comprises 15% of total fuel consumption, while HDRD rises to 34% of consumption. By 2050, HDRD becomes the dominant fuel for freight truck transportation in target-achieving runs, comprising 64% - 67% of total fuel consumption by trucks. As mentioned in Chapter 3, HDRD does not have the same "blend wall" restrictions that prevent biodiesel and ethanol from becoming larger portions of their respective blends (Natural Resources Canada, 2012), although it is more costly to produce. Using HDRD allows the sector to decarbonize without replacing trucks before the end of their lifespan. Consequently, its use becomes the dominant decarbonization mechanism for freight trucks. This result is consistent with other studies that explore the decarbonization of freight transportation with similar policies (Hoyle, 2020; Vass, 2016; Vass & Jaccard, 2017). The life-cycle emissions of HDRD are reduced as a response to stringent compulsory policies, further contributing to GHG reductions.

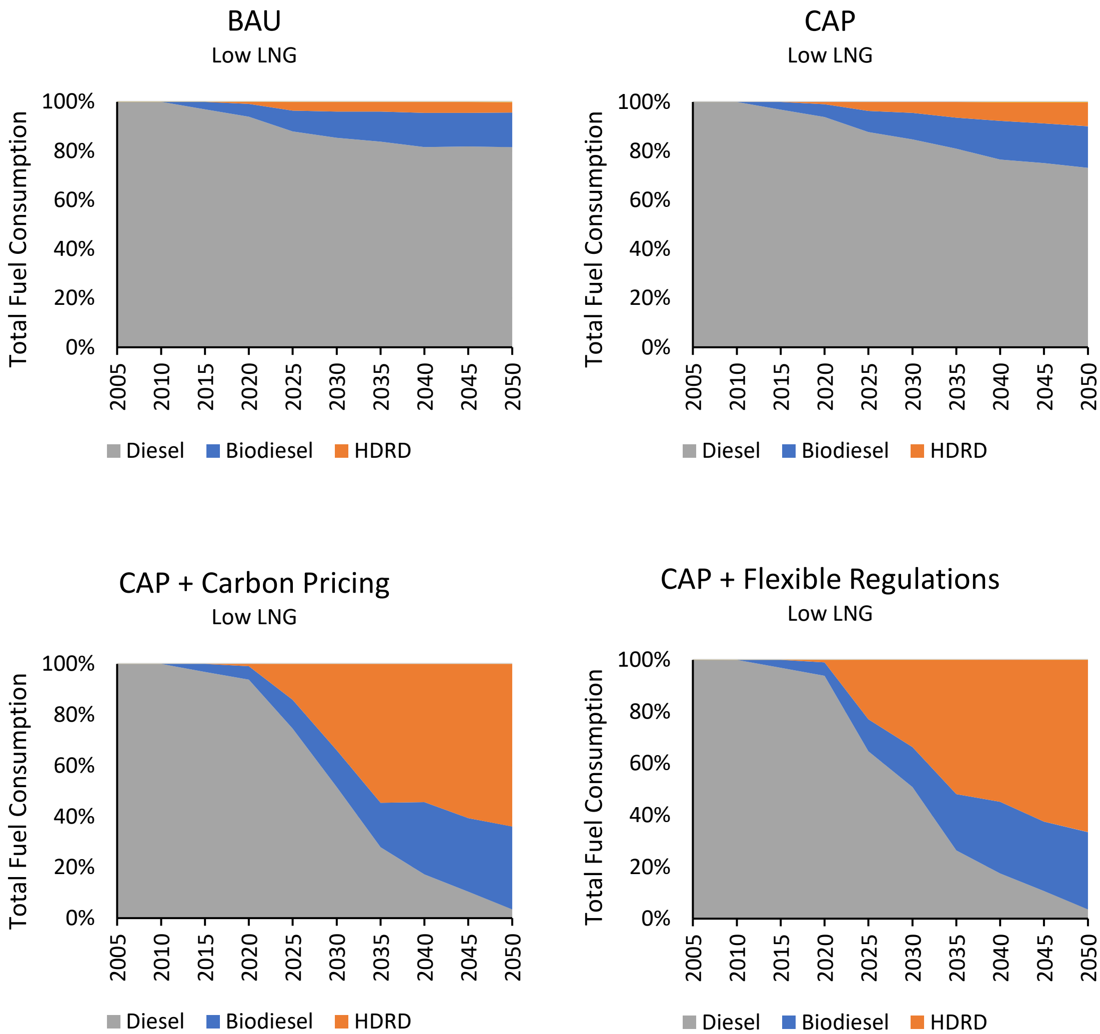
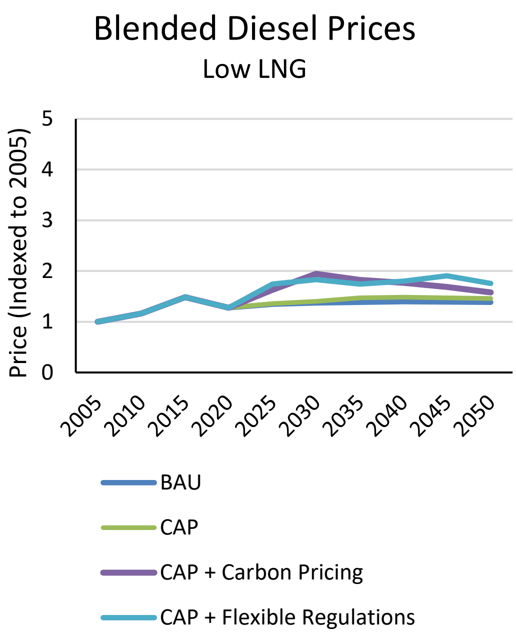


Figure 5 Total fuel consumption for road freight transportation under all runs.

Implementing stringent climate policy affects the relative cost of fuels (Figure 6). Under a carbon tax, the price of a fuel rises in proportion to its emissions intensity. Under the LCFS, diesel suppliers must either decarbonize to the benchmark, or buy credits from firms who over-comply or create Part 3 agreements. Both options will impose a cost on the supplier, also in proportion to their fuel's original emissions intensity. The transfer of funds from under-compliant firms to firms with credits has the effect of subsidizing biofuels – hence the drop in blended diesel prices under *CAP +*

Flexible Regulations between 2030 and 2035. However, it is uncertain if such a drop will occur if it becomes difficult to meet demand for biofuels. A limitation of this study is that I did not model supply costs for increasing HDRD use and am therefore unable to reflect how prices for HDRD might increase or decrease in response to increasing demand. Supplying increasing amounts of HDRD to meet demand is likely to get more challenging and therefore more costly. Should HDRD supplies prove inadequate, suppliers may need to turn to the other alternatives to decarbonize freight trucks.



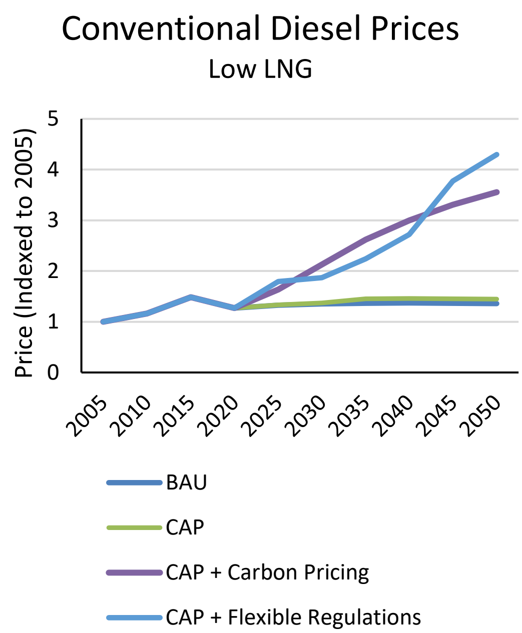


Figure 6 Changes in blended diesel and conventional diesel prices under each policy run. Note that blended diesel includes HDRD and conventional biodiesel.

