Trading Off Political Acceptability and Economic Efficiency: Policy Options for Reducing Canada's Electricity and Transportation Emissions

by

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Abstract

This study used the energy-economy model CIMS to assess policy options for achieving Canada's 2030 emissions reduction commitment under the Paris agreement, with a focus on electricity and transportation sector reductions. The results found that existing and promised policies will likely be far from sufficient to achieve the Paris target. Two alternative approaches to close the gap to achieving the target were explored: one relying solely on emissions pricing and one relying primarily on flexible regulations. While emissions pricing is generally regarded as the most economically efficient way to reduce emissions, the results found that an emissions price on the order of $\$200/tCO_2$ would likely be required to achieve the Paris target, which would likely be very difficult politically to implement. The proposed flexible regulations approach offers an alternative that may be somewhat less economically efficient but may have a better chance of being implemented and thus achieving the target.

Keywords: energy-economy modeling; climate change policy; Canada; Paris target

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CCS	carbon capture and storage
CEUD	Comprehensive Energy Use Database
CGE	computable general equilibrium model
CNG	compressed natural gas
E85	ethanol-85
EMRG	Energy and Materials Research Group
GHG	greenhouse gas
GDP	gross domestic product
HDRD	hydrogenation derived renewable diesel
LCFS	low carbon fuel standard
LDAR	leak detection and repair
LNG	liquefied natural gas
NEB	National Energy Board
NIR	National Inventory Report
NRCAN	Natural Resources Canada
OECD	Organization for Economic Cooperation and Development
PZEV	Partial zero emission vehicle
SMR	steam methane reforming
tCO_2	tonnes of carbon dioxide
UNFCCC	United Nations Framework Convention on Climate Change

Chapter 1. Introduction

Climate change is one of the most pressing issues of our time. Since the start of the industrial revolution, human activity has been increasing the concentration of greenhouse gases in the atmosphere, which is changing the radiative forcing of the planet and in turn causing the climate to change (IPCC, 2014). If global greenhouse gas emissions continue without abatement, devastating consequences can be expected, including increased intensity and frequency of extreme weather events, increased droughts and crop failure, increased spread of disease vectors, sea level rise leading to coastal flooding, and mass human displacement and migration.

In 1992 at the Earth Summit in Rio de Janeiro, Brazil, global leaders from 154 countries signed onto the United Nations Framework Convention on Climate Change (UNFCCC), with the goal of reducing global greenhouse gas emissions. While some countries have made substantial progress in reducing emissions, the UNFCCC process over the last two decades has largely failed to achieve the reductions necessary to stabilize global climate. However, in late 2015, efforts to keep concentrations of atmospheric greenhouse gases within safe levels were advanced with the signing of the UNFCCC Paris Agreement. This agreement has been referred to as a turning point, since for the first time, both developed and developing nations have agreed to take steps to reign in their emissions.

Canada has been a part of the UNFCCC process and has committed to contribute to global efforts to reduce greenhouse gas emissions. However, over the past two and half decades, Canada has set numerous emission reductions targets but has failed to put in place policies that are sufficient to meet those targets (National Round Table on the Environment and the Economy, 2012). In 2015, Canada set a new target under the Paris Agreement to reduce emissions to 30% below 2005 levels by 2030 (Government of Canada, 2015). Developing a strategy to meet such a target is not an easy task. All types of climate policies have both advantages and disadvantages, and the government will be required to make trade-offs as it designs its strategy.

Canada's past climate change strategies have consisted largely of non-compulsory policies, including programs that provide information and subsidies that incentivize energy efficiency and low carbon technologies. Research and historical experience have shown that non-compulsory policies, while politically relatively easy to adopt, are largely ineffective in achieving emission reductions (Jaccard, 2005). Rather, achieving substantial reductions requires compulsory policies, which could be either emissions pricing or regulations. To be effective, the compulsory policies must be applied at levels of stringency that are sufficient to meet the given emission reductions goal.

A near consensus exists among economists that emissions pricing, which can take the form of a carbon tax or cap-and-trade, is the most economically efficient way to reduce emissions. That is, emissions pricing is the least costly way to achieve any given amount of emission reductions. However, emissions pricing of sufficient stringency may be the most politically difficult climate policy to pursue, in that it is likely to provoke the most public opposition. A policy approach dominated by regulations may offer an alternative that, while still not necessarily easy to implement, may result in less public opposition and thus could enable policies to actually be passed that are stringent enough to achieve substantial emission reductions. While regulations are generally not as economically efficient as emissions pricing, if they are designed to have broad coverage and to allow flexibility in how emissions are reduced, their efficiency loss relative to emissions pricing can be lessened. Thus, if politicians are unwilling or unable to adopt stringent carbon pricing policies, a carefully-designed package of regulations could be an appealing choice to effectively meet emission reduction objectives.

If the current Canadian government is serious about achieving its Paris target, some combination or separate application of emissions pricing and regulations will be required, at levels that are stringent enough to drive the desired emission reductions. From fall 2015 to fall 2016, the federal government announced a number of new climate policies, including investment in low carbon technologies and innovation, methane regulations in the oil and gas sector, and a minimum national carbon price. On the surface, the policy approach may look promising. However, given Canada's history of failing to achieve its climate commitments, a critical independent assessment would be useful to evaluate whether the government's proposed strategy, however well-intentioned, will likely lead to success in achieving Canada's target or will once again fall short. If current policies fall short, alternative policy approaches and/or alternative levels of policy stringency should be considered.

With this current study, I sought to provide one such independent assessment of the government's strategy as it stood as of October 2016. The government stated at that time that additional policies were yet to be announced, and thus my study was intended to be a mid-term assessment to evaluate how large of a remaining gap needed to be filled by additional policy measures. I also explored two alternative policy approaches that could be used to achieve the Paris target – one relying solely on emissions pricing and one dominated by flexible regulations. I did so out of an awareness that some degree of a trade-off may be needed between economic efficiency and political acceptability when adopting stringent climate policies in the real world. Note that in focusing on the Paris target, I do not claim to offer an assessment of the target itself – although I have chosen to use it as a benchmark in this study, I am aware that some commentators may argue that Canada should adopt an even more ambitious target while others may argue that it is too ambitious.

The methodology of my study involved using the energy-economy model CIMS, which represents energy production and consumption throughout the Canadian economy, to simulate a number of different policy scenarios. The four scenarios I simulated are as follows:

1. an existing policies scenario, which includes all major current provincial policies and all federal policies adopted prior to the 2015 fall election;
2. a promised federal policies scenario, which adds to the existing policies scenario the federal policies announced since the election up until October 2016;
3. an emissions pricing scenario, which fills the gap to achieve the Paris target by relying solely on emissions pricing; and

4. a flexible regulations scenario, which fills the gap to achieve the Paris target by relying primarily on regulations as well as a modest carbon price.

The scenarios were evaluated in terms of their emissions, technological, and energy cost outcomes. I particularly focused on the electricity and transportation sectors as I was updating the model, running my scenarios, and evaluating the results. These sectors are key sources of emissions and thus are important areas in which emissions can be reduced. Some elements of this study, as I note throughout, were the result of collaboration with another Energy and Materials Research Group master's student, Mikela Hein, whose research focused on the industrial sectors[1].

The specific objectives of this study were as follows:

1. to evaluate the emission reduction performance of federal climate policies promised as of October 2016, in terms of how close the policies will come to achieving the 2030 Paris target;
2. to assess what carbon price trajectory would be required to achieve the Paris target, if emissions pricing were the dominant policy approach;
3. to outline a package of flexible regulations that would achieve the Paris target; and
4. to compare policy approaches dominated by emissions pricing and by flexible regulations in terms of: a) emissions by province, b) emissions by sector, c) technological outcomes, and d) energy costs. Based on the last two, I aim to provide a proxy assessment of the relative economic efficiency of the two approaches.

This study had a number of limitations. All models are a simplification of reality and the results are subject to uncertainties. I did not use a computable general equilibrium (CGE) model nor did I calculate policy costs, and thus I was unable to directly compare the economic efficiency of alternative policy approaches. Additionally, in the flexible regulations scenario, I included regulations in some but not all sectors of the economy.

[1] Also note that this study's results were used in a public report released in September 2016 that I was a part of producing: Jaccard, Hein & Vass (2016). Is win-win possible? Can Canada's government achieve its Paris commitment . . . and get re-elected?. Available at http://rem-main.rem.sfu.ca/papers/jaccard/Jaccard-Hein-Vass%20CdnClimatePol%20EMRG-REM-SFU%20Sep%2020%202016.pdf. Thus, there is some overlap between that report and this study.

Future research could help address these limitations by conducting a similar study that undertakes more extensive uncertainty analysis, links CIMS to a CGE model, and applies flexible regulations to all sectors of the economy.

The remaining sections outline the details of the study. Section 2 provides background information on the history of climate policy in Canada, different types of climate policies, the challenges of political acceptability for climate policy, and the use of energy-economy models to evaluate climate policy. Section 3 explains the methodology used for this study, including calibration, input assumptions, and other updates made to the CIMS model. Section 4 explains the assumptions for each scenario that was modeled. Section 5 outlines and discusses the results of the study. Section 6 summarizes the study's key findings and discusses limitations and possible directions for future research.

Chapter 2. Background

2.1. Overview of climate policy in Canada

Canada has a history of climate policy failure. Since the early 1990s, Canada has been a part of international negotiations and agreements to reduce global greenhouse gas emissions under the United Nations Framework Convention on Climate Change. Over the years, the Canadian federal government has repeatedly set new emission reduction targets, including a target set in 1988 to stabilize emissions at 1990 levels by 2000, the Kyoto Protocol target set in 1997 to reduce emissions by 6% below 1990 levels by 2012, and the Copenhagen Accord target set in 2009 to reduce emissions by 17% below 2005 levels by 2020 (National Round Table on the Environment and the Economy, 2012). Yet while the government has adopted a variety of plans and approaches to reduce emissions, these have been largely ineffective. Canada has consistently failed to meet its targets and will undoubtedly not achieve its 2020 Copenhagen target. Rather than stabilizing or reducing emissions, Canada's national emissions had grown by 2013 to 18% above 1990 levels (Environment Canada, 2015). Canada's poor performance on climate policy has been noticed internationally. For example, Canada ranked fourth last out of 32 OECD countries on the 2016 Climate Change Performance Index, a scoring system used to evaluate countries' performance on climate change policy action developed by non-governmental organizations (Burck, Marten, & Bals, 2015).

A wide variety of climate policies have been adopted by the Canadian federal and provincial governments, which possess shared jurisdiction over matters relating to the environment under the Canadian Constitution (Bélanger, 2011). Historically, most of the federal government's climate strategies have focused on information campaigns and energy efficiency subsidies, which have done little to reduce emissions (National Round Table on the Environment and the Economy, 2012). In the past decade, the federal government has also adopted regulations to reduce emissions from new coal plants, personal vehicles, and freight trucks, but they are relatively weak and alone will be far from sufficient to achieve substantial emission reductions by 2030. The provinces have stepped in with their own policies, which reflect varying degrees of ambition. Key provincial policies include a carbon tax and a clean electricity standard in BC, a regulation phasing out coal plants in Ontario, a cap-and-trade system in Quebec and Ontario, an emissions cap on the electricity sector in Nova Scotia, and a promised carbon levy and plans to phase out coal plants in Alberta (Boothe & Boudreault, 2016). This has resulted in a patchwork of policies across the country.

In 2015, Canada set a new emission reduction target as part of the international Paris Agreement, committing Canada to reduce emissions by 2030 to 30% below 2005 levels (Government of Canada, 2015). Yet the federal government's own emissions forecast from that year, which took into account all federal and provincial measures in place as of September 2015, projected that national emissions in 2030 would *exceed* 2005 levels by 2 to 17% (Environment and Climate Change Canada, 2016). Several substantial policy initiatives were announced by the provinces and the federal government in the fall of 2015 and spring of 2016. Still, an independent assessment of Canada's emissions that took into account policies adopted and in the developing stages as of April 2016 projected national emission reductions in 2030 of only 5% below 2030 levels (Sawyer & Bataille, 2016). Evidently, achieving Canada's 2030 target would require additional policies.

In the fall 2015 federal election, the Liberals led by Justin Trudeau took power after nearly a decade under Stephen Harper's Conservatives. There are some indications that the Liberal government may do more towards meeting Canada's international climate change commitments. The Liberal Party ran on a platform that promised a nation-wide price on carbon and to work with the provincial and territorial governments to develop a climate change strategy (Liberal Party of Canada, 2015). In the year after the election, the federal government unilaterally announced several climate change initiatives, including funding directed to climate change mitigation in its spring 2016 budget, proposed regulations on methane in the oil and gas sector, and a minimum national price on carbon rising to $\$50/tCO_2$ by 2022. At the same time, the federal government acknowledged in fall 2016 that more policies are needed to meet its international emission reduction commitments and at the time of writing was still in the process of further developing its pan-Canadian climate change strategy with the provincial and territorial governments.

2.2. Background on climate change policy

2.2.1. Types of climate policies

A variety of policy tools can be used by governments in trying to reduce greenhouse gas emissions, including information provision, subsidies, government investment, regulations, and carbon pricing. Each of these policy tools can be categorized along a spectrum from voluntary (emissions are reduced by choice) to compulsory (emissions must be reduced) (Figure 1).

Figure 1 Spectrum of compulsoriness of climate policy tools

Information provision is a voluntary policy tool, and it involves using education, moral suasion, and fact provision to try to convince people to voluntarily reduce emissions. Examples include educational campaigns informing people about the science of climate change, commercials trying to convince people to drive less or change to LED lightbulbs, and eco-labels providing information about the efficiency of fridges and other appliances. While some people may choose to reduce emissions in response to information provision, there is no guarantee that they will.

Subsidies offer positive incentives to individuals and firms who undertake actions that reduce emissions. Examples include rebates or tax incentives for people building energy efficient homes and feed-in tariff policies that support development of renewable energy projects. Subsidies are voluntary in that they are providing support or a reward for actions that reduce emissions rather than requiring those actions. Subsidies are often prone to high levels of free ridership, which occurs when a subsidy is received by someone who would have taken the action even in the absence of the subsidy. If subsidy is the only policy approach, there is no cost for those who decide to sustain or even increase their current emissions.

Government investment is generally considered a voluntary policy. Examples include funding for public infrastructure that may reduce emissions and funding of energy efficiency and fuel-switching in government operations. Governments may fund public transit improvements in the hopes that doing so will encourage more people to take transit instead of driving cars. Doing so would be considered a voluntary policy, since people may or may not increase their public transit use. Governments could also provide funds to reduce energy use (and thus possibly emissions) of government office buildings or to switch to lower emission government vehicle fleets. However, this is not really a compulsory policy since government is voluntarily reducing its emissions while requiring nothing of individual citizens and corporations. There is no cost if they sustain or even increase their emissions while government reduces the emissions over which it has direct responsibility.

Carbon pricing is broadly considered a compulsory policy, and it can take the form of a carbon tax or a cap-and-trade system. A carbon tax policy sets a price that must be paid per tonne of emissions produced. Individuals and firms can choose to reduce emissions to avoid or reduce tax payments. A cap-and-trade policy sets a maximum quantity of allowable emissions and allocates emissions permits that add up to that quantity. The government can either auction the permits or give them out freely, and firms can buy and sell the permits among each other. The market determines the price of the permits, and this cost is incorporated by retailers into the prices of gasoline, diesel, natural gas, jet fuel, heating oil and electricity, which makes cap-and-trade a carbon pricing policy. Again, firms can choose to reduce emissions to avoid having to purchase emissions permits. Carbon pricing falls toward the compulsory end of the spectrum in that it requires one of two actions – either emissions must be reduced or a price must be paid for emissions. No carbon emissions are free.

Regulations are also compulsory policies, and they can take a number of forms. Command-and-control (or prescriptive) regulations specify a particular action that must be taken or technology that must be adopted. Examples could include a policy that requires all coal plants to be shut down by a given date or a policy that requires 100% of new vehicles sold to be pure electric vehicles by a given year. These regulations are compulsory in that they require firms or individuals to take the same specified action or face a large fine.

In contrast to command-and-control regulations, flexible regulations are more technology neutral and provide a variety of options for how regulated entities can comply. One type of flexible regulation is an average sectoral performance standard, which could for example, require the electricity sector to achieve a declining average emissions intensity per megawatt hour of electricity produced throughout the sector. The standard could be met through a combination of actions such as closing coal plants, retrofitting coal plants with carbon capture and storage, or increasing generation with one or a combination of natural gas, nuclear and renewable energy technologies.

Another type of flexible regulation is a niche market regulation, which requires a growing minimum market share for emerging low emission technologies that would otherwise have difficulty competing with higher-emitting conventional technologies. An example is a partial zero-emission vehicle (PZEV) mandate, that would require vehicle manufacturers to achieve on average a rising minimum percent of very low or zero-emission vehicle sales. The PZEV sales could be met by any combination of pure electric, plug-in hybrid, biofuel, or hydrogen vehicles. The market-wide minimum average means that manufacturers unable to meet the minimum sales requirement could avoid fines by purchasing compliance certificates from manufacturers that exceed the minimum sales requirement. Flexible regulations are also compulsory because they require a given overall performance or market share requirement to be met; however, they are less compulsory than command-and-control regulations in that they dictate fewer specifics in terms of what actions must be taken, what technologies must be adopted, and which firms must undertake the emissions reductions.

When discussing climate policy, a distinction is often made between pricing and non-pricing policies, with carbon taxes and cap-and-trade considered pricing policies and all other policies considered non-pricing policies. Perhaps a more accurate distinction would be between compulsory policies with an explicit carbon price and those with an implicit carbon price. Carbon taxes and cap-and-trade policies set an explicit, visible price on carbon, through the carbon tax itself or through the price of permits under a cap-and-trade system. While other compulsory policies may not explicitly set a price on carbon, they carry an implicit price, in that they lead to actions that reduce emissions and incur costs. The implicit carbon price of a non-pricing compulsory policy is equal to the explicit carbon price that would have caused the same actions to occur as those caused by the non-pricing policy.

2.2.2. Comparing policies using four policy evaluation criteria

Given the diversity of policy tools available, policymakers are faced with the task of determining which climate policies should be adopted. This task is not easy, since each type of policy has both advantages and disadvantages. Evaluation criteria can be useful when weighing the pros and cons of alternative policies. Common criteria used when evaluating environmental policy include environmental effectiveness, economic efficiency, administrative feasibility, and political acceptability. This section explains the four criteria, and presents a brief comparison of climate policy types according to the criteria, with a focus on carbon pricing and regulations.

The first policy criterion, environmental effectiveness, measures whether the policy is likely to actually achieve the intended environmental objective. An example of an environmental objective in the case of climate policy would be to reduce carbon emissions by a specified amount. The most effective policies at achieving emission reductions are compulsory policies rather than those that rely on voluntary action. Thus, carbon pricing and regulations both meet the first necessary condition for policy effectiveness. However, a second condition is also required for effectiveness – policy stringency. For an emission reductions objective to be achieved, an emissions price must rise high enough or a regulatory requirement must grow stringent enough to drive the desired level of emission reductions.

The second policy criterion, economic efficiency, compares policies based on the costs required to achieve a given objective. All else equal, society would prefer policies that reduce a tonne of carbon through a lower rather than a higher cost action. Policies that perform best on the economic efficiency criterion are those that come closest to achieving the equi-marginal principle, which states that all actors should face the same cost for the last unit of pollution abated. Achieving the equi-marginal principle is aided by 1) broad policy coverage, in that as much of the economy as possible is covered by the policy, and 2) flexibility, in that the policy does not dictate how emission reductions are achieved and by whom, but rather lets households and firms through their actions in the market find the least cost ways to reduce emissions.

In theory, a uniform carbon price applied throughout the entire economy should perform best on the economic efficiency criteria. Some analysts have claimed that regulations are highly inefficient in comparison to carbon pricing (Ecofiscal Commission, 2015). However, these claims are often supported by analyses focused on command-and-control regulations rather than other more flexible regulations. Command-and-control regulations are generally much less cost-effective than emissions pricing since they are focused on mandating specific technologies in specific sectors, do not recognize the diversity of costs faced by different households and firms, require the government to predict what technology and energy forms would be best, and do not provide strong incentives for innovation to achieve further emission reductions.

Well-designed flexible regulations are likely to be more cost-effective than command-and-control regulations. Flexible regulations enable emission reductions to be achieved using a variety of different technologies, thus letting households and firms choose options that are lowest cost for them. Trading of compliance obligations enables firms that can achieve reductions at a lower cost to reduce their emissions instead of firms for which reductions are higher cost. Firms also have an incentive to innovate and compete to find new lower cost ways to comply with the regulation.

Furthermore, some of the theoretical cost-effectiveness advantages of carbon pricing do not always occur in real-world applications. Carbon price policies often do not result in complete and uniform coverage of the entire economy. Rather, often some sectors and industries are given breaks or are exempted from the policy entirely, particularly in the case of trade-exposed industries and sectors such as agriculture and waste where it is more difficult to monitor emissions. Also, revenues generated by carbon pricing are used for a variety of purposes as opposed to being used solely to reduce other inefficient forms of taxation, and thus the ‘double dividend’ efficiency gain of carbon pricing is often not achieved (Carl & Fedor, 2016). Moreover, it should be kept in mind that a policy can be cost-effective but ineffective. While a very low emissions price may be cost-effective, in that it achieves the lowest cost emission reductions, it will likely lead to only limited emission reductions.

The third policy criterion, administrative feasibility, looks at how logistically simple or difficult it would be for government agencies to carry out the policy. For example, a straightforward carbon tax could be applied relatively easily by adjusting existing tax rates on fuels. On the other hand, cap-and-trade systems and flexible niche market regulations could both be more complicated to administer due to the need to set up and oversee a market of tradable permits (Rhodes & Jaccard, 2013).

The fourth policy criterion, political acceptability, refers to the likelihood that a policy can be passed and implemented without facing substantial public opposition at a level of stringency that will be effective. Since politicians are interested in getting re-elected, most would be hesitant to adopt policies that perform poorly on this criterion. Unfortunately, the most politically acceptable policies tend to be ineffective, voluntary policies. Since voluntary policies do not require people to incur costs, people tend to support them, but for that same reason these policies tend to be ineffective. On the other hand, more effective compulsory policies often face greater opposition since they are compulsory and require costs to be incurred. Policies with highly visible costs, such as carbon taxes, tend to be the least politically acceptable, as will be explained in more detail in the following section. Political opposition tends to be particularly high when specific groups, industries, or regions feel that they will face disproportionally high costs relative to others. Fortunately, most policy types can be designed to help alleviate these distributional effects to some degree, through such measures as support for regions that are currently carbon-intensive, less stringent requirements for trade-exposed industries, tax rebates for low income households, and transitional support for workers moving out of carbon-intensive industries. However, these measures may be insufficient to quell opposition from those who feel negatively impacted, especially given the misinformation that is associated with public debates about policies that appear to have focused impacts.

If we assume that a government is serious about achieving an emission reductions target, that government should rely on a carbon price or regulations that are stringent enough to achieve the target, thus taking care of the environmental effectiveness criterion. We can also assume that a government serious about climate change would allocate the needed resources to carry out the required policy as long as it is not unreasonably complicated, so both carbon pricing and regulations would likely be acceptable in terms of administrative feasibility. If economic efficiency were the only remaining criterion, carbon pricing would likely then be the ideal policy choice. However, political acceptability cannot be ignored, and because of this final criterion, the ideal policy choice is not as clear-cut as some analysts – particularly economists – often imply. I focus on the implications of the political acceptability challenge in the following section.

2.3. The challenge of political acceptability

2.3.1. Effective climate policy as a political non-winner

For several reasons, effective climate policy in any form is unlikely to be a political win for a politician facing four-year election cycles. Climate policy requires people to accept tangible and certain costs imposed on them in the short-term, in exchange for far less tangible and uncertain benefits for themselves and others at some point in the future. This is problematic considering that people tend to place more value on losses than on gains (Kahneman & Tversky, 1979). Also problematic is the complex, amorphous, unfamiliar, future-oriented nature of the climate change threat, which makes climate change difficult for the human brain to process and less likely to trigger the innate human reactionary response to act against threats in comparison to more immediate, familiar, tangible threats (Marshall, 2014).

Furthermore, personal values and beliefs often act as a filter that shapes how people assess and deal with information, including information about climate change. According to the theory of cognitive dissonance, when a person is presented with information that does not align with his or her current belief systems and behaviours, this causes internal discord (Festinger, 1957). Unless the person then changes his or her behaviour to align with the new information, he or she will likely reject or ignore the new information to reduce this internal inconsistency. In the case of climate change, people are being told that their current ways of life and the comforts that they value, such as cars and electricity-consuming devices, are causing harm to people and the planet. Unless people are willing to drastically change their lifestyles, this information is uncomfortable, making it easiest for many people to ignore or downplay the threat, or even to entirely reject the science of climate change.

Along a similar line, the theory of cultural cognition suggests that people's factual beliefs about controversial policy issues are shaped by their cultural worldviews surrounding the activities that would be subject to regulation (Kahan & Braman, 2006). Thus, social influences, group dynamics, and the beliefs of others sharing similar worldviews all influence people's evaluation of information and policies. In the case of climate change policy that would impose regulation on free markets, people whose cultural worldview values free markets may be likely to resist climate change policy and even scientific facts about climate change.

Together, these and other psychological biases and social influences lead some people to ignore or reject the threat of climate change, and thus to not support climate policy. Meanwhile, the fossil fuel industry has a strong incentive to demonstrate strong opposition to climate policies. Groups that would appear to face concentrated costs from climate policy, such as individuals and corporations in the fossil fuel industry, can be highly motivated to lobby against the policy (Olson, 1965). This contrasts with groups that would receive much more diffuse benefits from a policy, as the general public would from climate policy, and thus have much less of an incentive to mobilize in support of the policy.

Another challenge for adopting effective climate policy is that the atmosphere is a global commons and thus the solution requires collective global action. In this way, climate change is a prime example of the classic tragedy of the commons, in which all actors acting alone in their own self interest would lead to a problematic outcome for all, whereas all actors acting in concert would achieve a positive outcome (Hardin, 1968). Without a legally binding international climate agreement, which the Paris agreement is not, each country cannot be certain that all other countries will act to mitigate climate change, thus making it more challenging to see the benefits resulting from one country acting. Indeed, here in Canada, the fact that Canada accounts for less than 2% of global emissions has been used to generate doubt and opposition by those arguing against strong national climate policy (BOE Report Staff, 2016; Government of Saskatchewan, 2016). Thus, despite the reality that collective action problems require each individual actor to contribute to the solution no matter how small or large their contribution to the problem, the international nature of the climate change threat presents a challenge for public acceptability of domestic climate policy.

Yet another political challenge for climate policy is deciding how to allocate the burden of emission reductions. This burden-sharing difficulty arises at the international level among countries and at the national level among sub-national regions. Here in Canada, some provinces – particularly Alberta and Saskatchewan – have much more emissions-intensive economies, which leads to concerns that climate policy could have disproportionately negative impacts on these provinces (Snoddon & Wigle, 2009). Economic modeling research has demonstrated that climate policies can be designed to mitigate negative economic effects on emissions-intensive provinces (Bohringer, Rivers, Rutherford, & Wigle, 2014; Peters, Bataille, Rivers, & Jaccard, 2010). However, some provinces may still feel that they will be negatively impacted by climate policy, which presents a political challenge for the federal government when adopting national climate policy.

Due to this wide variety of challenges, the political calculus does not favour effective climate policies. Politicians seeking near-term re-election may have difficulty in seeing the benefits of imposing policies that incur visible, immediate costs. Instead, politicians have tended to adopt non-compulsory information and subsidy policies that do not force significant costs on the public and industry and thus do not usually result in much public opposition. These policies may help appease the portion of the public that does want climate change to be addressed. Yet these policies are largely ineffective at achieving emission reductions, leading to the conundrum in which the most politically acceptable policies are the least effective and the most effective policies are the least politically acceptable.

2.3.2. The accentuated challenges of carbon pricing

While all effective climate policy is likely to be politically challenging, out of the two main types of effective climate policies – carbon pricing and regulations – carbon pricing appears to be the most politically challenging. Various public opinion polls and research studies have shown that carbon pricing tends to be less favourably received by the public in comparison to regulations and to government action on climate in general. Nation-wide surveys in Canada and the US have found that opposition to carbon taxes (41% in Canada, 71% in the US) and cap-and-trade (46% in Canada, 45% in the US) was substantially higher than opposition to a renewable portfolio standards (15% in Canada, 18% in the US) or regulations on coal-fired power generation (22% in Canada, 44% in the US) (Lachapelle, Borick, & Rabe, 2014). A fall 2016 Nanos telephone survey also found that while 21% of Canadians oppose or somewhat oppose a national plan to meet Canada's international emission reduction targets, 32% oppose or somewhat oppose a minimum national carbon price (Nanos, 2016). Additionally, a research study on attitudes towards climate policies in British Columbia, where a diverse portfolio of policies have been adopted, found that while the carbon tax was the policy that the most people were aware of, a much larger proportion of people strongly oppose or somewhat oppose the carbon tax (44%) in comparison to the clean electricity standard (11%) and the low carbon fuel standard (10%) (Rhodes, Axsen, & Jaccard, 2014). Even if a majority of the population supports carbon pricing, opposition by a third to nearly half of the population would likely cause concern for most politicians.

Real-world experiences also provide evidence of the political challenges of adopting carbon pricing, particularly carbon taxes. The fact that very few jurisdictions have adopted explicit carbon taxes, while many have adopted a variety of regulatory policies, is an indication of the political challenges of carbon taxes (Rabe & Borick, 2012). In cases where policies resembling a carbon tax have been proposed, the 'carbon tax' label is often avoided and the policy is instead re-labeled, as was done in the case of Stephane Dion's 'green shift' and the Alberta government's 'carbon levy'. Even with re-labelling, these policies face substantial political challenges. Stephane Dion's defeat in the 2008 Canadian federal election has been largely attributed to his 'green shift' carbon tax proposal, with Dion himself afterwards referring to a carbon tax as 'political suicide' (Harrison, 2012). The

BC provincial Liberal government also came under fire after adopting a carbon tax, with the NDP opposition launching an aggressive ‘Axe the Tax’ campaign and the Northern Central Municipal Association adopting a resolution that officially opposed the tax. Although the BC carbon tax is revenue neutral with all revenues returned to BC citizens and companies, a poll shortly after the tax was adopted found that over 70% of people believed they would pay more than they would receive in rebates (Harrison, 2013). Many different groups claimed that they were disproportionately harmed by the carbon tax, ranging from rural to suburban residents, and the cement to the greenhouse industry (Jaccard, 2012).