Electric and hydrogen truck motors are available in CIMS as an alternative to ICE truck motors. However, their capital costs are far higher than their ICE equivalents. Even when accounting for cumulative experience and technological improvements, their annualized costs are higher than equivalent ICE motors. Electric motors in medium- and heavy-duty freight suffer from the same refueling inconveniences as their light-duty counterparts. Recent innovations such as overhead catenary vehicles (already used to power buses in some municipalities) and dynamic induction vehicles – which are charged via electric coils implanted in the road – would alleviate the burden of having to charge a battery. However, these technologies are in early stages of development and would require costly charging infrastructure along most, if not all, of their intended route in order to be feasible. Similarly, hydrogen motors would require a considerable expansion of refueling infrastructure before they can be utilized for freight transport (Moultak et al., 2017).

It is difficult to determine the role of electricity and hydrogen in this sector given considerable uncertainty in the pace of potential technological improvements. Sufficient advances in electric and hydrogen-powered freight vehicles and infrastructure may yet make them the logical option for firms seeking to decarbonize their fleets. Thus, a decarbonized freight sector could utilize electricity, hydrogen, or biofuels as the dominant fuel type, or any combination of the three. I only model one decarbonization pathway out of many possibilities and I did not model a scenario that assumed support for accelerated deployment of these early-stage technologies.

Rail, marine, and air transportation

Rail, marine, and air transportation comprise a smaller portion of freight transportation emissions than trucks but are more challenging to decarbonize as they operate internationally and are vulnerable to competition from less regulated jurisdictions. These modes of transportation can only be fully decarbonized by climate policies under the assumption that other jurisdictions will be taking similar levels of climate action, thus increasing their own costs to the same degree and limiting changes in competitiveness. Otherwise, the government may need to provide carbon subsidies or some other form of relief to vulnerable sectors until this is the case. The carbon tax in *CAP + Carbon Pricing* and the LCFS in *CAP + Flexible Regulations* drive down emissions in these modes of transportation. Rail is mostly electrified by 2050, and there is a small increase in biodiesel blending in air and marine transportation.

As mentioned in the scenario assumptions, I turned off CIMS's macroeconomic functions in this modeling exercise. As a result, the overall demand for freight transportation (i.e. all modes combined including air, marine, road, and rail transport) does not decline in any simulation. However, rail and trucks compete to meet demand for freight transportation by land. As stringent climate policies increase the levelized costs of ICE trucks, road freight decreases 8% by 2050, while transportation by rail increases by 5%. Under target-achieving runs, rail is 27% electrified by 2030 and 85% electrified by 2050, which is why an increase in rail transportation towards 2050 does not contribute substantially to emissions. Attempts at rail electrification have been made in North America since the early 19th century, but the decline in fossil fuel prices made their continued operation economically unsound (Allen & Newmark, 2018). These results suggest that ambitious climate policy is likely to spur renewed interest in rail electrification. However, road transport has the advantage of being more flexible than set rail routes and will probably remain the dominant method of land freight transportation.

The volume of freight transportation may change depending on the stringencies of industrial and freight decarbonization policies in neighbouring jurisdictions and how they affect B.C.'s imports and exports, but the magnitude of this effect is difficult to determine. Further research with a general equilibrium model might provide more insight into how climate policies in other jurisdictions will impact demand for freight transportation in B.C.

5.1.6. Comparison with the Navius Research study

Because Navius Research has also modeled the effect of B.C.'s current policies, I am able to examine their study's technological and sectoral results and compare them against my own. Navius Research used their general equilibrium model, gTech, to determine the outcomes of the current policy package. GTech's represented economy is assumed to grow by a certain percentage of GDP. Unlike CIMS, which relies on exogenous demand forecasts, economic growth in gTech can change endogenously depending the impact of policies on production costs. However, as policies under both studies are intended to have minimal effects on vulnerable industries, their results are similar.

Navius Research (2017) indicated that implementing the current policy package would result in B.C. reducing its emissions 30% by 2030, or a 19MtCO2e reduction. In this study, I estimate a 15MtCO2e reduction by 2030 under a Low LNG scenario and a 13MtCO2e reduction under a High LNG scenario. Freight transportation accounts for most of the difference in GHG reductions between my study and the Navius Research study.

Navius Research estimated that emissions from freight transportation under their *CAP* run would be approximately 8.2 MtCO2e by 2030, down from 13.2MtCO2e in their

BAU run (Table 6 Comparison of freight transportation emissions between Navius Research study and this study.. Under my *CAP* run, I find that the freight transportation sector would produce approximately 14.3MtCO2e emissions by 2030 in both LNG scenarios. This difference (6.1MtCO2e) is larger than the cumulative difference between the studies; it is offset by several sectors in my study that produce slightly less (less than 1MtCO2e) emissions than comparable sectors in Navius Research's study. The bulk of the difference can be attributed to greater heavy-duty vehicle decarbonization and rail decarbonization in Navius Research's study.

Table 6 Comparison of freight transportation emissions between Navius Research study and this study.

	Navius BAU	Navius CAP	This study BAU	This study CAP
Heavy-Duty Vehicles	8.8	5.4	11.1	11.0
Railways	0.8	0.0	0.5	0.5
Domestic Navigation	1.8	1.5	1.8	1.7
Off-Road Vehicles	1.8	1.3	1.1	1.1

Unlike CIMS, the Navius gTech model calculates transportation demand forecasts endogenously, as demand from other sectors changes in response to climate policies. Demand for each mode of transportation in gTech grows steadily, much like the exogenous forecast used in CIMS (Table 7). This suggests that a reduction in transport demand as a result of climate policies is not a factor in the difference between our two studies.

Table 7 Demand growth forecast comparison between the Navius Research study and this study. Note that Navius Research presents their demand forecasts indexed to their calibration year of 2010. I present CIMS's demand forecast the same way for comparison purposes.

gTech Mode Type	2010	2015	2020	2025	2030
Heavy-Duty Vehicles	1.00	0.93	1.25	1.54	1.87
Transit	1.00	1.15	1.31	1.45	1.63
Air	1.00	1.37	1.33	1.44	1.54
Rail	1.00	1.07	1.39	1.62	1.78
Other Transportation	1.00	1.03	1.03	1.15	1.25
Overall growth in CIMS[6]	1.00	0.87	1.01	1.12	1.22

Given that declining demand for freight transport is not likely to play a role, I attribute the difference in freight GHG reductions to several other factors:

- Navius Research's study adds minimum market share mandates to the transportation sector, requiring that 10% of new market share in heavy freight transportation be allocated to electric motors and an additional 16% to natural gas motors. Electric buses are allocated 94% of new market share in transit by 2030. While the CleanBC document discusses incentive programs to increase the market share of zero-emission freight trucks and buses, it did not explicitly commit to any policies, compulsory or otherwise. For this reason, I do not model these minimum market shares.

- In the Navius study, use of clean energy[7] in freight trucks rises from 9% of energy consumption in the reference scenario to 40% of energy consumption under the *CAP* scenario. In my study, electricity and biofuel consumption rises to about 15% of total energy consumption for trucks. Likewise, rail in the Navius Research study shifts completely to clean energy by 2030 but does not transition at all

[6] Individual transportation modes in CIMS generally follow this same growth pattern and thus are not displayed here. However, rail and heavy-duty vehicles in CIMS compete to service land freight transportation demand and can see changes in mode share as a result of different policy runs. I discuss this further in Chapter 5.

[7] In their 2017 methodology publication, Navius Research provided model forecasts for electricity and biofuel consumption in aggregate as "clean" energy. I aggregate my electricity and biofuel consumption results in the same way in this section for comparison purposes.

under *CAP* in my study. The slower energy transition in my study results in fewer GHG reductions relative to the Navius study.

- There is likely a difference in technology capital costs that contributes to a slower energy transition and thus a lower level of emissions reductions in this sector. GTech derives the values for marine freight and all air transportation from past parameterization work done for CIMS but relies on a large body of academic literature and grey literature to parameterize trucks in the freight transportation sector. Capital costs for low-emission alternatives may be lower, leading to lower estimates of freight GHG emissions. Without knowing the exact values used in the gTech study, it is difficult for me to estimate how much this factor contributes to the difference in GHG reductions.

Other small differences arise (generally less than 1MtCO2, some less than 0.5MtCO2) in other sectors, owing to differences in input data, forecast assumptions, and modeling methodology. In addition to modeling B.C.'s policies for their study, Navius Research also modeled the implemented and announced policies of the rest of the Canada. I have not accounted for the actions of other jurisdictions in the same way and thus expect some discrepancies in estimated reductions. For a numerical comparison of this study's emissions projections and the Navius Research (2017) projections, see Appendix B.

5.2. Building sectors

Buildings in CIMS are separated into two sectors: residential and commercial. Although both sectors rely on natural gas for some of their services, the differences between the High LNG scenario and Low LNG scenario are too small to attribute to any one factor with certainty. Thus, I report results for the Low LNG and High LNG scenarios together unless otherwise noted.

5.2.1. Residential sector results

The main decarbonization mechanism under all runs is a transition from natural gas to electricity. Natural gas is the main energy source for the residential sector in historical years (2005-2015). *CAP + Carbon Pricing* reduces residential emissions by 98% in 2050 relative to 2005 levels, while *CAP + Flexible Regulations* reduces residential emissions by 92% by 2050. The high-stringency RNG mandate under *CAP + Flexible Regulations* causes a shift towards electrification of residential services. The increase in natural gas costs due to biomethane content incentivizes consumers to shift towards electricity-powered technologies. *CAP + Carbon Pricing* creates a similar effect with the carbon tax, increasing natural gas costs until many consumers switch to electricity.

As a reminder, *CAP* implements a rising carbon tax, the Step Code, and the renewable natural gas mandate to decarbonize residential buildings. The cost of biomethane combined with the carbon tax makes gas-burning technologies less competitive than those running on electricity. High-emission HVAC is to be slowly phased out as part of the Step Code's mandatory introduction in 2032. Assuming that the government follows through with its (currently non-binding) commitment, electricity use rises from 35% of total energy consumption in 2005 to 76% in 2050. Under runs that meet the targets, electricity comprises approximately 90% of all residential energy consumption use by 2050.

Natural-gas consuming technologies are slowly phased out in runs that meet the emissions targets. Heat pumps (an electric space-heating technology) are the dominant furnace technology under both *CAP + Carbon Pricing* and *CAP + Flexible Regulations*, comprising 88% of the furnace total market share by 2050. Cooking ranges and water heaters under both target-achieving runs are increasingly electricity-powered, but natural gas-consuming technologies remain viable for some households in 2050 in all runs and scenarios.

5.2.2. Commercial sector results

The commercial sector experiences trends in emissions reductions that are similar to those of the residential sector. Historical fuel use in the commercial sector is largely split between electricity and natural gas. Under *CAP,* emissions fall by 25% in 2030 and by 40% in 2050 from 2005 levels. Electrification drives emissions reductions, rising to 59% of total energy consumption by 2050. Under *CAP + Carbon Pricing*, electricity rises to 98% of total commercial energy consumption by 2050. Under *CAP +*

Flexible Regulations, electricity rises 93% - 98%. The target-achieving runs achieve approximately 95% emissions reductions relative to 2005 levels.

The greatest source of emissions in the commercial sector is HVAC services. In historical years, natural gas powers most HVAC services. Policies at their *CAP* stringencies are not sufficient to push levelized costs for electric HVAC lower than those of natural gas HVAC. Under runs that meet the emissions targets, HVAC transitions increasingly towards electricity. *CAP + Carbon Pricing* causes electric HVAC to rise to 98% of the total market share by 2030 under both LNG scenarios. *CAP + Flexible Regulations* also incentivizes an increase in electric HVAC to 90% of the total market share. Blended natural gas holds the remaining market share and the share of conventional natural gas decreases gradually as a result of the RNG mandate.

Other building technologies are also replaced with their electric counterparts under stringent climate policy. Hot water heating by natural gas is replaced by electric heating in all runs, except *BAU*. Under runs that meet the emissions targets, total market share in 2050 for electric hot water heating ranges from 74% to 95%. Cooking ranges are also a small part of commercial emissions. Under all runs, electric cooking ranges eventually dominate the market as blended natural gas becomes more costly due to its biomethane content. The highest market share, 97%, of electric cooking ranges by 2050 occurs under the *CAP + Carbon Pricing*. It can be observed from *CAP + Carbon Pricing* that the most economically efficient mechanism in the commercial sector would be to transition services to consume electric alternatives.

A key uncertainty of this study is the pricing of biomethane. I did not model a supply curve for biomethane, which would describe the cost of biomethane for a given level of production. A supply curve would add another layer of economic realism to the simulation by creating a feedback between the cost of biomethane production and the quantity demanded. Electrification under an RNG mandate could be slower or faster than what I have modeled, depending on the resulting price of blended natural gas. However, the shape of a supply curve for biomethane is highly uncertain. I therefore instead set the biomethane price conservatively high to approximate the high prices that could result from increased demand and limited feedstock availability. The increasing stringency of the RNG mandate further disincentivizes consumption of blended natural gas; as such, biomethane consumption peaks at 6% of total energy consumption despite being a growing proportion of the blend.

5.3. Industrial sectors

In this section, I refer to several sectors within CIMS: Chemical products, industrial minerals (encompassing production of materials such as cement, lime and glass), metal smelting (representing aluminum and nickel, among others), mineral mining, pulp and paper manufacturing, agriculture, petroleum refining, petroleum crude, and coal mining. I address natural gas extraction in a separate section. As natural gas is not a major part of any production process in these sectors, there is little variation between the two LNG scenarios. Thus, I only present figures for the Low LNG scenarios.

Most emissions in the industrial sectors arise from fossil fuel use for heat generation (via boilers or furnaces) and a small amount of emissions are from production processes (such as those emitted from the production of cement). However, fossil fuels only account for a portion of industrial energy use. Electricity comprises at least 36% of total energy share in 2050 in all runs, including *BAU*. Electricity use rises in every run under both LNG scenarios and replaces fossil fuel use for heat generation. Another large portion of total fuel use is biomass, which is mostly consumed by the pulp and paper sector for electricity generation and process heat. Under all runs, biomass use declines from its peak of 52% in 2015 due to gradually decreasing demand for pulp and paper products; it comprises between 41% - 45% of total energy consumption by 2050.