These higher levels of opposition to carbon taxes specifically, and carbon pricing in general, are not surprising given the general public aversion to taxes. Research has shown that the general public tends to believe that taxes are too high and are negatively impacting the economy, even much more than PhD economists believe that to be the case (Caplan, 2007). This anti-tax bias, in which people resent taxes and have difficulty acknowledging the benefits they receive due to taxation, is consistent with the previously mentioned loss aversion theory, in which people place higher value on losses than gains (Kahneman & Tversky, 1979). The fact that even a revenue neutral carbon tax tends to be viewed negatively is also consistent with loss aversion theory, since people likely take more notice of what they pay due to the carbon tax than to the revenue that is returned back to them via income tax cuts or other compensating payments. Especially since many people have difficulty prioritizing action to mitigate the threat of climate change, as discussed in the previous section, it makes sense that many would oppose policies that impose visible, direct costs on carbon. Thus, as a highly visible or salient type of policy, carbon pricing tends to face the highest amount of public opposition (Harrison, 2012).

2.3.3. The case for considering a regulatory approach

Given the substantial political challenges involved in adopting carbon pricing and then raising the carbon price to the levels needed to meet emission reduction targets, it may be prudent for politicians to consider using the other main form of effective climate policy – regulations. While any effective climate policy is likely to be difficult, regulations are likely to be less challenging in comparison to carbon pricing. Regulations will likely not perform as well as carbon pricing in terms of economic efficiency, but designing regulations to be flexible can reduce the economic efficiency loss. Climate policy experts acknowledge that no policy instrument is clearly superior when all desirable characteristics are considered (Goulder & Parry, 2008). Thus, trade-offs must be made, and in this case, a trade-off may need to be made between economic efficiency and political acceptability in order to achieve the end goal of effective climate policy.

Real world experience again can provide insight, in that most substantial emission reductions to date in North American have occurred as a result of regulations, as opposed to carbon pricing. In Canada, the policy that has led to the largest reduction in emissions was Ontario's regulation that phased out coal power plants (Jaccard, 2016). In British Columbia, the carbon tax at its current rate is not the policy that will likely lead to the most emission reductions; rather, it has been estimated that the clean electricity standard is likely to reduce emissions by four to six times more annually than the carbon tax by 2020 (Rhodes & Jaccard, 2013). Additionally, regulations have played a key role in reducing emissions in California, the US state that has made some of the strongest policy efforts to reduce emissions.

Various climate policy experts have suggested that it may be advantageous to consider pursuing 'second-best' climate policies such as regulations. In economic theory, the general theory of second best explains that if a constraint exists that prevents attaining all optimal conditions, the next best result does not necessarily require attaining all the other optimal conditions (Lipsey & Lancaster, 1956). This theory applied to climate policy would suggest that if the first-best policy cannot be achieved due to an external constraint, such as a lack of stakeholder support for the policy, it would become optimal to pursue a second-best policy approach (Bennear & Stavins, 2007; Jenkins, 2014). Thus, while in a world without political economy constraints carbon pricing would be considered the optimal policy from an economic efficiency standpoint, if political acceptability constraints make it impractical to implement carbon pricing at the levels needed to achieve emission reduction objectives, regulations that perform less well in terms of economic efficiency but better in terms of political acceptability may be the optimal policy choice (Jaccard, 2016). Regulations could actually end up being more economically efficient than carbon pricing implemented at sub-optimal levels, since there are costs in the form of externalities from insufficient climate change mitigation (Jenkins, 2014). Economic modeling research has demonstrated that if optimal carbon pricing cannot be implemented in the near-term, technology regulations can be a valuable complement to sub-optimal carbon pricing in that they lead to additional emission reductions and help prevent technological lock-in, thus enabling long-term emissions targets to be achieved at a lower cost than with an initially sub-optimal carbon price on its own (Bertram et al., 2015). In this way, regulations can help pave the way for more ambitious carbon pricing in the future.

In sum, while carbon pricing may be the ideal policy to cost-effectively reduce carbon emissions in a theoretical world without political constraints, in the real world, regulations may have some advantages over carbon pricing. It is for this reason that this study explores a partial regulatory approach as one of the options for achieving Canada's emission reduction targets.

2.4. Use of models to evaluate climate policy

Energy-economy models can be a useful tool to evaluate the emission and economic impacts of climate policy. These models generally fall into three broad categories: conventional bottom-up models, conventional top-down models, and hybrid models.

Bottom-up models contain detailed representation of energy-consuming and producing technologies, with a focus on the financial costs of technologies (Jaccard, 2009). Often used by engineers, physicists, and environmental advocates, these models aim to show how improved energy efficiency, changing technologies, and fuel switching will influence energy use and emissions. Many bottom-up models are based on cost-minimization, meaning that all decision-makers seek to minimize deterministic financial costs. Some of these are optimization models, in which all technology decisions for all energy end-uses are made simultaneously in an integrated, cost-minimizing fashion. However, most bottom-up models are extreme partial equilibrium, in which the cost-minimizing choice for each energy end-use is made without any consideration of the technology choice for any of the other energy end-uses. All bottom-up models assume that lower energy-consuming technologies and fuels are perfect substitutes for higher energy-consuming technologies that provide the same energy services. Thus, they often show that energy efficiency can be profitable and that emission reductions can be achieved at relatively low costs.

Top-down models do not contain detailed representation of technologies, but instead show the aggregate relationships among energy and other inputs to the economy and how these inputs translate into outputs. Often used by economists, these models are based on parameters estimated from historical market data, and thus are intended to represent the actual real-world decisions of consumers and firms, which are often not based on financial costs alone but may also incorporate preferences and consideration of risks. One type of top-down model called a computable general equilibrium model (CGE) seeks to represent full macro-economic responses, including changes in overall economic demand and production in response to price changes. CGEs use elasticities of substitution to show the substitutability with changing prices between different inputs to the economy and different forms of energy. Using sets of simultaneous equations, they can then show how the economy would respond to policies that change the relative prices of different inputs and energy forms.

Bottom-up and top-down models both have strengths and weaknesses. The key strength of bottom-up models is their technological detail, which enables these models to incorporate changing costs and characteristics of new and emerging technologies. However, their focus on financial costs may miss the full social cost of technological change, since technologies providing the same energy services may not always be perfect substitutes and new technologies with longer paybacks often present risks. Therefore, bottom-up models may underestimate the full costs of emission reductions. Top-down models seek to be more behaviourally realistic by representing the full costs of technological change through estimating parameters based on real-world data. Many top-down models also represent the full macro-economic response of the economy to policy. However, as technologies continue to evolve, model parameters estimated based on historical data may become less valid. The lack of technological detail makes it difficult for top-down models to represent economic responses as available technologies change. Thus, top-down models may overestimate the costs of emissions reductions, as they do not fully capture potential cost savings from technological evolution.

Hybrid models draw on the strengths of both bottom-up and top-down models in order to at least partially overcome the drawbacks of both model types. The CIMS model used in this study is one such hybrid model (Jaccard, 2009). As described in the following sections, CIMS incorporates 1) detailed representation of technologies, 2) parameters to realistically reflect real-world behaviour, and 3) partial macro-economic feedbacks.

Chapter 3. Modeling Methodology

3.1. Model overview

To address my research objectives, I modeled Canada's energy system using CIMS, an energy-economy-emissions model developed over the past several decades by the Energy and Materials Research Group at Simon Fraser University. CIMS models how capital stocks of energy producing and consuming technologies throughout the economy evolve over time (Jaccard, 2009). Both energy-consuming sectors (transportation, buildings, industry) and energy-producing sectors (electricity, oil, natural gas, coal, biofuels) are represented. The Canadian version of the model is broken down into seven regions: British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, and Atlantic Canada. The Atlantic Canada region includes New Brunswick, Nova Scotia, Prince Edward Island, Newfoundland, and the three territories, all of which are grouped together due to their relatively small size in comparison to the rest of the provinces.

CIMS contains data on the capital stocks of technologies in a base year (currently 2000), and assesses changes in capital stocks over successive five-year periods until 2050. At the end of each five-year period, the model first assesses which technologies have reached the end of their life and should be retired, and which technologies should be retrofitted to newer, more efficient technologies. Then, CIMS assesses the gap between forecasted demand for services and the total capacity of remaining capital stocks that can supply those services, and determines which new technologies should be purchased to fill the gap.

To determine which new technologies to purchase, CIMS uses the following equation:

Equation 1 CIMS market share algorithm

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

Equation 1 determines how much new market share (MS) a particular technology (j) will capture out of all technologies (k) that could perform a given service. The decision takes into consideration financial costs, specifically capital costs (CC), maintenance and operating costs (MC), and energy costs (EC). However, since factors other than financial costs can affect decisions about technology choices, CIMS contains three parameters to more realistically reflect the behaviour of actual decision makers in the economy. When possible, these parameters have been estimated based on empirical data, including actual market data and stated preference surveys, although at times they are estimated based on expert judgement. First, a discount rate (r) is used in annualizing capital costs over a technology's lifespan (n), in order to reflect the fact that decision makers tend to give more weight to current than future costs. Second, the equation includes an estimation of intangible costs (i), which are non-financial costs based on perceptions of risk and individual preferences. Examples of intangible costs include the inconvenience of having to wait at the bus stop in the rain to take public transit or the time and effort it takes to research and install energy-saving home retrofits. Third, a market heterogeneity parameter (v) is employed to reflect that decision makers may face different financial costs and have variation in terms of preferences and perceptions of risk.

Two other important equations that CIMS uses are the declining capital cost and declining intangible cost functions (EMRG, 2007). In the model, capital costs of new technologies decline as a function of cumulative production (based on both production within the model and an external forecast of global production) to account for decreases in capital costs due to both economies-of-scale in manufacturing and gains due to innovation as manufacturers gain experience producing technologies. In a similar manner, intangible costs of new technologies decline as a function of cumulative market share, accounting for changing perceptions of risk, changing preferences, and increased supporting infrastructure as new technologies becomes more widespread and familiar.

Within CIMS, sub-models representing individual sectors are linked, which can allow prices and quantities of fuels to adjust to policy-induced changes in demand, and sectoral output levels to adjust to policy-induced changes in energy costs. In this way, CIMS achieves a partial equilibrium between supply and demand; however, unlike full macroeconomic models, CIMS does not achieve equilibrium in terms of government budgets, employment, and investment, and it does not represent non-energy goods and services in the economy (Jaccard, 2009).

CIMS is well-suited for this study, as it can model both regulations and carbon pricing. Due to its detailed representation of energy technologies in all sectors of the economy, CIMS is particularly suitable for this study’s focus on flexible regulations targeted at specific groups of technologies and specific sectors. Each sector of the economy is represented in CIMS as a series of embedded energy decision nodes. For example, the personal transportation sector has nodes representing choices between fueling an internal combustion engine with gasoline or ethanol, purchasing a vehicle with a conventional or an alternative fuel drivetrain, and traveling by vehicle, public transit, bike, or foot. These decision nodes enable a flexible niche market regulation to be modeled by targeting a group of low emissions technologies and specifying an overall increasing market share for the group of technologies, without specifying an outcome for individual technologies competing within the group. In the case of personal vehicles, a partial zero emission vehicle (PZEV) regulation can be modeled by requiring an increasing aggregate market share of PZEVs, but the various PZEVs (electric, hydrogen, ethanol-85) compete to determine each of their individual market share within the aggregate. CIMS also has the capacity to model economy-wide carbon pricing policies and sector-specific performance standards, the latter of which is modeled as a shadow price on emissions.

However, due to its lack of full-macroeconomic feedbacks, CIMS does not fully represent how climate policy may affect output and the structure of the economy. As climate policy increases the costs of emissions-intensive energy sources that are currently relied on to produce many goods and services, demand for and production of these goods and services should decrease to some degree. This decrease may result in a slight decline in overall economic activity and structural change away from emissions-intensive goods and services (such as producing cement and steel) towards those with lower emissions (such as information and computer-based services). Also, if Canada adopts stringent climate policy while its trading partners do not, lower-cost imported goods may substitute for domestically-produced goods, again leading to output declines in domestic sectors. A computable general equilibrium (CGE) model would fully show these effects, but in CIMS they are only partially represented. Additionally, with respect to carbon pricing, the impact on economic activity can be influenced by how revenues are used. Possible uses of revenue could include income tax cuts to households and firms, subsidies to low carbon technologies, or investment in infrastructure projects. However, CIMS is unable to represent the different effects on the economy of different revenue recycling schemes; a CGE would be required to show this.

Thus, CIMS is unable to show how overall economic activity, as measured by GDP, may change in response to climate policy. While ideally CIMS would be used in conjunction with a CGE to show GDP effects, I chose to only use CIMS to maintain a reasonable scope for this study. I believe that the lack of full-macroeconomic feedbacks in CIMS was not a major limitation for this study for several reasons. First, CIMS does have partial macro-economic feedbacks, which I turned on for this study. Second, I assumed that all revenue collected from carbon pricing is recycled back to the sector from which it was collected, which occurs in CIMS through the revenue recycling function. This assumption is often valid for political acceptability reasons, and would mean reduced output effects. Third, if we assume that either Canada is acting in concert with the rest of the world or implements measures to protect trade-exposed sectors, output effects would again be reduced. Fourth, I made adjustments to account for the fact that CIMS may overestimate the carbon price needed to achieve a given reduction in emissions. The carbon price may be overestimated both since CIMS doesn't fully represent output and structural effects in the way that a CGE does and also since CIMS likely to some degree underestimates declining costs for low-emission technologies due to technological change. I judgementally assumed that the carbon price is overestimated by 25%. When running a specified carbon price, such as the promised federal minimum carbon price, I ran a price in CIMS that is 25% higher than the actual price. When determining what price is needed to achieve a given emission reduction, such as to meet Canada's Paris target, I assumed that the price run in CIMS is 25% higher than the actual needed price. Finally, since I cannot calculate GDP from CIMS, I used energy price changes as a proxy for the economic effects of different policy scenarios.

3.2. General model settings, calibration, and parameters

3.2.1. General model settings

CIMS has several general model settings that control the model's macroeconomic functions (Table 1). For this study, I turned on the model's energy supply and demand function, which enables energy production and consumption by different sectors to interact. Within the energy supply and demand function, the user can specify for each form of energy whether its production levels and price are either set based on a fixed trajectory determined outside of the model or determined based on demand within the model. In modeling, parameters determined outside of the model are called exogenous, while parameters determined within the model are called endogenous.