The current policy package does not result in substantial emissions reductions from these sectors, even as the carbon price rises to its announced stringency. However, under the *CAP* run, emissions for all industrial sectors fall 29% below 2005 levels by 2050. And under *CAP + Carbon Pricing*, 2050 emissions fall by 42%, while under *CAP + Flexible Regulations*, emissions fall by 37%.

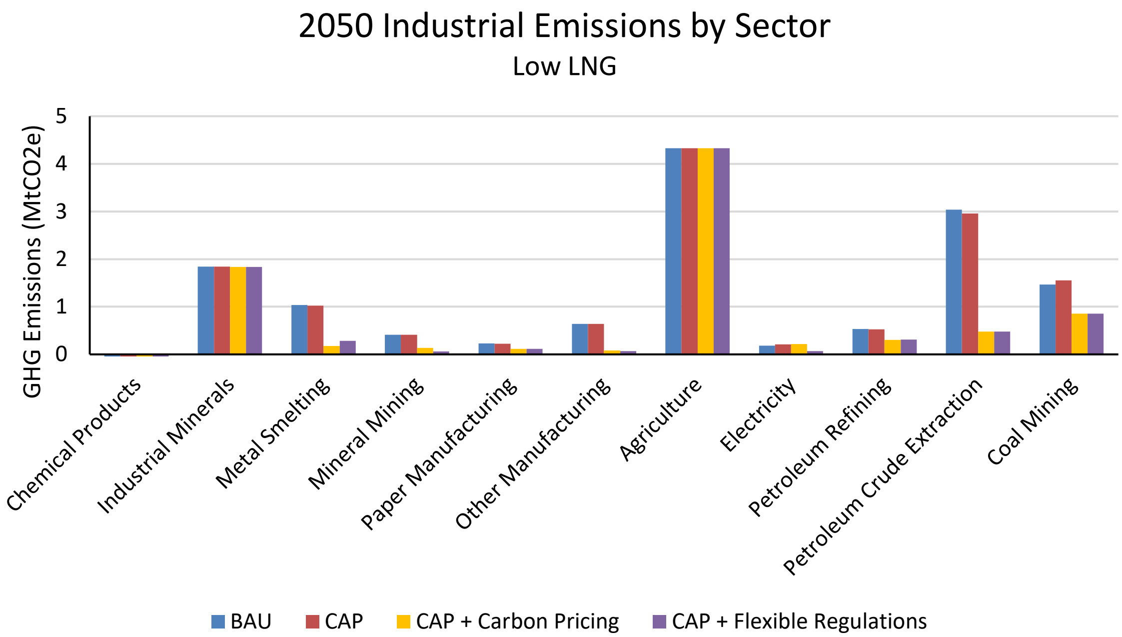


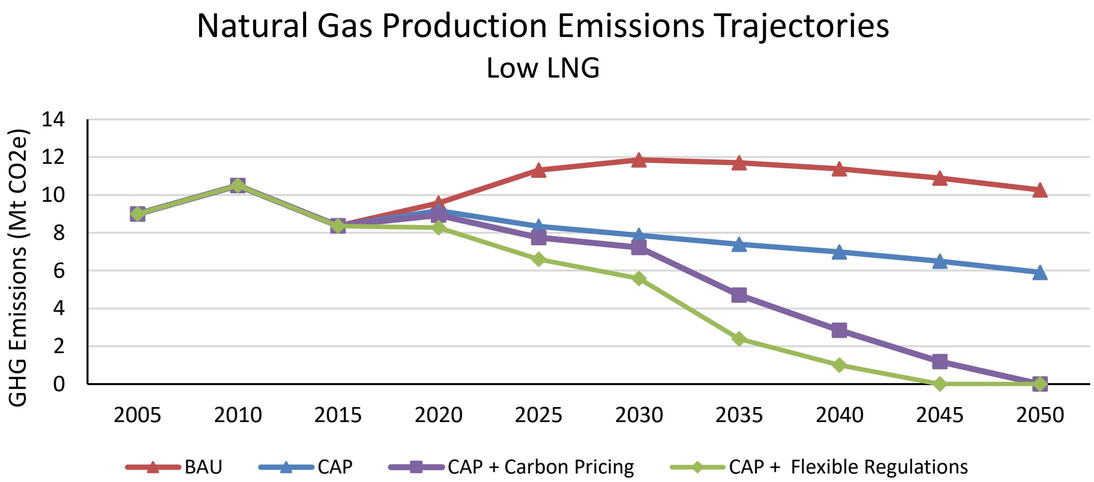
Figure 7 2050 emissions by industrial sector the Low LNG scenario.

The transition from fossil fuels to electricity takes different forms depending on the industrial sector. For example, the metal smelting industry transitions from coal-fired and gas-fired furnaces to electric arc furnaces. Where there is no electric alternative, an option that utilizes carbon capture and storage eventually dominates the market. The key factor is that there is a zero-emissions alternative to the emissions-intensive technologies for most services in every industrial sector. These become cost-competitive when ambitious climate policy is applied. With further innovations it may become more cost-effective to fully decarbonize industry, but existing technology is adequate to meet the targets.

This policy, as it is modeled, mimics the economic efficiency of a carbon price. However, it is limited by my assumptions on how the rest of the world will approach climate policy. Emissions intensity benchmarks can only be applied at this level if the rest of the world implements similarly stringent climate policies, thereby reducing the vulnerability of EITE industries to outside competition. Absent strong climate action in other jurisdictions, B.C. will have to implement policies to protect EITE industries, such as carbon tariffs. Additionally, I assume perfect credit trading between firms. Like the carbon tax, these standards would be most effective if they were applied at the same stringency in every country, in order to maximize credit trading opportunities and lower marginal abatement costs. Trading flexibility across jurisdictions may be especially important for B.C., as most industrial sectors in B.C. maintain just a handful of facilities each. B.C. might able to link such a system with the national output-based pricing system to increase economic efficiency. There is historical precedence for this kind of linkage; California and Quebec have had their cap-and-trade credit markets linked since 2014.

5.4. Natural Gas Extraction

The natural gas extraction sector is responsible for a large portion of historical emissions (Figure 8). Emissions from the natural gas sector stem from its production, transportation, and processing. They arise either from methane leakage during one of these stages, or from natural gas that is combusted to power services such as heat or motive force. B.C. employs several natural gas extraction methods, with tight extraction (drilling underneath impermeable rock) and some shale extraction (fracturing shale formations) projected to form the bulk of extraction in the coming years. Under *BAU*, emissions in 2050 fall by 8% under a Low LNG scenario and rise 30% under a High LNG scenario. With the addition of *CAP*, emissions in this sector fall by 31% under the Low LNG scenario and by 10% under the High LNG scenario. Recall that *CAP* includes methane regulations that require firms to improve detection and repair of methane leaks, thus reducing emissions relative to the *BAU* scenario. The target-achieving runs induce just under 100% emissions reductions in both LNG scenarios.



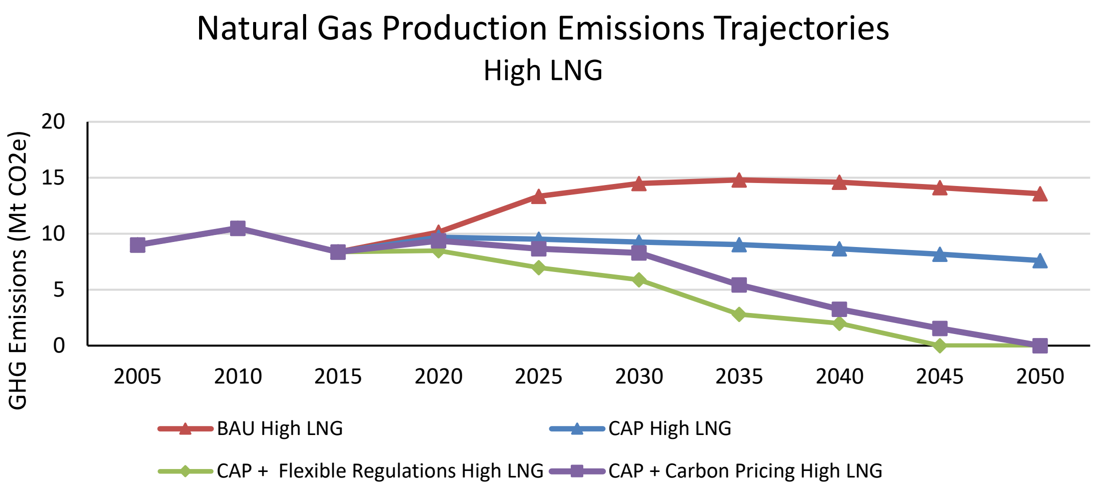


Figure 8 Natural gas extraction emissions trajectories for all modeled policy runs. Trajectories presented for both High and Low LNG scenarios.

The rising carbon price in *CAP + Carbon Pricing* incentivizes improvements in leak detection and repair beyond the original methane regulations included in *CAP*. Each extraction method employs increasingly aggressive leak detection and repair programs, which reduces methane leakage substantially. Natural gas extraction also requires heat production and motive force. Heat production becomes more efficient, while compressors and turbines are largely transitioned to their electric counterparts. Under *CAP + Carbon Pricing*, 84% of compressors are electric, while gas turbines are completely replaced with electric induction motors. Gas distribution is also subject to aggressive leak detection and repair, as is processing. As a result of the industrial emissions standards, *CAP + Flexible Regulations* transitions technologies in the natural gas sector in a manner similar to *CAP + Carbon Pricing*. Compressor engines and gas turbines are overtaken by their electric counterparts, LNG compression consumes mostly electricity instead of natural gas, and aggressive leak detection and repair becomes the norm.

Chapter 6. Conclusion

6.1. Summary of findings

I had several objectives in conducting this research. Firstly, I aimed to evaluate the emissions reductions and economic impacts that would result from currently implemented and announced policies in British Columbia. Secondly, I wanted to model alternative pathways to reach the 2030, 2040, and 2050 emissions targets. Finally, I wanted to explore how LNG expansion would impact B.C.'s ability to meet its climate targets. I focused on policy pathways that would maximize four policy criteria: environmental effectiveness, economic efficiency, administrative feasibility, and political acceptability. I placed special emphasis on political acceptability by modeling a run that relied significantly on flexible regulations, a policy type that has seen less opposition than a pure carbon pricing approach in B.C. and other jurisdictions. I compared the technological, energy and emissions outcomes of each set of policies to determine how carbon pricing would influence the economy versus an equivalent set of flexible regulations. Through these objectives, I sought to further inform B.C.'s decarbonization strategy.

In comparing a business-as-usual run, the current policy package, and policy runs that meet the emissions targets, I noticed several trends:

- In both a High and Low LNG scenario, the current policy package will not meet the 2030 emissions target, although it does effectively reduce emissions in multiple sectors. There are multiple policy packages that can meet the 2030, 2040, and 2050 climate targets.

- Under target-achieving runs, emissions fall more slowly in some sectors leading up to 2030 before dropping quickly through to 2050. This suggests that decarbonizing certain sectors, such as freight transportation, will prove challenging in the short term.

- Biofuels play a key role in decarbonizing sectors that do not yet have electricity-powered alternatives at reasonable costs. In particular, HDRD demand rises in the freight transportation sector in all scenarios that meet the climate targets. Future innovations in fuel alternatives that I did not consider for this study may decrease reliance on HDRD.

- Policy runs that meet the emissions targets disincentivize natural gas use across sectors. The rising cost of blended natural gas in target-achieving runs diminishes domestic consumption considerably.

- Without policies that severely restrict production and transport emissions, LNG expansion will increase B.C.'s GHG emissions substantially. It is possible to meet B.C.'s climate targets with an LNG expansion, but stringent climate policy is required to induce decarbonization of every aspect of the production process.

Across sectors in *CAP + Carbon Pricing* and *CAP + Flexible Regulations*, technology and fuel use shares follow similar trajectories. This suggests that a package of flexible regulations can be designed to mimic the economic efficiency of a carbon tax. Additionally, most emissions reductions can be done with existing policies and technologies. While policymakers are not limited to existing policies in their mandate to reduce emissions, using existing policies may alleviate some administrative burden.

My approach to creating the flexible regulations package was to be as economically efficient as possible. This required me to model policies tailored to each sector, particularly the industrial sectors. Policy work at the federal level on the OBPS suggests that such a tailored approach is possible. Moreover, a tailored approach does not necessarily entail a separate policy for each industry. Building credit trading mechanisms that allow facilities across sectors to trade with each other could be key for an economy as small as B.C.'s.

This study focused primarily on four specific policy criteria. Policymakers may choose to emphasize certain policies over others due to their performance on criteria other than economic efficiency. While a few policies under the current package emphasize specific technologies (i.e. the ZEV mandate) and are therefore less flexible, they have to date gone largely unnoticed or uncontested by the public. Additionally, policies such as the ZEV mandate may provide other co-benefits, such as improved air quality (Kinnon et al., 2019). Subsidies, while economically inefficient, are often very popular amongst some constituencies. Policymakers will always have a broad range of motivations for implementing policies. They are likely incorporating or weighing criteria differently from what has been done in this research.

6.2. Limitations and future research

My research had a specific goal of providing two policy alternatives that emphasized different policy types. Here I summarize some of the limitations of my study for future researchers to consider.

1. While studies have found that regulations face less opposition than carbon prices (Rhodes et al., 2017), there is no guarantee that regulations at very high stringencies will go unopposed by the public. As the past three decades have shown, climate policies will need to be in place for decades to meet the climate targets, which is ample time for opponents to attack policies or vote in a new government that repeals them.

2. To meet the climate targets in this study, I model runs that emphasize specific policy types. This is not to suggest that there are only two pathways to meet the emissions targets.

3. Certain sectors, such as freight transportation, face significant uncertainty in terms of the pace and direction of technological advancements. Additional research into the role these uncertainties play in decarbonization could provide further insight for decision-makers.

4. Finally, I do not simulate the emissions that result from the combustion of exported LNG. As I focus specifically on domestic emissions, LNG combustion falls outside the scope of my study.

Energy-economy models are simplifications of a complex system, aimed at providing insight in ways that will be useful for changing or improving the system. While there are many ways to improve the way a model represents reality, many features and outcomes will be based on assumptions included. Additional research using a variety of models, tools, methods, and expert opinion will help further inform the conversation on effective climate policy in British Columbia.

References

Allen, J. G., & Newmark, G. L. (2018). *The Life and Death of North American Rail Freight Electrification*. https://doi.org/10.1177/0361198118768532

Argonne National Laboratory. (2011). *Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model Energy Systems Division*.

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

Bataille, C. (2005). *Design and Application of a Technologically Explicit Hybrid Energy-Economy Policy Model with Micro and Macro Economic Dynamics*.

Bataille, C. (2007). *CIMS Introduction, Algorithms & Operations Manual*.