I set production and prices to follow exogenous trajectories for crude oil, natural gas, coal, and refined petroleum products. Since these forms of energy are internationally traded at near-universal prices, I assume that production is not sensitive to domestic demand and that any of the commodity not consumed domestically can be exported[2]. I also assume that prices are not sensitive to domestic demand since Canada is a relatively small economy and thus is a price taker in these particular global energy markets. I set prices to be determined endogenously by demand within the model for electricity and biofuels (production for both was already automatically endogenous). Aside from some trading with the US, Canada's electricity market is almost entirely a domestic market and thus driven by demand within Canada. A net export parameter within the electricity sector accounts for trade with the US. I also assume that much of the demand for biofuels within

[2] This assumption is a simplification, since a variety of global market circumstances could affect Canada's ability to export energy commodities. For example, strong global efforts to reduce greenhouse gas emissions could reduce global demand for oil and thus Canada's ability to export crude. I address this possibility by running each scenario twice with different exogenous forecasts for oil production, as discussed below. Exploring a variety of assumptions about global markets for other energy commodities is outside the scope of this study.

Canada could be met by domestic production and thus that this production and prices are driven by domestic demand[3].

Table 1 General model settings

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:	Exogenous
Coal:	Exogenous
Refined petroleum products:	Exogenous
Electricity:	Endogenous
Biofuels:	Endogenous
Macro feedbacks	On
Energy trade	Off
GHG pre-cognition	Average, starting in 2020
Revenue recycling	On

I also turned on the macroeconomic feedbacks in CIMS, which as discussed above is not a full general equilibrium model but does have partial macroeconomic feedbacks. The feedbacks include 1) Armington elasticities in the non-energy industrial sectors, which adjust output of manufactured products as costs of manufacturing those products change, and 2) activity elasticities for freight transportation and buildings, which adjust output in those sectors based on changes in output of manufactured products. The elasticities for manufactured goods partially represent import substitution away from Canadian products if Canada has more ambitious climate policies than its trading partners. They also partially represent structural change in the economy, occurring both in Canada and globally, in

[3] Again, this assumption is a simplification, since increasing domestic and global demand for biofuels would likely result in Canada engaging in more biofuel trade. However, I considered the assumption of a largely domestic biofuel market to be sufficient for the purpose of this study.

which carbon-intensive manufactured goods contract relative to lower-carbon goods and services due to climate policies being adopted around the world.

I did not use the energy trade function for this study. The energy trade function contains Armington elasticities that would adjust domestic energy production based on changes in costs of production, similar to the Armington elasticities for manufactured goods. However, given the complexities of global energy markets, I believe that using fixed exogenous forecasts for oil, natural gas, and coal will allow for a simpler, more transparent, and more plausible representation of energy production than if I allowed for adjustments using Armington elasticities. Using the Armington elasticities for energy could risk overstating the magnitude of changes in production or could even change production in the wrong direction. For example, with natural gas, global demand could either rise or fall with climate policy, given that natural gas is less carbon-intensive than oil and coal but more carbon-intensive than renewables. While relying on one exogenous forecast for natural gas production is a simplification, for the purposes of this study I believe it is a better choice than allowing for adjustments with elasticities.

I set the greenhouse gas pre-cognition function to ‘average’, beginning in the 2016 to 2020 period. This function reflects that technology acquisition decisions may take into account not only the current carbon price but also the expectation of future changes in the carbon price. It can be set to either ‘current’, which means that technology costs are calculated using only the current carbon price; ‘average’, which means that technology costs are calculated using the average carbon price over the technology’s lifetime; or ‘discounting’, which means that technology costs are calculated using the discounted total emissions charges expected over the technology’s lifespan. I chose the ‘average’ setting to represent decision-making with some foresight, but perhaps with not as well-calculated foresight as under the full ‘discounting’ method. I chose to start the function in the 2016 to 2020 period since decisions made in the past would not have taken into account carbon prices that have recently been announced or that could be adopted in the near future.

Finally, I turned on the revenue recycling function, which assumes that all carbon pricing revenue is returned to the sector from which it was collected. Thus, the carbon price revenue itself is not included when the model calculates a sector’s average cost of production and in turn changes in output. This is a simplification since in reality some carbon price revenue could end up being used for other purposes.

3.2.2. Calibration of historical emissions

The model was calibrated to align historical emissions with Canada's most recent National Inventory Report (NIR), which contains emissions data up to 2013 by province and emissions source (Environment Canada, 2015). Total national emissions in CIMS in each of 2005, 2010, and 2013/2015 are within 2% of the NIR emissions data (Table 2)[4]. Provincial emissions in CIMS are within 8% of NIR emissions data. Sectoral emissions in CIMS are within 16% of NIR data (Table 3). The NIR does not break down emissions into categories that exactly match the sectors within CIMS, which could explain some of the differences in sectoral emissions. Also, CIMS emissions reflect an average over a five-year period, whereas the NIR data are for one particular year. Given time constraints and the large amount of time that would be required to further reduce the differences between CIMS and the NIR data, the amount of difference outlined here was considered acceptable for this study.

Table 2 Comparison of CIMS and NIR emissions, Canada total and by region

(Values are greenhouse gas emissions in Mt CO_2eq)

	2005			***2010***			***2013/2015***		
	CIMS	NIR	Difference	CIMS	NIR	Difference	CIMS	NIR	Difference
Canada	730	749	-2%	712	707	1%	722	726	-1%
British Columbia	60	64	-6%	60	60	1%	61	63	-3%
Alberta	234	234	0%	249	243	2%	265	267	-1%
Saskatchewan	73	70	5%	75	70	7%	74	75	-1%
Manitoba	20	21	-4%	20	20	-1%	21	21	-1%
Ontario	197	211	-6%	175	178	-2%	169	171	-1%
Quebec	90	90	0%	85	83	2%	86	83	4%
Atlantic	56	59	-5%	49	53	-8%	45	46	-3%

[4] Note that years in CIMS refers to the five-year period up to that year, whereas NIR data reflect emissions specifically in that year. The 2011-2015 period in CIMS was compared to 2013 NIR data, the most recent year of reported data.

Table 3 Comparison of CIMS and NIR Emissions, by sector

(Values are greenhouse gas emissions in Mt CO_2eq)

	2005			***2010***			***2013/2015***		
	CIMS	NIR	Difference	CIMS	NIR	Difference	CIMS	NIR	Difference
Residential	48	48	0%	44	45	-1%	42	46	-9%
Commercial	34	34	2%	35	30	16%	34	30	13%
Transportation	183	185	-1%	191	194	-2%	198	198	0%
Electricity	118	124	-5%	97	102	-5%	74	88	-15%
Oil and Gas	158	159	0%	168	159	6%	187	177	6%
Industry	94	107	-12%	83	92	-9%	94	100	-5%
Agriculture	67	64	4%	65	60	9%	63	64	-1%
Waste	28	28	0%	29	27	7%	29	25	16%

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

CIMS uses sectoral activity level forecasts as a key driver of emissions projections. The sector activity levels specify the levels of demand, production or other activity in each sector, such as person kilometers travelled in personal transportation, metres squared of floor space in commercial buildings, or barrels per day extracted by the petroleum industry. The activity levels in turn drive energy technology acquisition and energy consumption, and thus emissions. Table 4 shows the exogenous national average annual growth in activity in each sector[5]. As previously noted, the CIMS macro-economic elasticities modify these exogenous activity levels to some degree. Activity level forecasts are set for each sector in each province; therefore, the growth rates for each individual province will in most cases be somewhat higher or lower than the national total growth rates displayed in the table.

[5] Note that exogenous sectoral activity levels for electricity and biofuel production are not shown, as activity in these sectors is driven entirely by demand within the model.

Table 4 National average annual growth in activity, by sector

		2015 to 2030	2030 to 2050
Buildings	Residential	1.0%	0.7%
	Commercial	2.1%	1.1%
Transportation	Personal	1.5%	0.8%
	Freight	2.3%	1.0%
Oil & Gas	Petroleum Extraction	6.0%	-0.1%
	Petroleum Refining	0.5%	-0.1%
	Natural Gas Extraction	1.5%	0.0%
Industry	Chemical Products	2.6%	0.7%
	Coal Mining	-2.6%	-0.3%
	Industrial Minerals	0.6%	0.8%
	Iron and Steel	1.2%	0.3%
	Metal Smelting	2.4%	1.4%
	Mining	1.8%	0.8%
	Other Manufacturing	3.0%	1.0%
	Pulp and Paper	0.8%	0.1%
Other	Agriculture	0.0%	0.0%
	Waste	1.2%	0.6%

*Petroleum extraction is displayed for the high oil price assumption (as discussed in the following section).

Sector activity level forecasts for the petroleum extraction, natural gas extraction, and coal mining sectors were based on the reference case projections from the National Energy Board (NEB)'s *Canada's Energy Future 2016* Report (National Energy Board of Canada, 2016) (Table 5). The exception is petroleum extraction in Alberta, which is discussed in the following section. The NEB forecasts only go until 2040, and so the 2040 data were also used for the 2045 and 2050 periods. For coal, the NEB report displayed national coal production as opposed to production broken down by province. The forecasted percentage splits among provinces already existing within CIMS were thus used when calculating coal production for the three coal producing provinces.

Table 5 Energy production levels by province

		2015	2020	2035	2050
Coal (Mt/year)	BC	27,236	27,306	27,614	27,769
	AB	30,801	26,881	15,902	13,792
	SK	9,843	10,163	7,176	9,984
Crude (Thousand bbl/day)	BC	37	48	88	88
	AB (high)	3,098	4,257	6,674	6,653
	AB (low)	3,098	3,022	2,946	2,912
	SK	479	498	482	444
	MB	46	29	17	15
	ON	1	1	0	0
	AT	240	298	148	101
Natural Gas (billion ft3/day)	BC	3.8	5.1	7.9	8.1
	AB	10.0	9.8	9.5	9.5
	SK	0.4	0.4	0.2	0.2
	AT	0.3	0.2	0.1	0.0

*For Alberta Crude, high = high oil price assumption, low = low oil price assumption (as discussed in the following section).

Historical sector activity levels for the personal transportation sector, which are measured in person kilometers traveled, were aligned with historical data from the Natural Resources Canada Comprehensive Energy Use Database (NRCAN CEUD) (Natural Resources Canada, 2016a). Forecasts were calculated using Statistics Canada provincial population forecasts and using the assumption that a 1% increase in population corresponds to a 1.5% increase in person kilometers traveled, as has been the trend over the past 15 years (Statistics Canada, 2016). Freight transportation activity levels, measured in tonne kilometers traveled, were also aligned with historical data from the NRCAN CEUD, and future projections were based on existing assumptions in CIMS. During the process of calibrating, I also adjusted sector activity levels for waste in all provinces and for residential and commercial buildings in a number of provinces in order to align with historical emissions data from the National Inventory Report (Environment Canada, 2015). The remainder of the sector activity level forecasts were left as previously existing in CIMS. These forecasts were derived by previous researchers based on a combination of industrial production data and forecasts, population data and projections, other statistical data, and projections from the GEEM energy-economy computable general equilibrium model.

End-use energy price forecasts are another key set of parameters used in CIMS. Price forecasts for natural gas and refined petroleum products (gasoline, diesel, light and heavy fuel oil, etc.) were also based on the reference case projections from NEB's *Canada's Energy Future 2016* Report (National Energy Board of Canada, 2016). As with energy production levels, the NEB's prices for the 2040 period were also used for the 2045 and 2050 periods. Baseline electricity prices were also based on the NEB report, and then CIMS adjusts these prices endogenously based on demand within the model. Coal prices were not reported in the NEB report and thus were left as already existing in CIMS.

Other fuel prices are also not reported by the NEB and thus were derived from other sources. The price for biomass used in the power sector can vary considerably depending on the type of biomass, which could include wood chips, forest residues, wood waste, and a variety of other sources. I approximated the price of biomass to be $2/GJ, which is in the middle of estimates of biomass prices from the International Renewable Energy Agency (2012) and the US National Renewable Energy Laboratory (2016). Prices for biomethane, which is available in CIMS in industrial sectors as a low emission alternative to natural gas, were based on the master's research of another EMRG graduate student, Mikela Hein. Biofuel, liquefied natural gas, compressed natural gas, and hydrogen fuel production and pricing were modeled endogenously in CIMS, as discussed in Section 3.3.4.

3.2.4. Oil price uncertainty

Key uncertainties when modeling energy systems include energy prices, technology prices, GDP and population growth (both important drivers of sector activity levels), and human preferences. While it was beyond the scope of this study to conduct sensitivity analyses on the many different CIMS parameters and exogenous inputs, the global oil price was chosen as a particularly important uncertainty to explore.

The global oil price has an impact on Canada's emissions in two key ways. First, a higher oil price would mean higher end use prices for refined petroleum products, which is particularly important for transportation emissions. Higher gasoline and diesel prices could help convince drivers and trucking companies to purchase alternative fuel vehicles (such as electric or hydrogen vehicles), to purchase more fuel-efficient vehicles, and to fill up on other lower carbon fuels (such as ethanol and biodiesel). People may also drive less and choose alternatives such as public transit or active transportation. Lower gasoline and diesel use in the transportation sector would make it easier to achieve emission reductions. Second, a higher global oil price would make it more economically attractive to expand oil sands production. Given that oil sands production is one of the most emissions-intensive industrial activities in the country, higher oil prices could, in this case, make it more difficult to achieve emissions reductions. The reverse is also true – with lower global oil prices, it would be more difficult to reduce emissions in transportation but easier to contain emissions from oil sands production.

In this study, I addressed uncertainty about global oil prices by simulating two versions of each policy scenario: a high oil price and a low oil price. The two oil prices are deliberately contrasted in order to explore the range of possible effects of oil price uncertainty. The global oil price has fluctuated a substantial amount over the years due to a wide variety of factors, and it is unknown what factors may impact it into the future. However, one interesting factor to consider is the impact of global climate action on oil prices. In a world in which there is a strong global effort to reduce carbon emissions, demand for oil should fall, leading to falling global oil prices. Therefore, the low oil price version could be one way of reflecting strong global climate action, while the high oil price version could represent weaker global climate action. Of course, these two futures could arise from a number of other factors unrelated to the level of global climate action.

The high oil price version is based on the reference scenario from the NEB (2016) report (Table 6). The global oil price rises to US$80/barrel (bbl) in 2020 and $100 in 2040, resulting in an average Canadian gasoline price of CAD$1.35/L in 2020 and $1.65 in 2040. All other refined petroleum product prices are also based on the NEB reference scenario. Oil sands output rises from current production levels of 2.5 million barrels per day (mbd) to 6 mbd by 2030, holding constant thereafter at 6 mbd to 2050. In the low oil price version, I assume that the global price of oil stays constant at US$50/bbl to 2050. Prices for refined petroleum products follow the NEB reference scenario up until 2020, after which they are held constant at the 2020 level for the remainder of the simulation period. For example, the average Canadian gasoline price is held at $1.15/L from 2020 onwards. Oil sands output is held constant at today's level of 2.5 mbd.