Baumol, W. J., & Oates, W. E. (1971). The Use of Standards and Prices for Protection of the Environment. *The Swedish Journal of Economics*, *73*(1), 42–54.

Bergman, L., & Henrekson, M. (2003, January 7). CGE Modeling of Environmental Policy and Resource Management. Retrieved from http://www.ictp.trieste.it/~eee/workshop/smr1533/Bergman%20-20%Handbook-1.doc

BC Oil & Gas Commission. (2018). *Acid Gas Disposal Wells Summary Document*. *September 2018*.

Beck, M., Rivers, N., Wigle, R., & Yonezawa, H. (2015). Carbon tax and revenue recycling: Impacts on households in British Columbia. *Resource and Energy Economics*, *41*, 40–69. https://doi.org/10.1016/j.reseneeco.2015.04.005

Bumpus, A. G. (2015). Firm responses to a carbon price: corporate decision making under British Columbia’s carbon tax. *Climate Policy*, *15*(4), 475–493. https://doi.org/10.1080/14693062.2014.937389

Carbon Pricing Leadership Coalition. (2017). *Report of the High-Level Commission on Carbon Prices*.

Chetty, R., Looney, A., & Kroft, K. (2009). *Salience and Taxation: Theory and Evidence*. 1145–1177.

Christoph, B., & Rutherford, T. F. (2012). *The Costs of Compliance : A CGE Assessment of Canada's Policy Options under the Kyoto Protocol*. *2010*, 177–211. https://doi.org/10.1111/j.1467-9701.2009.01229.x

Coulombel, N., Boutueil, V., Liu, L., Viguié, V., & Yin, B. (2019). Substantial rebound effects in urban ridesharing: Simulating travel decisions in Paris, France. *Transportation Research Part D: Transport and Environment*, *71*(June 2018), 110–126. https://doi.org/10.1016/j.trd.2018.12.006

Davis, M., & Kumar, A. (2018). How will Canada's greenhouse gas emissions change by 2050 ? A disaggregated analysis of past and future greenhouse gas emissions using bottom-up energy modelling and Sankey diagrams. *Applied Energy*, *220*(April), 754–786. https://doi.org/10.1016/j.apenergy.2018.03.064

Dobson, S., & Winter, J. (2018). Assessing policy support for emissions-intensive and trade- exposed industries. *The School of Public Policy Publications*, *11*(October), 0–48.

Electrigaz. (2008). *Feasibility Study – Biogas upgrading and grid injection in the Fraser Valley, British Columbia* (Issue June).

Evans, G. (2007). *International Biofuels Strategy Project* (Issue November).

Fischer, G., Prieler, S., van Velthuizen, H., Berndes, G., Faaij, A., Londo, M., & de Wit, M. (2010). Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. *Biomass and Bioenergy*, *34*(2), 173–187. https://doi.org/10.1016/j.biombioe.2009.07.009

Galbraith, J. K. (1952). *American Capitalism: The Concept of Countervailing Power*. Houghton Mifflin Company.

Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R. C., Gross, K. L., & Robertson, G. P. (2013). Sustainable bioenergy production from marginal lands in the US Midwest. *Nature*, *493*(7433), 514–517. https://doi.org/10.1038/nature11811

Gomes, I. (2015). Natural Gas in Canada : what are the options going forward? In *Oxford Institute for Energy Studies* (Issue May).

Goulder, L. H., & Parry, I. W. H. (2008). *Instrument Choice in Environmental Policy*. *2*(2), 152–174. https://doi.org/10.1093/reep/ren005

Government of British Columbia. (2007). Climate Change Accountability Act. *2007*, *c*, 1–12. http://www.bclaws.ca/civix/document/id/complete/statreg/07042_01

Government of British Columbia. (2018). *B.C.'s new LNG Framework to deliver record investment, world's cleanest LNG facility* (Vol. 13, Issue 3). https://doi.org/10.1177/155005948201300303

Hallbar Consulting. (2017). *Resource Supply Potential for Renewable Natural Gas in B. C.*

Hoberg, G., St-laurent, G. P., Schittecatte, G., & Dymond, C. C. (2016). Forest Policy and Economics Forest carbon mitigation policy : A policy gap analysis for British Columbia. *Forest Policy and Economics*, *69*, 73–82. https://doi.org/10.1016/j.forpol.2016.05.005

Holland, S. P., Hughes, J. E., & Knittel, C. R. (2009). Greenhouse Gas Reductions under Low Carbon Fuel Standards? *American Economic Journal: Economic Policy*, *1*(1), 106–146. https://doi.org/10.1257/pol.1.1.106

Hoyle, A. J. (2020). *Modelling the Effect of Canada ' s Clean Fuel Standard on Greenhouse Gas Emissions by*.

Huffman, J. L. (1994). Markets, Regulation, and Environmental Protection. *Montana Law Review*, *55*(2).

Hymel, K. M., Small, K. A., & Dender, K. Van. (2010). Induced demand and rebound effects in road transport. *Transportation Research Part B: Methodological*, *44*(10), 1220–1241. https://doi.org/10.1016/j.trb.2010.02.007

International Energy Agency. (2020). Outlook for biogas and biomethane. In *World Energy Outlook Special Report*. https://doi.org/10.1787/040c8cd2-en

Jaccard, M. (2009). International Handbook on the Economics of Energy Edited. *International Handbook on the Economics of Education*, 1–860. https://doi.org/10.4337/9781845421694

Jaccard, M. (2012). The political acceptability of carbon taxes: lessons from British Columbia. In *Handbook of Research on Environmental Taxation* (pp. 175–191).

Jaccard, M., & Bataille, C. (2002). If sustainability is expensive, what roles for business and government? A case study of GHG reduction policy in Canada. *Journal of Business Administration and Policy Analysis*, *30–31*, 149–184.

Jaccard, M., Nyboer, J., Bataille, C., & Sadownik, B. (2003). *Modeling the Cost of Climate Policy : Distinguishing Between Alternative Cost Definitions and Long-Run Cost Dynamics*. *24*(1), 49–73.

Jaccard, M., Rivers, N., & Horne, M. (2004). The morning after:optimal greenhouse gas policies for Canada's Kyoto obligations and beyond. *Commentary - C.D. Howe Institute*, *Mar*, 1–31.

Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A Process for Capturing CO2 from the Atmosphere. *Joule*, *2*(8), 1573–1594. https://doi.org/10.1016/j.joule.2018.05.006

Kinnon, M. Mac, Zhu, S., Carreras-sospedra, M., Soukup, J. V, Dabdub, D., Samuelsen, G. S., & Brouwer, J. (2019). Considering future regional air quality impacts of the transportation sector. *Energy Policy*, *124*(September 2018), 63–80. https://doi.org/10.1016/j.enpol.2018.09.011

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., & Stern, N. (2018). Making carbon pricing work for citizens. *Nature Climate Change*, *8*(8), 669–677. https://doi.org/10.1038/s41558-018-0201-2

Lacroix, K., & Richards, G. (2015). An alternative policy evaluation of the British Columbia carbon tax: Broadening the application of Elinor Ostrom's design principles for managing common-pool resources. *Ecology and Society*, *20*(2). https://doi.org/10.5751/ES-07519-200238

Lepitzki, J., & Axsen, J. (2018). The role of a low carbon fuel standard in achieving long-term GHG reduction targets. *Energy Policy*, *119*(March 2018), 423–440. https://doi.org/10.1016/j.enpol.2018.03.067

Loulou, R., Goldstein, G., & Noble, K. (2004). *Documentation for the MARKAL Family of Models*. *October*.