Table 6 Two versions of the global oil price and Alberta oil sands production

Oil Price	Oil Price Trajectory (Western Texas Intermediate: $/bbl, 2010 USD)	Gasoline Price Trajectory (Canadian average: $/L, 2010 CAD)	Oils Sands Output (million barrels/day)
High Oil Price	Rises steadily from today's price to $80 in 2020 and $100 in 2040	Rises steadily from today's price to $1.35 in 2020 and $1.65 in 2040	Rises steadily to 6 mbd by 2030, then stays constant to 2050
Low Oil Price	Remains at $50 up to 2050	Remains at $1.15 up to 2050	Remains at today's 2.5 mbd up to 2050

3.3. Sector input assumptions and calibration

This study focused in particular on the electricity and transportation sectors, which in Canada have substantial potential for emission reductions. This section summarizes my updates and assumptions for those sectors.

Note that in the process of calibrating and updating the model, some of the discount rates and market heterogeneity parameters in some sectors were adjusted to better align with data I was using for calibration and to values that were judged to be more plausible for the purposes of this study. The behavioural parameters used can be found in Appendix 1.

3.3.1. Electricity sector

Costs and availability of electricity generation technologies were updated for this study. Electricity generation technologies in CIMS include the following: coal (single cycle), natural gas (single and combined cycle), coal and natural gas with carbon capture and storage, light and heavy fuel oil (single cycle), diesel (single cycle), nuclear, large-scale hydro, small-scale hydro, biomass, wind, solar photovoltaic, solar thermal, and geothermal. The electricity sector is divided into baseload, shoulderload, and peakload sub-nodes, with lower capacity factors for dispatchable generation sources assumed for shouderload and peakload, to represent variation in load at different times of the day and year[6].

Costs of key electricity generation technologies were updated based on data and forecasts from the US government's Energy Information Administration (2015) and National Renewable Energy Lab (2016). Although costs of each generation type vary by location, the US-based data were assumed to provide a reasonable estimate of average costs for Canada. Carbon capture and storage (CCS) costs for coal and natural gas were based on a published review of cost estimates from a variety of sources, which found the average levelized cost per tonne of CO_2 avoided to be $101 for coal and $132 for natural gas (Bataille, Melton, & Jaccard, 2014). Table 7 shows the updated costs of key baseload generation technologies. Costs of hydro generation were not updated, as province-specific costs had already been estimated for CIMS and were assumed to not have changed substantially in recent years. Levelized costs of new large-scale hydro vary by province from $67 to 100 per MWh, while costs of new small-scale hydro vary from $80 to 162 per MWh. Costs were also not updated for other technologies that are available in CIMS but are expected to make only a limited contribution to new generation.

Table 7 Cost assumptions for key baseload electricity generation technologies

Technology	Capital Cost in 2015 (2015$/kW)	Operating Cost (2015$/MWh)	Assumed Capacity Factor	Levelized Cost in 2015 (2015$/MWh)
Coal (combined cycle)	3,400	7.80	85%	82
Natural gas (combined cycle)	1,000	7.60	85%	55
Coal with CCS (combined cycle)	7,000	18.20	85%	153
Natural gas with CCS (combined cycle)	2,500	11.80	85%	82
Biomass	4,000	17.00	85%	117
Wind	1,900, declining to 1,700 at maturity	15.20	35%	104 to 133, declining to 100 to 126 by 2030
Solar PV	3,000 declining to 1,100 at maturity	16.70	15%	241 to 480, declining to 137 to 258 by 2030

*Note: levelized costs include capital, operating, fuel, and integration costs for intermittent renewables. Levelized costs for coal and natural gas vary by province due to differences in fuel costs. A range of levelized costs is shown for wind and solar, representing higher costs with greater amount of renewable integration.

[6] For fossil fuel and biomass generation, assumed capacity factors are 85% for baseload, 30% for shoulderload, and 15% for peakload. Capacity factors for large-scale hydro vary by province, generally around 60% for baseload and below that for shoulderload and peakload.

When comparing costs of electricity generation technologies, it should be considered that some technologies like coal, natural gas, nuclear, large-scale hydro, and biomass are dispatchable, i.e. can be turned on at any time to meet demand, whereas other technologies like wind, solar, and run-of-the-river hydro are intermittent, i.e. can only generate power when the wind is blowing, the sun is shining, or the river is flowing. In addition to accounting for capital, operating, and fuel costs, calculating the true economic value of dispatchable and intermittent technologies would need to account for the value of network reliability and the value of electricity at the time of day each technology actually supplies electricity (Joskow, 2011). To account for intermittency, some modellers use optimization models that incorporate detailed hour-by-hour or minute-by-minute load and generation profiles. While it would be possible to build a detailed optimization model of the Canadian electricity sector and link it to CIMS, doing so was beyond the scope of this study.

One possible method to account for intermittency within the CIMS framework would be to add the cost of energy storage to the costs of intermittent renewables, in essence turning them into dispatchable sources of energy. However, large-scale energy storage currently has high costs, has not yet been widely deployed, and in most cases is likely unnecessary at lower levels of intermittent renewables penetration. A study by Safaei and Keith (2015) found that for the United States, bulk energy storage is unlikely to be economical if low-carbon dispatchable generation has reasonable costs and if emissions controls are not extremely tight (i.e. up to emission reductions of approximately 70% compared to current average electricity emissions intensity in the US). Ontario provides a model of how emissions in the electricity sector could be substantially reduced without deploying high-cost energy storage. Prior to the start of the coal phase-out in 2004, approximately a quarter of Ontario’s electricity was generated by coal. As coal plants were closed and renewable generation increased, low-cost, lower-carbon natural gas generation was used as back-up for intermittent renewables. My treatment of intermittent renewables in this study, inspired by the Ontario case, factors in the cost of building and using dispatchable back-up generation to ensure grid reliability when integrating intermittent renewables into the grid.

For wind, solar, and run-of-river hydro technologies, I added a 'back-up generation' service demand, which requires a small amount of back-up generation to be built and utilized for each unit of renewable generation. The back-up generation technologies were assumed to have low capacity factors since they would only be operating when the intermittent renewables were unable to meet demand. I allowed three lower-carbon dispatchable technologies to compete in the back-up generation node: natural gas, natural gas with carbon capture and storage, and biomass. For each of wind and solar, I included both a low and a high intermittent renewable penetration version, to represent the tendency for integration costs to increase as increasing amounts of intermittent renewables are added to the grid. The market share of the low penetration version was constrained so that the high penetration version would be needed to achieve higher levels of intermittent generation. I assumed a threshold for moving to the high penetration version of 30% generation for wind and 15% for solar, which I approximated based on estimates in the literature that intermittent renewables could account for between 20 to 45% of total annual generation without substantially increasing system operating costs (International Energy Agency, 2014; International Renewable Energy Agency, 2015).

To approximate the parameters for this back-up generation set-up (see Table 8), I relied on insights gained from estimates of integration costs from the literature and from experimenting with a simple optimization model I built based on hour-by-hour electricity load and capacity factor data for Ontario. I ran the optimization model multiple times requiring different levels of wind, solar, and small hydro generation, and then compared how much additional natural gas capacity and generation were required at different levels of renewable generation. Due to how the market share competition adds generation in CIMS – with some dispatchable generation being built that could be used as back-up generation even if not build specifically as back-up generation – my calculations on their own would have likely overestimated the amount of back-up capacity needing to be built for each unit of variable renewable capacity. Thus, I judgementally adjusted downwards the amount of back-up generation required to align more closely with external estimates of integration costs, which range from approximately $10 to 25/MWh at lower levels of variable renewable penetration[7]. I also judgementally lowered the amount of back-up generation needed for small hydro to take into the account that a lot of small-scale hydro generation has seasonal storage. While a more rigorous method could likely be developed to parameterize this set-up, given time limitations and the scope of this study I believe that my approximations are sufficient to capture the general idea that increased back-up generation is needed with increasing intermittent renewable integration.

Table 8 Costs and parameters for intermittent renewable generation with back-up generation

Technology (% of Total Generation)	Levelized Cost of Generation in 2015, Including Back-up Generation ($2015/MWh)	Integration Cost (2015 $/MWh)	Capacity Factor of Intermittent Technology	MW of Back-up Capacity per 1 MW of Intermittent Capacity	Capacity Factor of Back-up Generation	MWh of Back-up Generation per 1 MWh of Intermittent Generation
Small Hydro	approx. 125 to 150	8	varies by province	varies by province	19%	0.06
Wind (up to 30%)	104	15	35%	0.23	19%	0.13
Wind (more than 30%)	133	42	26%	0.10	19%	0.07
Solar (up to 15%)	241	20	15%	0.13	19%	0.17
Solar (more than 15%)	480	159	7%	0.06	19%	0.15

*Integration costs here include the cost of building back-up capacity; for the higher penetration versions, integrations costs also include the cost of additional wind or solar capacity due to lower capacity factors at higher levels of penetration. Note that even though integration costs are higher at higher levels of integration, less back-up capacity and generation is needed per unit of wind and solar capacity and generation since each unit of wind and solar are operating at reduced capacity levels.

The electricity sectors in each province were calibrated to align with NEB historical data on total electricity generation and share of each generation technology (National Energy Board of Canada, 2016)[8]. Several assumptions were made about the future availability of some technologies. I assumed that no new nuclear generation will be built anywhere in Canada, considering that no new nuclear plants have been built in Canada since the early 1990s and that public opposition would likely present a major challenge to building new nuclear generation. In provinces where hydro generation currently dominates

[7] For example, wind integration costs in BC were estimated as $13/MWh at 15% wind penetration, $19 at 25%, and $17 at 35% (BC Hydro, 2010). For Quebec, wind integration costs have been estimated at $22/MWh (Howatson & Churchill, 2006). Solar integration costs for the European Union were estimated at $20/MWh at 10% penetration and $25 for 18% (International Renewable Energy Agency, 2015).

[8] In calibrating electricity generation in Alberta, assumptions about oil sands electricity consumption were updated based on a report from the Canadian Energy Research Institute (Murillo, 2015).

(BC, Manitoba, Quebec, Newfoundland), I assumed that no new fossil fuel baseload or shoulderload generation will be built, and only a small amount of fossil fuel peakload generation might be built. In those regions, I limited largescale hydro to capture no more than 50% of new market share in each period, based on the assumption that there are not unlimited low-cost large hydro sites available; in other provinces, higher costs kept large hydro generation to plausible levels without imposing restrictions. Carbon capture and storage technologies were only made available in Alberta and Saskatchewan, which have good potential for CCS due to their location above the Western Canadian Sedimentary Basin and are the main provinces where interest in CCS has been demonstrated to date.

Cogeneration in industrial sectors contributes a notable amount of electricity to the grid in some provinces, particularly in Alberta and to a lesser extent Ontario and British Columbia (Nyboer, Griffin, & Bennett, 2016). Key sectors where cogeneration is currently significant include the Alberta oil sands, pulp and paper, and chemical manufacturing. I calibrated CIMS to align with historical cogeneration and to keep future cogeneration within plausible levels, based on available data and forecasts from the Canadian Industrial Energy End-Use Data and Analysis Centre (2016), the Alberta Electricity System Operator (2014), and the Oil Sands Community Alliance (2014). Limitations are necessary on cogeneration since high upfront costs and long payback periods will likely discourage some decision makers from investing in cogeneration, even if it may be financially ideal in the long-term. Still, cogeneration could end up being significant in some sectors. Cogeneration in the Alberta oil sands generated approximately 16 TWh in 2016, and could rise to between 31 and 43 TWh by the mid-2020s, as forecasted by the Alberta Energy System Operator and the Oil Sands Community Alliance, respectively.

3.3.2. Personal transportation sector

For this study, vehicle costs were updated in both the personal and freight transportation sectors[9]. In CIMS, capital costs for personal vehicles are divided into the cost of the vehicle body and the cost of the motor (Table 9 and Table 10). Each vehicle

[9] While the costs of personal vehicles and freight trucks were updated, the costs of other technologies in these sectors (buses, rail, ships, airplanes) were maintained as previously existing in CIMS.

body demands a given amount of motor services, which can be met by a conventional gasoline motor or various alternative vehicle motors such an electric motor or an ethanol-85 (E85) flex-fuel motor. For this study, motor capital costs were estimated based on a combination of advertised manufacturer's vehicle sale prices in 2016 and estimates of vehicle technology costs in reports from the U.S. National Research Council (2013) and MIT (Kromer & Heywood, 2007). Costs for electric and plug-in hybrid vehicles were set to align with the assumption that battery packs currently cost approximately $650-700/kWh, and could fall to $150-200 at maturity. Declining capital cost parameters were estimated based on past studies using CIMS and to help align future cost projections[10].

Table 9 Vehicle body capital costs and motor services demand

Vehicle	Capital Cost (2005$)	Motor Services Demand
Car - Small	$16,200	0.62
Car - Large	$25,000	1.00
Truck - Small	$28,400	1.52
Truck - Large	$37,200	0.81

Table 10 Capital and intangible costs of personal vehicle motor services

Motor	Capital Cost (2011-2015 period, 2005$)	Capital Cost at Maturity (2005$)	Capital Cost Progress Ratio	Exogenous Annual Rate of Capital Cost Decline	Fixed Intangible Cost (2005$)	Initial Declining Intangible Cost (2005$)
Gasoline - standard efficiency	$5,000	$5,000				
Gasoline - high efficiency	$6,000	$6,000				
Gasoline - hybrid	$10,500	$6,300	0.95	0.7%		$500
E85 Flex Fuel - high efficiency	$6,250	$6,250			$500	$2,500
E85 Flex Fuel - hybrid	$10,700	$6,400	0.95	0.7%	$500	$1,750
Plug-in Hybrid	$22,400	$10,900	0.88	0.7%	$100 to $600	$1,000 to $1,500
Electric	$24,600	$8,700	0.88	0.7%	$1,350 to $2,350	$1,500
Hydrogen	$65,000	$32,500	0.80	2.0%	$1,000	$2,500

*Note that to arrive at the total vehicle cost, the motor capital and intangible costs would be multiplied by the motor services demand and added to the vehicle body cost. Also note that a lower progress ratio value means a faster decline in costs with increased adoption.

Intangible costs and the market heterogeneity parameter were set to approximately align the baseline existing policies scenario with historical trends and future

[10] For all motor technologies with declining capital costs, the rate parameter is 40 and the shape parameter is 0.006, as estimated by previous CIMS researchers.

projections. Government statistical data and projections on vehicle sales in Canada weren't readily available, and thus US-based data and projections from the EIA's Annual Energy Outlook, as well as several non-academic sources, were used to approximate the Canadian market for calibration (Desrosiers, 2015; EIA, 2016; Flavelle, 2015; Klippenstein, 2016). When setting intangible costs, judgemental assumptions were made on what portions of intangible costs were fixed (which includes factors such as convenience anxiety due to electric vehicles not being able to travel distances of several hundred kilometers on a single charge) and what portion would decline over time with increased vehicle adoption (such as lack of familiarity with electric vehicles or less widespread re-charging infrastructure). Slightly different intangible costs for electric and plug-in hybrid vehicles were set in some provinces with low electricity rates to prevent unreasonably high market penetration of these vehicles in the existing policies scenario.

Each vehicle motor consumes a given amount of fuel per unit of service demand (Table 11). For E85 flex fuel vehicles, gasoline and E85 compete to meet fuel demand. Fuel efficiencies were estimated based on a combination of NRCAN (2016b) data on 2016 vehicle fuel efficiencies and estimates in reports from the International Renewable Energy Agency (2013) and the U.S. National Research Council (2013). The fuel efficiency of all vehicle types will likely continue to improve over time, but this dynamic is not fully represented in the version of CIMS used for this study. The shift to more efficient internal combustion engines is likely to be most important in terms of emissions, and therefore high efficiency gasoline and E85 flex fuel motors were included to approximate this shift.

Table 11 Fuel consumption by vehicle motor type (L equivalent/100 vehicle km)

Motor	Gasoline or Ethanol	Electricity	Hydrogen
Gasoline - standard efficiency	9.7		
Gasoline - high efficiency	7.4		
Gasoline - hybrid	5.3		
E85 Flex Fuel - high efficiency	7.4		
E85 Flex Fuel - hybrid	5.3		
Plug-in Hybrid	1.1	2.6	
Electric		2.6	
Hydrogen			7.4

*Note that these values represent fuel consumption for an average large car, which demands 1 unit of motor services per km travelled. Fuel consumption per km travelled would be lower for an average small car and higher for an average truck.

3.3.3. Freight transportation sector

In the freight sector, truck capital costs represent the entire cost of the vehicle and are divided into trucks for intra-city transport (light-medium) and inter-city transport (heavy) (Table 12). Capital costs were estimated based on previously existing values within CIMS and reports from the International Council for Clean Transportation and the UC Davis Institute of Transportation Studies (den Boer, Aarnik, Kleiner, & Pagenkopf, 2013; Fulton & Miller, 2015; Jaffe et al., 2015). The natural gas heavy freight truck represents an average of trucks running on liquefied natural gas and compressed natural gas. As with personal transportation, declining capital cost parameters were estimated based on past studies using CIMS and to help align future cost projections. Intangible costs for diesel trucks were set to align with historical average fuel efficiencies as reported by NRCAN (2016a), while intangible costs for other types of trucks were estimated judgementally as a proportion of capital costs.

Table 12 Capital and intangible costs of freight trucks

Motor	Capital Cost (2011-2015 period, 2005$)	Capital Cost at Maturity (2005$)	Capital Cost Progress Ratio	Exogenous Annual Rate of Capital Cost Decline	Fixed Intangible Cost (2005$)	Initial Declining Intangible Cost (2005$)
Light-Medium						
Diesel - standard efficiency	$50,000					
Diesel - medium efficiency	$55,500					
Diesel - high efficiency	$62,300					
Plug-in Hybrid	$148,600	$97,800	0.92	4.5%	$250	$500
Electric	$153,900	$93,300	0.92	4.5%	$500	$1,000
Hydrogen	$208,500	$71,000	0.85	5.0%	$250	$2,000
Heavy						
Diesel - standard efficiency	$106,300					
Diesel - medium efficiency	$110,600					$2,500
Diesel - high efficiency	$121,900					$5,000
Natural gas	$150,800				$1,500	$8,000
Hydrogen	$411,000	$181,500	0.85	5.0%	$2,000	$10,000

Fuel efficiencies were estimated based on values previously in CIMS, historical data on diesel truck fuel consumption from NRCAN, and reports from the International Council for Clean Transportation and the UC Davis Institute of Transportation Studies (den Boer et al., 2013; Fulton & Miller, 2015; Natural Resources Canada, 2016a) (Table 13). The fuel efficiency values are in terms of fuel consumption per tonne kilometer travelled, assuming an average payload of 0.9 tonnes for light-medium trucks and 6.7 tonnes for heavy trucks, as calculated based on NRCAN data from 2000 to 2013. For diesel vehicles, regular diesel and hydrogenation derived renewable diesel (HDRD) compete to meet fuel demand. Medium and high efficiency diesel trucks are included to approximate the continual improvement in vehicle efficiency, which could be an important source of emission reductions in freight[11].

Table 13 Fuel consumption by vehicle motor type (L equivalent/100 tonne km)

Motor	Diesel or HDRD	Electricity	Hydrogen	Natural Gas
Light-Medium				
Diesel - standard efficiency	19.6			
Diesel - medium efficiency	17.2			
Diesel - high efficiency	15.4			
Plug-in Hybrid	3.3	6.3		
Electric		10.4		
Hydrogen			15.2	
Heavy				
Diesel - standard efficiency	5.2			
Diesel - medium efficiency	5.0			
Diesel - high efficiency	4.6			
Natural gas				5.8
Hydrogen			4.1	

3.3.4. Fuel production

Biofuel production

For this study, updates were made to the ethanol and biodiesel production sectors, which account for upstream emissions and production costs for these fuels. Energy and emissions were calculated based on papers and assessments from the Argonne National Laboratory and the California Air Resources Board, and costs were based on an IRENA report and a report commissioned by NRCAN (California Air Resources Board, 2009; Eco Ressources Consultants, 2012; Huo, Wang, Bloyd, & Putsche, 2008; IRENA, 2013; Wang, Han, Dunn, Cai, & Elgowainy, 2012). Biofuels can be produced using a variety of feedstocks and production methods, but for simplicity I chose to represent a limited number of methods. For ethanol, I included conventional ethanol derived from corn and

[11] Three levels of fuel efficiencies for diesel trucks were needed for freight in order to accurately model freight fuel efficiency standards (in contrast to only two levels of fuel efficiencies for personal gasoline vehicles).

cellulosic ethanol derived from corn stover. Cellulosic ethanol is a newer and lower emission way of producing ethanol. For biodiesel, I included hydrogenation derived renewable diesel (HDRD) derived from soybeans. HDRD is chemically the same as conventional diesel and can be used in any blend in diesel vehicles without engine modification. Conventional biodiesel, while somewhat less expensive to produce than HDRD, can only easily be blended into conventional diesel up to 15 to 20% without engine modification. Although canola would likely be a more common feedstock for HDRD in Canada, data on HDRD produced from soybeans were more readily available and soybeans-derived HDRD is likely a close enough general approximation to represent production from other feedstocks.

Biofuel supply chains involve several steps, including agricultural production of feedstocks, converting feedstocks to biofuels, and transportation of feedstocks and fuels. In CIMS, the key sources of emissions are represented, with both high and lower emission options, as follows: tractors producing feedstocks can run on conventional diesel or biodiesel; boilers for producing the fuels can run on natural gas, coal, electricity, or biomethane; and hydrogen for producing fertilizer for feedstocks and for producing HDRD itself can be produced through natural gas-based steam methane reforming or electrolysis. Costs and emissions for each form of biofuels vary depending on whether conventional or low emissions options are used (Table 14). In CIMS, I included nitrous oxide emissions from fertilizer application for growing feedstocks, which accounts for most of the remaining emissions when low-emission fuels are used.

Table 14 Production emissions and costs for conventional and low emission methods of biofuel production, as calculated within CIMS

	Emissions (g CO2eq/MJ)		**Production costs (2015$/Leq)**	
	Conventional production	Low emission production	Conventional production	Low emission production
Corn ethanol	49	14	1.23	1.45
Cellulosic ethanol	23	6	Starting: 1.69 At maturity: 1.20	Starting: 1.79 At maturity: 1.35
HDRD	34	10	1.54	1.87

*Note that $/Leq means the cost per litre of gasoline or diesel equivalent. Ethanol has a lower energy density (22.6 MJ/L) than gasoline (35 MJ/L), whereas HDRD and conventional diesel have the same energy density (38.3 MJ/L).

Calculating emissions and costs for biofuel production presents the challenge of deciding how to account for land-use and co-products. Land-use emissions can be divided into direct land-use emissions, which include loss of carbon sinks from clearing land to grow feedstocks and emissions from soils during feedstock production, and indirect land-use emissions, which occur when biofuel feedstock production displaces existing production and results in land clearing for agricultural production elsewhere (Eco Ressources Consultants, 2012). Land-use emissions were not calculated in this study, as it was assumed that given the vast amount of agricultural and fallow land in Canada, a substantial amount of biofuel could be produced without requiring substantial land-clearing. This assumption that Canada has large amounts of readily available land for biofuel production also led to the assumption that any amount of demand for biofuel in Canada can be met without increasing production costs. However, an alternative assumption could have been that with increased production, scarcity of land and competition with food production would lead to increasing production costs. While it was beyond the scope of this study, future research could explore how different assumptions about land use and availability would affect biofuel production emissions and costs.

Various co-products can be produced along with biofuels. Non-energy co-products can be sold to generate additional revenue; examples include distillers grain produced along with conventional corn ethanol and soymeal produced along with soybean-derived HDRD, both of which can be used for animal feed. Energy co-products can either be used in the biofuel production plant itself or can be sold; examples include electricity cogenerated by boilers along with cellulosic ethanol and bio-propane produced alongside HDRD production. When calculating costs and emissions, a variety of methods can be used to allocate emissions and costs between biofuels and their co-products. Different methods can produce different results, and most methods have both strengths and weaknesses (Huo et al., 2008). For corn ethanol, I allocated 80% of emissions to ethanol, with the remainder to the distiller's grain co-product, based on a 20% emissions credit for distiller's grain in Wang (2012). I subtracted revenue for distiller's grain from the production plant operating costs. For cellulosic ethanol, the key co-product is electricity, which can be mostly accounted for endogenously within CIMS by feeding the electricity back into the model, and therefore I do not make exogenous assumptions about emissions and cost allocation. For HDRD, I allocated 80% of emissions to HDRD, with the remainder to the soymeal co-product, an approximation that follows the same allocation I used for ethanol. I calculated costs for HDRD using a cost of production estimate that I assume would have already accounted for co-product revenue, and thus I did not make any further adjustments to HDRD costs for co-products.

Given the wide variation in ways of producing biofuels and the lack of consensus on how to account to land-use change and co-products when calculating biofuel emissions, estimates of biofuel production emissions vary greatly. Governments in British Columbia and California have calculated emissions for biofuels produced under various methods for the purposes of their low carbon fuel standards (BC Government, 2016; California Air Resources Board, 2016). For ethanol, estimates range from -4.23 to 120 g CO_2/MJ, with an average of 42 g in BC (indirect land-use change emissions are not accounted for) and 73 g in California (land-use change accounts for 30 g)[12]. For HDRD, estimates range from 3.64 to 95 g CO_2/MJ, with an average of 34g in BC (indirect land-use change emissions are not accounted for) and 82 g in California (land-use change accounts for 62 g). My estimates fall within this wide range of estimates and therefore I believe they are reasonable for the purposes of this study.

In addition to production costs, the final retail prices for biofuels include marketing margins and taxes. In Canada in 2015, the average marketing margins were 9 cents per litre and the average taxes were 38 cents per litre for gasoline (Natural Resources Canada, 2016c). I assumed that similar marketing margins and taxes would also apply to ethanol and HDRD, and thus I set the retail price trajectory for ethanol and HDRD as the cost of production plus 47 cents per litre. CIMS endogenously adjusts the retail prices according to changes in the cost of production. Taking note again of the costs of production in Table 14 above, the retail prices of biofuels work out to be considerably higher than current gasoline and diesel prices. For both ethanol and HDRD, I also added a declining intangible cost that starts at 35 cents per litre and can decline to 0. This accounts for the current near absence of biofuel refueling stations in Canada, an initial barrier that would need to be overcome for biofuels to be a viable low emission option.

[12] For context, combustion emissions are 68 g/MJ and 71 g/MJ for gasoline and diesel respectively. The California Air Resources Board (2016) estimates lifecycle emissions to be 95 g/MJ for both gasoline and diesel.

LNG and CNG Production

Since natural gas vehicles could play a role in the transition to low carbon transportation, I added a node to the freight transportation sector to represent production of liquefied natural gas (LNG) and compressed natural gas (CNG). Although tailpipe emissions from natural gas vehicles are approximately one-third to one-quarter less than those of diesel vehicles, liquefying or compressing natural gas for use in vehicles can result in considerable emissions, with some estimates finding that the lifecycle emissions of LNG and CNG may actually exceed those of diesel in some circumstances (Jaffe et al., 2015). I approximated upstream emissions from LNG and CNG production by including consumption of natural gas to liquefy LNG and consumption of electricity to compress CNG. I based fuel consumption on the default values of the GREET 2.0 model, which specifies that 0.1 GJ of natural gas is required to liquefy natural gas into 1 GJ of LNG and 0.02 GJ of electricity is required to compress natural gas into 1 GJ of CNG (Wang, 2012). Other upstream emissions are already accounted for in CIMS in the natural gas sector. Given the uncertainty in lifecycle emissions from LNG and CNG production, particularly due to uncertainty surrounding natural gas leakage from upstream operations and vehicle tanks, my method here may underestimate lifecycle emissions.

The retail price of LNG and CNG is primarily determined by the cost of the natural gas itself and the cost of liquefying or compressing the natural gas so that it can be dispensed as fuel. I set the retail price of LNG and CNG to be approximately 10 to 30% less expensive than diesel in 2015, depending on the province, with the price varying over time with changes in the price of natural gas. Since LNG and CNG are not yet widely available, data on their pricing is relatively limited. One source estimated the 2015 average price of natural gas for vehicles in Vancouver, Edmonton, and Toronto to be between 79 and 88 cents per litre of diesel equivalent, which is approximately 25% less than the price of diesel (Natural Resources Canada, 2016c). Various other sources estimate the costs of LNG and CNG to be anywhere from essentially on par with diesel to 40% less than the cost of diesel (Go with Natural Gas, 2012; US Department of Energy, 2016; Zhao, Burke, & Zhu, 2013). I chose 10 to 30% less than the cost of diesel as a middle-ground approximation. I set constant production costs in all provinces but let the retail costs vary based on the price of natural gas in each province. I did not include intangible costs in the price of LNG and CNG fueling since the inconvenience of currently limited LNG and CNG refueling stations is already reflected in the declining intangible costs of the natural gas trucks.

Hydrogen Production

In most previous versions of CIMS, hydrogen within the transportation sector did not account for upstream production emissions and had an externally specified price trajectory. To account for production emissions and changing costs when moving to low-emission production emissions, I added a node within the personal and freight transportation sectors to endogenously represent hydrogen production. The hydrogen production methods I made available are steam methane reforming (SMR), SMR with carbon capture and storage, and electrolysis. SMR and electrolysis production can be either small-scale decentralized or large-scale centralized, while SMR with carbon capture and storage was assumed to only be possible at a large centralized scale. SMR without carbon capture and storage has emissions per unit of energy that are approximately equivalent to those of diesel and gasoline, while SMR with carbon capture and storage and electrolysis can be essentially zero-emission if electricity is coming from zero-emission sources.

Costs and energy consumption for each production method were based on a report from the National Renewable Energy Lab and costs for distribution infrastructure were based on those calculated in a previous Energy and Materials Research Group master's research project (Muncaster, 2008; Ramsden, Steward, & Zuboy, 2009). Costs for electrolysis are currently substantially higher than costs for SMR, but there is potential for electrolysis to become close to cost competitive with SMR in the future (Table 15). In the short-term, distributed production is the least costly; however, if hydrogen production were to become widespread and distribution infrastructure were built out, economies of scale would likely make centralized production more cost-effective. The actual retail price of hydrogen fuel is sensitive to natural gas and electricity prices. Currently, hydrogen fuel would be considerably costlier than gasoline and diesel. As with natural gas vehicle fueling, I did not include intangible costs in the price of hydrogen fuel since the inconvenience of currently limited hydrogen refueling stations is reflected in the declining intangible costs of the hydrogen vehicles.