Luke, L., & Noble, B. (2019). Consideration and influence of climate change in environmental assessment: an analysis of British Columbia's liquid natural gas sector. *Impact Assessment and Project Appraisal*, *37*(5), 371–381. https://doi.org/10.1080/14615517.2018.1533515

Morrow, W., Gallagher, K. S., Collantes, G., & Lee, H. (2010). Analysis of policies to reduce oil consumption and greenhouse-gas emissions from the US transportation sector. *Energy Policy*, *38*(3), 1305–1320. https://doi.org/10.1016/j.enpol.2009.11.006

Moultak, M., Lutsey, N., & Hall, D. (2017). *TRANSITIONING TO ZERO-EMISSION HEAVY-DUTY FREIGHT VEHICLES*. *September*.

Murray, B., & Rivers, N. (2015). British Columbia's revenue-neutral carbon tax: A review of the latest "grand experiment" in environmental policy. *Energy Policy*, *86*, 674–683. https://doi.org/10.1016/j.enpol.2015.08.011

National Energy Board. (2016). *Canada's Energy Future 2016*.

Natural Resources Canada. (2012). *Study of Hydrogenation Derived Renewable Diesel as a Renewable Fuel Option in North America*.

Navius Research. (2016). *Modelling the Impact of the Climate Leadership Plan & Federal Carbon Price on British Columbia ' s Greenhouse Gas Emissions* (Vol. 1).

Navius Research. (2017). *Supporting the development of CleanBC* (Vol. 33, Issue 1).

Pfenninger, S. (2017). Energy scientists must show their workings. *Nature*, *542*, 393–393.

Pindyck, R. S. (2018). *The Use and Misuse of Models for Climate Policy*. *June*, 100–114. https://doi.org/10.1093/reep/rew012

Posada, F., & Facanha, C. (2015). Brazil Passenger Vehicle Market Statistics. In *ICCT - The International Council on Clean Transportation* (Issue October). https://theicct.org/sites/default/files/publications/Brazil PV Market Statistics Report.pdf

Rhodes, E., Axsen, J., & Jaccard, M. (2017). Exploring Citizen Support for Different Types of Climate Policy. *Ecological Economics*, *137*, 56–69. https://doi.org/10.1016/j.ecolecon.2017.02.027

Rhodes, E., & Jaccard, M. (2013). A Tale of Two Climate Policies : Political Economy of British Columbia ' s Carbon Tax and Clean Electricity Standard. *Canadian Public Policy*, *39*, S37–S51.

Rivers, N., & Jaccard, M. (2005a). Canada's efforts towards greenhouse gas emission reduction : a case study on the limits of voluntary action and subsidies. *International Journal of Global Energy Issues*, *23*(4), 307–323.

Rivers, N., & Jaccard, M. (2005b). *Combining Top-Down and Bottom-Up Approaches To Energy-Economy Modeling Using Discrete Choice Methods*. *26*(1), 83–106.

Robertson, G. P., Dale, V. H., Doering, O. C., Hamburg, S. P., Melillo, J. M., Wander, M. M., Parton, W. J., Adler, P. R., Barney, J. N., Cruse, R. M., Duke, C. S., Fearnside, P. M., Follett, R. F., Gibbs, H. K., Goldemberg, J., Mladenoff, D. J., Ojima, D., Palmer, M. W., Sharpley, A., … Wilhelm, W. W. (2008). Agriculture: Sustainable biofuels redux. *Science*, *322*(5898), 49–50. https://doi.org/10.1126/science.1161525

Rudd, A. E. S. (2012). *Cost Effectiveness of Climate Change Policies for the United States*. 123.

Talebian, H., Herrera, O. E., Tran, M., & Mérida, W. (2018). *Electri fi cation of road freight transport : Policy implications in British Columbia*. *115*(January), 109–118. https://doi.org/10.1016/j.enpol.2018.01.004

Trussart, S., Messier, D., Roquet, V., & Aki, S. (2002). *Hydropower projects: a review of most effective mitigation measures*. *30*, 1251–1259.

U.S. Energy Information Administration. (2020). *Annual Energy Outlook 2020*.

Vass, T. (2016). *Trading Off Political Acceptability and Economic Efficiency: Policy Options for Reducing Canada's Electricity and Transportation Emissions*. *659*.

Vass, T., & Jaccard, M. (2017). *Driving Decarbonization : Pathways and Policies for Canadian Transport*.

World Bank Group. (2019). *State and Trends of Carbon Pricing 2019* (Issue June). https://doi.org/10.1596/978-1-4648-1435-8

Appendix A. Summary table of policies modeled

Sector	Policy	Description	CIMS Start Year	Modeling Methodology
Economy-wide	Carbon Tax	Broad price on CO2 emissions for all products in the economy.	2005	Applied a broad price to CO2 emissions.
Natural gas extraction	Methane Regulations	Requires a 45% reduction in methane emissions from the natural gas extraction sectors.	2015	Phased out new market share for production technologies that do not include leak detection and repair by 2025.
	RNG Mandate	Requires a % of biomethane to be added to the natural gas supply stream.	2020	Required a rising % minimum market share of RNG production technologies in place of natural gas production technologies.
Personal transportation	ZEV Mandate	Requires 10% of new vehicles sold in 2025 be ZEVs. Rises to 30% by 2030 and 100% by 2040.	2025	Separated ICE vehicles to compete separately from ZEV vehicles. Within the ZEV competition, created a representative ICE vehicle technology that requested services from the ICE competition. Forced the new market share of the representative ICE vehicle to decline over time.
Sector	**Policy**	**Description**	**CIMS Start Year**	**Modeling Methodology**
Personal transportation	ZEV Subsidies (federal and provincial)	Provincial subsidy: provides $3,000 for a fully electric vehicle or $1,500 for a plug-in hybrid vehicle. Federal subsidy: provides $5,000 for a fully electric vehicle or $2,500 for a plug-in hybrid vehicle.	2020	Created a proxy fuel to represent money provided by the subsidy. Assigned a portion of the “fuel” to technologies that will receive the subsidy. Added a negative fuel price to simulate cost savings.

	Federal vehicle emissions standard	Regulates the CO2/km that can be emitted by passenger vehicles and light-duty trucks.	2010	Phase out of standard ICE vehicle motor and e-85 motor.
Personal & freight transportation	LCFS	Requires a decreasing emission intensity for fuels over time. While there is an overall intensity target, emissions reductions are specified per fuel stream. - Fuel providers that exceed the target generate credits, while providers that do not meet the target generate deficits and must purchase credits. - Projects that contribute to the decarbonization of the fuel stream may be eligible for a set number of Part 3 agreement credits, which can also be sold to fuel providers.	2010	Added an “LCFS fuel” attribute to each fuel production technology. The amount of “LCFS fuel” is anchored to their emissions per unit production. A price is applied to the LCFS fuel to simulate the price increase that would result from fossil fuel suppliers paying hydrogen, electricity, and biofuel producers for LCFS compliance credits. - The model is re-run at different LCFS fuel prices until a certain carbon intensity is achieved for the target years - This modeling method assumes an equilibrated credit trading market, with no excess Part 3 agreements or a phase out of Part 3 agreements.
Freight Transportation	Federal vehicle emissions standard	Regulates the CO2e/tonne-mile of freight vehicles.	2010	Phased out the standard freight motor by 2015.
Residential, commercial, industrial sectors	RNG Mandate	Requires a % of biomethane to be added to the natural gas supply stream.	2020	Created a competition between a representative RNG technology and a natural gas technology to fuel building services. Both technologies use natural gas as a fuel, but the RNG representative technology is more expensive to create a price signal.