Table 15 Estimated costs of different methods of hydrogen fuel production

	Capital cost ($2015/GJ of output per year)		Operating cost ($2015/GJ of output per year)	Saskatchewan retail price (2015$/litre diesel equivalent)		British Columbia retail price (2015$/litre diesel equivalent)	
	Current	*At Maturity*		*Current*	*At Maturity*	*Current*	*At Maturity*
SMR Distributed	150	140	7	1.90	1.80	2.20	2.20
SMR Centralized	290	100	4	2.70	1.30	3.20	1.70
SMR with CCS Centralized	300	110	5	2.80	1.40	3.10	1.70
Electrolysis Distributed	200	140	10	3.50	3.20	2.70	2.40
Electrolysis Centralized	350	120	6	4.50	2.80	3.20	1.70

*Retail prices are sensitive to natural gas and electricity prices. Prices are shown for Saskatchewan (lower natural gas price, higher electricity prices) and British Columbia (higher natural gas prices, lower electricity prices) to illustrate a range of possible prices.

Chapter 4. Scenario Assumptions

For this study, four scenarios were modeled covering the 2000 to 2050 period. The scenarios particularly focus on 2030, which is the year by which Canada has committed to reduce emissions by 30% below 2005 levels under the Paris agreement[13]. The scenarios are continued to 2050 since global emissions must continue to fall substantially by the middle of the century to prevent global temperature from rising more than 1.5 degrees Celsius by the end of the century. However, my primary concern in the scenarios is with achieving the 2030 Paris 30% emission reduction target and not with achieving any specific target for 2050. The four scenarios are as follows: 1) existing policies, 2) promised federal policies, 3) Paris – emissions pricing, and 4) Paris – flexible regulations.

The first two scenarios assess how close current and proposed policies will come to achieving Canada's 2030 Paris target. The existing policies scenario includes all key compulsory policies adopted by provincial governments as of fall 2016 and by the federal government prior to the fall 2015 federal election. It serves as a baseline to evaluate what progress would likely be made towards achieving the Paris commitment if the current federal government did not adopt any new climate policies. The promised federal policies scenario adds to the existing policies scenario all policies announced by the current federal government since it was elected in fall 2015 and up until October 2016[14]. The scenario acts as a mid-term assessment of the incremental effect of policies promised by the federal government and of the remaining gap that will need to be filled with additional policies to achieve the Paris target.

The last two scenarios are designed to achieve Canada's 2030 Paris target using two alternative approaches, based on the assumption that existing and promised policies will be insufficient. These scenarios add policies to those from the previous two scenarios, thus filling the gap to achieving Paris. The policy approaches in these scenarios could be

[13] For my scenarios, I focused on domestic emission reductions and did not include credits for land-use, land-use change, and forestry or international offsets as possible ways to achieve Canada's emissions target.

[14] October 2016 was chosen as a cut-off simply because that was when the modeling was completed for this study.

implemented by the federal government alone, based on the assumption that the provinces might not voluntarily adopt policies that will be stringent enough to meet Canada's emission reductions targets.

The emissions pricing scenario fills the gap to achieving Paris by relying solely on economy-wide emissions pricing. As already noted, most economists agree that emissions pricing is the most economically efficient way to achieve emissions reductions. As such, some influential entities have emphasized that carbon pricing is the most practical approach to achieving emission reductions, even going as far as to suggest that carbon pricing is essential to reduce emissions (Ecofiscal Commission, 2015). This scenario is intended to show how high of a carbon price would be required if the Canadian government were to follow the advice of emissions pricing advocates and rely primarily on emissions pricing to achieve Paris, thus prioritizing economic efficiency alone.

The flexible regulations scenario fills the gap to achieving Paris by relying primarily on a package of flexible regulations, complemented by an initially low but increasing emissions price. As outlined in the background section, regulations may have an advantage over emissions pricing in terms of political acceptability, and if designed to maximize flexibility, their economic efficiency loss relative to emissions pricing may not be as large as some pricing advocates have suggested. Flexible regulations may be particularly advantageous at the outset of the transition to a low carbon economy. They avoid rapid increases in, for example, the price of gasoline, while nonetheless ensuring that the necessary low- and zero-emission technologies and energy forms begin now to penetrate the market, albeit initially in limited applications. Over time, the regulations should help bring down the barriers to adopting low emission technologies and energy forms by: 1) driving innovations that decrease the production costs of low-emission technologies, 2) increasing public familiarity with low-emission technologies and thus reducing perceptions of risk, 3) stimulating increasing demand for low-emission technologies so that manufacturers can enter into mass production which lowers cost, and 4) fostering the development of infrastructure needed to support the adoption of low emission technologies (such as biofuel refueling at gasoline stations and electric rechargers at apartments and offices). With these barriers lowered and low emissions technologies and energy forms increasingly seen as viable options in technological and financial terms, the regulations should pave the way for increased political acceptability of higher carbon prices in the 2030 to 2050 timeframe. In this way, flexible regulations and emissions pricing act as substitutes in the near-term, but complements in the long-term. This scenario illustrates one possible policy package of flexible regulations that would achieve the Paris commitment and is intended to demonstrate how some amount of economic efficiency could be traded-off for a likely increase in political acceptability.

Each scenario was run twice, assuming either a high or low global oil price. The global oil price was a key uncertainty in this modeling exercise, since it could significantly impact emissions from both the oil sands and from end-uses that use refined petroleum products. The high and low oil price assumptions were outlined above in section 3.2.4. The remaining policy and modeling assumptions of each scenario are detailed in the following sections.

4.1. Existing policies scenario

The existing policies scenario serves as a baseline by assuming there will be no substantial increases in the stringency of existing climate policies in Canada. The scenario includes all key compulsory climate policies in Canada adopted to date by provincial governments, as well as policies adopted by the federal government prior to the fall 2015 federal election. The majority of the policies included in this scenario have already been passed into legislation. A small number have been recently announced but not yet passed into legislation; however, the politicians putting them forward have demonstrated that they are politically committed to seeing them through. In contrast, targets and policies that are announced with limited demonstration of how they will be achieved are not included[15].

The following is a summary of the policies in the existing policies scenario (a more detailed description of each policy and how it was modeled is included in Appendix 2):

[15] For example, I did not model the Ontario provincial government's target of 5% electric and hydrogen passenger vehicle sales by 2020, which is purportedly to be reviewed and increased every five years thereafter. The government specifically states that it does not want to turn the target into a legislated mandate, which indicates a lack of full commitment to the target.

- **Federal:** I included the federal light-duty and heavy-duty vehicle emissions standards, which set minimum emissions standards for vehicles up to 2025, as well as the coal performance standard, which requires new and end-of-life plants to meet an emissions-intensity standard equivalent to natural gas plants (in essence requiring end-of-life coal plants to either shut down or retrofit with carbon capture and storage technologies).
- **British Columbia:** I modeled the carbon tax that rose to $30/tCO_2$ by 2012, and is now frozen (and thus declining after correcting for inflation). I also modeled the clean electricity regulation, which was updated in summer of 2016 to require 100% of electricity generation in the province to be from clean or renewable electricity (with allowances to address reliability).
- **Alberta:** I modeled the existing Specified Gas Emitters Regulation (SGER), which requires large industrial emitters to meet increasing intensity standards or pay a price for emissions above the standard. By 2017, the regulation requires a 20% reduction in emissions intensity and a price of $30/tCO_2$ over the standard. I also modeled the Climate Leadership Plan announced in 2016, which includes: a carbon levy on all combustion fuels used outside of industry, rising to $30/tCO_2$ by 2018 (with no commitment to increase it thereafter); product and sector-based industry performance standards, which are still under development to replace the SGER (I approximate these as a $30 emissions price); a phase out of all coal electricity generation by 2030; a commitment to replace two-thirds of phased-out coal capacity with renewable energy capacity; a performance standard for oil sands operations in the high oil price future to ensure that oil sands emissions remain under the 100 Mt cap (a performance standard is not required in the low oil price future as oil sands emissions remain under 100 Mt without policy); and regulations to reduce methane emissions from oil and gas operation by 45% by 2025.
- **Saskatchewan:** I modeled the Boundary Dam coal power plant carbon capture and storage retrofit and the target of 50% renewable electricity capacity by 2030 announced in 2016.
- **Manitoba:** I modeled the phase out of coal electricity generation that was completed in 2010.
- **Ontario:** I included the province's cap-and-trade policy, which will begin in 2017 and will be linked to the Quebec and California cap-and-trade system. I also modeled the phase out of coal electricity generation that was completed in 2014, and the province's feed-in-tariff that offered fixed contract prices for renewable generation and is being transitioned to include a procurement process for larger renewable electricity projects.
- **Quebec:** I modeled the $3 carbon tax that began in 2007, and the subsequent cap-and-trade system that started in 2013 and was linked to California's cap-and-trade system in 2014. I also included the zero-emissions vehicle mandate, which was passed in fall 2016 and will require automakers to sell a minimum number of near zero-emissions vehicles, increasing to 15.5% of sales by 2025.

- **Atlantic:** I modeled Nova Scotia's declining electricity sector emissions cap, which requires the combined emissions of all electricity-producing facilities in the province to be no greater than 4.5 Mt CO_2 by 2030, as well as the province's renewable portfolio standard, which requires a minimum of 40% renewable generation by 2020.

Also included are all provincial and federal low carbon and renewable fuel standards, energy efficiency standards in provincial building codes, federal energy efficiency standards for energy-consuming technologies, and provincial landfill gas regulations. For the most part, I did not model subsidy and incentive programs, as these do not guarantee emission reductions and often only last for limited durations. They also are prone to high levels of free-ridership, that is, subsidies are claimed by those who would have purchased the technology even in the absence of the subsidy (Rivers & Shiell, 2016).

Note that in-province emission reductions from the Quebec and Ontario cap-and-trade policies were modeled, but not purchases of emission reduction allowances from California, their non-Canadian allowance trading partner. I modeled the policy as a carbon price rising in line with the policy floor price, which began at $10.75 in 2013 and increases at an annual rate of 5% plus inflation. I set the price at 10% above the floor price, as this has been the average trading price over the past three years, and I adjusted the price assuming an ongoing exchange rate of 1 CAD = 0.75 USD to account for Ontario and Quebec buying permits from California. This chosen approach provides my best estimate of the evolution of emissions actually produced in Canada. While it cannot be certain what reductions will occur within the boundaries of each of the three emissions trading partners (since it depends on the interplay of their different targets and reduction costs), the evolution of the allowance trading floor price provides one plausible indication of the carbon emissions price trajectory, which in turn will determine emission reductions in the two Canadian jurisdictions. Despite this chosen methodology, I also report the effect of the emissions caps achieved through permit purchases for comparison.

The three subsequent scenarios build on the existing policies scenario, meaning that their policies are modeled in addition to the already existing policies.

4.2. Promised federal policies scenario

The second scenario estimates the likely incremental effect of climate policies that the new Canadian government has pursued since its election in late 2015. One of the key components of its climate strategy thus far has been promoting investment in low-emission energy and technology (Government of Canada, 2016b). The federal budget of March 2016 contains a variety of funding commitments that fall under this umbrella (Government of Canada, 2016a). In this case, I modeled subsidies and public investments in order to demonstrate to what degree they will likely contribute to the federal government's emission reductions commitment. While the full details on how all the funding will be used over the course of the next several years cannot yet be known, I made the generous assumption that most of it will go to actual investment in technologies (as opposed to government overhead costs) and that the funding will be targeted at technologies that have the potential to lead to substantial emissions reductions.

To represent the federal budget funding commitments, I modeled subsidies targeted to low emission technologies in residential and commercial buildings, electricity generation, and oil and gas, to represent possible uses of funding commitments such as the $2 billion low carbon economy fund, $50 million for cleaner oil and gas technologies, the $125 million Green Municipal Fund, $2.1 billion in funding for federal infrastructure investment (including 'greening' government operations), and the $2 billion Post-Secondary Institutions Strategic Investment Fund (which includes funding for reducing greenhouse gases at universities.) I also included subsidies to electric vehicles to represent investment in alternative fuel infrastructure. See Appendix 3 for further details on the technology subsidies and how they were modeled. I modeled the $3.4 billion Public Transit Infrastructure fund as a 2% increase in national transit ridership, a very generous assumption given past trends of ridership increases in Canada with transit investment and given that ridership rates in most European countries remain low in comparison to vehicle use despite generally better funded and developed transit systems[16]. I did not model funding targeted at clean tech innovation, research and development, and demonstration. While innovation can be valuable, this funding does not guarantee any technological breakthrough that will reduce emissions.

In addition to the budget, the federal government announced in spring of 2016 its intention to regulate methane emissions from the oil and gas sector in partnership with the United States (Government of Canada, 2016c). I modeled this policy through increased use of methane leak detection and repair (LDAR) in the oil and gas sector to achieve the stated goal of reducing methane emissions in the oil and gas sector by 40 to 45 percent below 2012 levels by 2025. The modeling method involved both forcing retrofit of existing technologies and processes to use LDAR by 2025, as well as eliminating technologies and processes without LDAR from new technology competitions starting in 2020 so that technologies and processes with LDAR captured all the new market share.

At the beginning of October 2016, the government announced its plan for a minimum national carbon price (Government of Canada, 2016d). The price will begin at $\$10/tCO_2$ in 2018 and will rise by $10 per year to $50 in 2022. The government did not outline a plan for additional increases to the price beyond 2022. Provinces have the option to design their own carbon pricing strategy, which could either be through a carbon tax or a cap-and-trade system. The federal government said it will provide a carbon pricing system for any provinces and territories that do not have their own pricing policies in place by 2018.

[16] The proportion of Canadian commuters using transit rose from 10.1% in 1996 to 10.5% in 2001 to 11.0% in 2006 to 12.0% in 2011 (Statistics Canada, 2011). Note that this is commuters only, so the mode share for all travel purposes is likely lower. Federal funding for transit was on average $201 million annually from 2002-06 and $664 million from 2007-11 (Canadian Urban Transit Association, 2015). Proposed federal funding in the budget is $1,133 million annually for 3 years. This is approximately double the funding provided from 2007-11, a period during which commuter transit mode share rose by 1 percentage point (pp). While we cannot directly attribute this 1 pp increase to the federal funding, we can assume that the doubled federal funding likely won't lead to more than a 2 pp increase. For context, most European countries, which generally have better developed transit systems, have transit mode share remaining under 20% (ex. Denmark was 18% in 2009, Norway was 10% in 2013) (Danish Ministry of Transport and Building, 2011; Eurostat, 2016; Norwegian Centre for Transport Economics, 2014).

I ran this scenario twice with two different versions of this new minimum national carbon price. In one version, I assume that the price remains frozen at $50 after 2022 for the remainder of the simulation (which I will call Promised Federal Policies - $50). In the other version, I assume that the price continues to rise after 2022 to $100 by 2030, remaining at $100 for the remainder of the simulation thereafter (which I will call Promised Federal Policies - $100). The minimum price was applied to all provinces, except that in years when an existing provincial carbon pricing policy from the existing policies scenario exceeds the minimum national price, the provincial price is used to represent the assumption that provincial governments will continue on their current paths. I assumed that the price would be indexed to inflation and would cover all fossil fuel combustion emissions and non-combustion process emissions in all sectors, except for waste and agriculture, since emissions from those sectors are more difficult to monitor and in most provincial policies to date have either been completely excluded or only included through offset schemes. Note that at the time of running the scenario it was not yet fully clear whether the price would in fact be indexed to inflation and cover process emissions.