Residential and commercial sectors	B.C. Step Code		Mandatory in 2030	Phase out of low-efficiency technologies by 2030 for the following services: - Air conditioning - Natural gas and oil furnaces - Standard building shells - Water heating - Lighting Motive power
Sector	**Policy**	**Description**	**CIMS Start Year**	**Modeling Methodology**
Residential	Residential Heat Pump Subsidies	Provides $1,200 to convert and electric furnace system to a heat pump and $2,000 to convert an oil, propane, or natural gas system	2020	Created a proxy fuel to represent money provided by the subsidy. Assigned a portion of the “fuel” to technologies that will receive the subsidy. Added a negative fuel price to simulate cost savings.
Electricity	Clean Energy Act	Requires all electricity to be generated from zero-emissions sources by 2025.	2010	Forced the phase out of all non-zero emission electricity production technologies. Allowed for potential electricity production from natural gas with CCS.
Biofuel and hydrogen	Performance Standards	Require a decreasing upstream emission intensity over time.	2020	Forced phase-outs of high-emissions production technologies over time.
Industrial sectors	Emissions Intensity Standards	Requires each sector reduce their emissions by x% from baseline over time. - Sectors will have different emissions reductions requirements.	2020	I will structure this similarly to the LCFS above. I will add a proxy Fuel to All technologies in each sector and levy a price on that Fuel to induce changes in the technology mix over time. - As with the LCFS, this method assumes perfect trading of credits and no excess of credits.

Appendix B. Comparison of emissions with Navius Research Study

Sectors in gTech and CIMS are not equivalent, and CIMS does not disaggregate its emissions to the same level as gTech. Here I report the values from Navius Research's study exactly as they appeared in the methodology report and arrange the values from my own study to align as closely as possible. I report the 2030 emissions only; for results from the Navius Research study from 2010-2025, see their report, *Supporting the development of CleanBC*.

Table 8 Reference case 2030 emissions comparison of Navius Research results and results from this study.

gTech Sector	gTech (MtCO2e)	CIMS (MtCO2e) Low LNG	CIMS (MtCO2e) High LNG
Buildings and communities	8.6	9.9	9.9
Commercial and Institutional	2.3	4.1	4.1
Residential	3.3	4.1	4.1
Industrial Processes and Product Use	0.6	N/A	N/A
Waste	2.5	1.7	1.7
Transportation	22.0	27.7	27.9
Domestic Aviation	1.5		
Light-Duty Vehicles	7.0		
Heavy-Duty Vehicles	8.8		
Railways	0.8		
Domestic Navigation	1.8		
Off-Road Vehicles	1.8		
Industrial Processes and Product Use	0.3		
Industrial	29.6	21.7	24.7
Public Electricity and Heat Production	0.1	0.2	0.2
Petroleum Refining Industries	0.4	0.9	0.9

Mining	0.4	0.4	0.4
Upstream Oil and Gas Production	10.9	11.7	14.0
Manufacturing Industries	4.5	1.1	1.1
Construction	0.1	N/A	N/A
Agriculture and Forestry	0.5	N/A	N/A
Pipeline Transport	1.2	Included under “Upstream Oil and Gas Production”	Included under “Upstream Oil and Gas Production”
Fugitive Sources - Coal Mining	0.9	1.5	1.5
Fugitive Sources - Oil and Natural Gas	5.1	Included under “Upstream Oil and Gas Production”	Included under “Upstream Oil and Gas Production”
Cement Production	1.3	1.3	1.3
Lime Production	0.3		
Aluminum Production	0.7	1.0	1.0
Other Industrial Processes and Product Use	0.2	N/A	N/A
Agriculture	2.9	4.0	4.0
Enteric Fermentation Manure	1.8		
Manure Management	0.5		
Agricultural Soils, Burning and Fertilizer	0.6		
Total	60.3	60.6	62.5

Table 9 *CAP* policy run 2030 emissions comparison of Navius Research results and results from this study.

gTech Sector	gTech (MtCO2e)	CIMS (MtCO2e) Low LNG	CIMS (MtCO2e) High LNG
Buildings and communities	6.2	7.9	7.9
Commercial and Institutional	1.5	3.2	3.2
Residential	2.5	3.0	3.0
Industrial Processes and Product Use	0.6	N/A	N/A
Waste	1.5	1.7	1.7
Transportation	15.4	22.2	22.2
Domestic Aviation	1.5		
Light-Duty Vehicles	5.5		
Heavy-Duty Vehicles	5.4		
Railways	0.0		
Domestic Navigation	1.5		
Off-Road Vehicles	1.3		
Industrial Processes and Product Use	0.3		
Industrial	22.4	20.9	22.3
Public Electricity and Heat Production	0.1	0.2	0.2
Petroleum Refining Industries	0.3	0.9	0.9
Mining	0.3	0.4	0.4
Upstream Oil and Gas Production	7.0	10.1	11.5
Manufacturing Industries	4.0	1.1	1.1
Construction	0.1	N/A	N/A
Agriculture and Forestry	0.5	N/A	N/A
Pipeline Transport	1.2	Included under	Included under

		“Upstream Oil and Gas Production”	“Upstream Oil and Gas Production”
Fugitive Sources - Coal Mining	0.8	1.5	1.5
Fugitive Sources - Oil and Natural Gas	2.9	Included under “Upstream Oil and Gas Production”	Included under “Upstream Oil and Gas Production”
Cement Production	1.3	1.7	1.7
Lime Production	0.2		
Aluminum Production	0.6	1.0	1.0
Other Industrial Processes and Product Use	0.2	N/A	N/A
Agriculture	2.9	4.0	4.0
Enteric Fermentation Manure	1.8		
Manure Management	0.5		
Agricultural Soils, Burning and Fertilizer	0.6		
Total	43.9	51.0	52.4

Differences in emissions may also stem from two other factors:

LNG Emissions

There is a small difference in LNG production emissions when comparing my study and Navius Research’s study. Navius Research added LNG emissions ex post, as they judged that the transfer of labour from the rest of the economy to LNG (holding population growth fixed) would reduce emissions to an excessive degree. Additionally, Navius Research did not run their policies under separate LNG scenarios. Their LNG production assumptions were provided by the provincial government. Since these are not public, I was not able to run the same assumptions for a closer comparison of my study and Navius Research's study. Under my Low LNG scenario, natural gas production emissions for my *CAP* run were approximately 1MtCO2e less than Navius Research's *CAP* run in 2030. Under my High LNG scenario, emissions from my run were approximately 1MtCO2e higher than their run.

Building Emissions

2030 commercial building emissions in my study are approximately 1.5MtCO2e higher than Navius Research's study. We use different sources to parameterize technologies in our studies. Most of the values parameterizing building technologies in the Navius Research study come from more recent sources than my study. Differences in capital, operational, and energy costs between the studies will contribute to the discrepancy in GHG reductions. Different assumptions concerning declining capital costs may also contribute to a difference in GHG emissions. Without knowing the exact values used in the Navius Research study, I cannot reasonably estimate how much these differences contributed to the overall discrepancy in building emissions. Apart from parameterization, these studies are relatively similar in terms of assumptions and calibration. We calibrate our emissions in this sector to the same set of data, although we calibrate to different years (Navius Research calibrates for 2005 to 2010 while I calibrate for 2005 to 2015). The policies we model leading up to 2030 are the same as well.