The federal government has indicated that the policies announced to date (as of October 2016) do not constitute its complete climate strategy and that more policies will be announced in late 2016 and early 2017 (Cheadle, 2016). Thus, this scenario serves as a mid-term assessment, evaluating the likely incremental effects of the elements of the government's strategy presented thus far and estimating the gap remaining to be filled by additional policies if the government is to achieve its 2030 Paris target.

4.3. Paris – Emissions pricing scenario

The third scenario relies on a steadily rising economy-wide emissions price to achieve Canada's 2030 Paris commitment. I modeled it by running the scenario until I found a price trajectory that would achieve the 2030 target. I assumed that the carbon price would be either maintained or increased beyond 2030 to continue moving towards Canada's 2009 Copenhagen commitment to reduce national emissions by 65% by 2050; however, I assumed that due to politically acceptability constraints, the price would not rise higher than $250. The carbon price was simulated in place of, rather than as additive to, the weaker carbon pricing policies in the previous two scenarios. However, I did maintain the regulatory and other policies from the previous scenarios. Like the minimum national carbon price from the previous scenario, I applied the carbon price to both combustion and process emissions, but not emissions in the agriculture and waste sectors. The carbon price could represent either a carbon tax or a cap-and-trade system.

Governments have various available options for how to use the revenue generated by a carbon tax or cap-and-trade with auctioned emissions allowances. For my scenarios, I assume that revenues are redistributed in ways that minimize policy-induced transfers between provinces, industrial sectors, and individuals. Returning all revenue through lump sum rebates or reductions in other types of taxes could help minimize distributional effects and declines in output, without distorting the carbon price signal when governments, firms and households make investment and operating decisions involving energy forms, technologies, buildings, and infrastructure. In CIMS, I represent this by turning on the model's revenue recycling function, which returns carbon pricing revenue to the province and sector from which it was collected. Note that under a cap-and-trade system, the government could choose to freely give out allowances, which could be done in a way that results in outcomes similar to a cap-and-trade with auction and full revenue recycling.

An important consideration when simulating the effect of stringent climate policies is whether other countries will be adopting policies of similar stringency. If Canada adopts stringent policies but other countries do not, we could see substantial leakage, which would involve 1) high-emitting firms relocating to countries with weaker or no policies and 2) trade substitution of cheaper products from countries with weaker policies for Canadian products that would be now somewhat more expensive due to climate policy. This leakage could be reduced, however, if Canada adopts trade measures to protect domestic industries, such as by applying carbon tariffs on imports from countries with weak climate policies. Leakage would not be a concern if all countries are acting in concert and there is no relative difference in carbon pricing or regulatory stringency. In my scenarios, I assume that Canada is somewhat, but not dramatically, ahead of key trading partners, and that, where necessary, it implements policies to minimize leakage effects. The model's partial equilibrium feedbacks do capture the potential for a small amount of leakage; however, the revenue recycling method discussed above reduces total costs to industries, thus representing one possible method of helping to protect trade-exposed industries and reduce leakage.

4.4. Paris – Flexible regulations scenario

The fourth scenario focuses on the federal government applying a set of flexible regulations that would play a key role in driving the Canadian energy transition to achieve the 2030 and 2050 emission reductions commitments. The regulatory package includes regulations in the electricity, transportation, and industrial sectors designed to ensure the 2030 commitment is met while minimizing economic inefficiencies and offering protection to trade-exposed industries[17]. These sectors were focused on for illustrative purposes and to contain the scope of the list of regulations. However, similar policies for buildings, waste, and agriculture would likely also play a role in a comprehensive regulatory package.

A modest emissions price was applied in addition to the flexible regulations. While the regulations are especially important over the next 15 years, and are thus a substitute for a rapidly rising emissions price, they also set the stage for more aggressive emissions pricing in the period after 2030, should the government wish to make such a shift. The emissions price in this scenario was kept low in the earlier years, but rose later. It started at \$20/tCO_2 in 2021, rising slowly at first to approximately \$30 in 2030, and then rising more rapidly to \$80 in 2050 (all in 2016\$). This price trajectory was chosen to approximately follow the likely trajectory of the Quebec-Ontario-California cap-and-trade system.

Electricity

In the electricity sector, I modeled a regulation that requires the elimination by 2030 of all coal-fired electricity generation that does not have carbon capture and storage. This regulation built on the federal government's regulation for new and end-of-life coal plants by also requiring coal plants that have not reached end-of-life by 2030 to either close or

[17] The regulations in the electricity and transportation sectors are the focus of my study. The regulations for industry were primarily designed by Mikela Hein for her master's research, but I have also included them here in my study in order to present a more complete package of regulations to meet Canada's 2030 target.

retrofit to carbon capture and storage technologies. Since coal-fired electricity generation is a large contributor to emissions and technologically feasible alternatives are readily available at reasonable costs, this is one area where an inflexible regulation is likely appropriate. The regulation was modeled in CIMS by requiring all existing coal plants to either retire by 2030, to retrofit to carbon capture and storage in the case of coal plants in Saskatchewan, or to be replaced by wind and biomass using the CIMS retrofit function in the case of the Atlantic region[18].

Additionally, I applied a flexible near-zero emission electricity standard, which requires provinces to generate a given percentage of electricity from near-zero and zero-emission sources. In provinces that currently rely on hydro generation (British Columbia, Manitoba, Quebec, and Newfoundland), the performance standard requires 100% zero-emission electricity generation by 2030. In provinces that currently rely more on fossil fuels and lack large hydropower options (Alberta, Saskatchewan, Ontario, New Brunswick, Nova Scotia, Prince Edward Island, and the territories), the performance standard requires 90% zero-emission electricity generation by 2030. Coal plants with carbon capture and storage fall under the zero-emissions category in proportion to the rate of emissions captured.

The standard was modeled in CIMS by 1) setting the new market shares of fossil fuel generation technologies to either zero (in the case of hydro provinces) or low levels (in the case of non-hydro provinces), 2) forcing the small amount of existing natural gas, diesel, and fuel oil in hydro provinces to be replaced with biomass using the CIMS retrofit function, and 3) forcing some existing natural gas generation in non-hydro provinces to retrofit to have carbon capture and storage or to be replaced by renewables. Although I only applied this regulation to the electricity sector in CIMS, if applied in the real world, this regulation should also cover electricity generated through cogeneration in industry, thus preventing substitution of high-emitting industrial generation for utility generation that could in effect circumvent the regulation.

[18] The modeling of the electricity regulations was in some cases prescriptive in that I made assumptions about which specific technologies would be adopted to replace fossil fuel generation. This was done in instances where other methods of modeling the regulation would have caused problems for the already calibrated model.

The differentiated standard was designed to reduce distributional effects among the provinces. Provinces currently more reliant on fossil fuel generation, and that have less hydro power potential to exploit, will be required to take significant actions to reduce emissions. However, their standard is somewhat less stringent in recognition that they lack low-cost hydropower reservoirs for ensuring the reliability of electricity from intermittent renewable sources. Jurisdictions without large hydro reservoirs may find it costly to develop energy storage options other than natural gas stand-by plants as the means for ensuring reliability as more intermittent renewables enter the supply mix.

Personal vehicle transportation

In the personal transportation sector, I modeled a partial-zero-emission vehicle (PZEV) mandate. The policy requires vehicle manufacturers, on average, to meet a minimum aggregate PZEV sales requirement of 5% by 2020, 35% by 2025, 70% by 2030, and 100% by 2040. Eligible vehicles include pure electric vehicles, plug-in hybrid electric vehicles, hydrogen fuel cell vehicles, and flex-fuel vehicles that can fill up with ethanol-85. A potential concern with including ethanol-85 flex-fuel vehicles in the regulation is that these vehicles could be sold but continue to fill up on conventional gasoline. This issue initially led ethanol flex-fuel vehicles to be a compliance loophole in the US vehicle emissions standards (Davis, 2016). However, this was corrected by only giving flex-fuel vehicles credit in proportion to the percentage of such vehicles actually filling up with ethanol in the country, which can be estimated from national gasoline, ethanol and vehicle sales statistics (Environmental Protection Agency, 2012). Following this approach, the regulation I modeled only gives credit to flex-fuel vehicles in proportion to the amount that such vehicles use ethanol as a share of their annual fuel use.

I also modeled a low carbon fuel standard (LCFS) covering the energy used by personal vehicles. The LCFS serves as a complement to the PZEV mandate in that it could help overcome the near-absence of ethanol-85 refueling infrastructure in Canada, thus making flex-fuel vehicles a more viable low-carbon option under the PZEV. The LCFS requires fuel distributors, on average, to meet a growing percent of low carbon fuel sales, equal to 10% low emission fuels by 2025, 40% by 2030, and 90% by 2040. Ethanol-85 qualifies as a low carbon fuel, and would likely be cross-subsidized through a small increase in gasoline prices to bring its cost slightly below that of gasoline, encouraging its use by flex-fuel vehicle drivers. To achieve energy form and technology neutrality, fuel distributors could also purchase credits from electricity utilities based on data from smart meters on electric and plug-in hybrid vehicle owners recharging their vehicles, or from hydrogen fuel distributors.

The PZEV regulation was modeled in CIMS by gradually reducing the amount of new market share that could be captured by gasoline-powered vehicles. The LCFS was modeled in CIMS through a combination of 1) forcing an increasing minimum market share of ethanol in the ethanol-gasoline competition and 2) a small but increasing emissions price on gasoline to represent increases in gasoline prices from cross-subsidizing ethanol and from purchase of credits from electricity utilities and hydrogen distributors. To set the market share parameters and emissions pricing levels that contributed to achieving both the PZEV and LCFS, I ran the model multiple times, each time calculating the national percent sales of PZEV vehicles (adjusting to account for ethanol fueling by flex-fuel vehicles and some gasoline fueling for plug-in hybrids) and the national percent sales of low carbon fuels (based on ethanol fueling and credits for the number of electric, plug-in hybrid, and hydrogen vehicles on the road). I adjusted the parameters and emissions price until I found those that met the requirements of both regulations.

Freight truck transportation

In the freight truck sector, the regulations I modeled for inter- and intra-city trucks follow a somewhat different design in comparison to the personal vehicle regulations. Due to the larger loads and longer distances travelled by freight trucks, particularly heavy-duty inter-city trucks, electric freight vehicles face greater barriers. Additionally, the development of biofuel applications would likely differ in the two sectors. Vehicles require engine modification to run on high blends of ethanol, which is likely to be the key biofuel candidate that could replace gasoline for personal vehicles. On the other hand, most trucks do not require engine modification to run on a high blend of hydrogenation-derived renewable diesel (HDRD), which could become a key biofuel candidate to replace diesel for trucks. HDRD could simply be blended with conventional diesel in increasing quantities over time, without the need for new refueling infrastructure or new truck engines. Therefore, there is some likelihood that switching fuels will play a substantial role in decarbonizing freight, without necessarily requiring the same degree of change in vehicle technologies as in personal vehicles. (Biodiesel, which is chemically different from HDRD and would require engine modification at higher blends, may also play a role, but for simplicity I am presuming the dominance of HDRD.)

Rather than a PZEV standard, I modeled an average emissions standard for new trucks that has greater stringency in comparison to the current federal heavy-duty vehicle emissions standards. The standard would need to be met on average by truck manufacturers and would be tradeable to allow flexibility. This was modeled in CIMS by making standard efficiency trucks unavailable to capture new market share in 2020 in light-medium freight and by limiting the new market share for natural gas trucks in heavy freight. I also ran a LCFS that is similar in design to the LCFS for personal vehicles, and requires fuel distributors to meet a minimum low carbon fuel sales requirement of 20% by 2025, 40% by 2030, and 80% by 2040. Again, flexibility can be achieved through the purchase of compliance credits from electricity utilities, hydrogen fuel distributors, and perhaps to a smaller degree liquefied and compressed natural gas vehicle fuel distributors (since natural gas has a lower carbon intensity compared to diesel). The modeling method in CIMS was similar to that used for the personal vehicles LCFS: I used minimum market shares to require an increasing minimum blend of HDRD in diesel, and I used a small emissions price on fuels to represent purchase of compliance credits and to prevent natural gas vehicles from overtaking the market. Parameters were adjusted until national fuel sales met the minimum requirements.

Buses and rail

I also modeled regulations to reduce emissions from buses and rail. For urban public transit buses, inter-city buses, passenger trains, and freight trains, the regulations require new market shares of buses and trains running on diesel or other fossil fuels to fall to zero within the 2030 to 2035-time period. The regulations are flexible in the sense that any combination of electricity, biodiesel, hydrogen, or other low carbon fuels could replace conventional diesel and other fossil fuels. The regulations were modeled in CIMS by gradually decreasing the maximum new market share of the conventional technologies. While I did not model regulations for airplanes and ships, due to complications related to their exposure to international leakage, in the long-term, regulations would also likely be needed to spur emission reductions in these areas of transportation.

Biofuel and hydrogen production

To mitigate upstream emissions from fuels used in the transportation sectors, I modeled performance standards for biofuel and hydrogen-fuel production. (The electricity regulations already cover upstream emissions for any electricity-powered transportation.) The performance standards drive all ethanol, HDRD, and hydrogen fuel production to near-zero emission levels by 2030. This can be achieved by switching to production processes that do not use fossil fuels, such as biodiesel tractors for production of biofuel feedstocks, biomethane or electric boilers for biofuel production plants, and electrolysis for hydrogen production. In CIMS, the regulations were modeled by making emitting technologies unavailable to capture new market share and by forcing their early retirement. While some nitrous oxide emissions are associated with biofuels as a result of agricultural production of feedstocks, I calculated, as outlined above, that production emissions could be driven to below 15% of the current per-litre production emissions of conventional gasoline and diesel. I also assume that policy checks are in place to minimize emissions from land-use change caused by biofuel production, such as would occur if forests were cut down to clear land to grow corn for ethanol. Given Canada's vast landmass, including underutilized agricultural land, some level of biofuel production could occur without substantial land-use loss or cost increases for food production, although as noted above, this could be an area for further exploration.

Industrial sectors

Although the focus of my study was on electricity and transportation, I also included regulations for industry in order to illustrate a more comprehensive regulatory package with broader coverage of the economy that would achieve Canada's 2030 target. As previously explained, the industrial sector regulations were designed by another student in the Energy and Materials Research Group, Mikela Hein, for her master's research project. The regulations are sector-specific performance standards that require, beginning in 2020, each sector to achieve a declining average emissions intensity per unit of output. This type of regulation is flexible in that 1) a performance standard does not specify which technologies or fuels must be used to achieve the standard, and 2) since it is an average intensity standard for the entire sector, facilities that can reduce emissions to levels below the intensity requirement at a lower cost can sell compliance permits to facilities for which it would be costlier to achieve the standard. The standards modeled here were designed to protect trade-exposed and carbon-intensive sectors by applying less stringent standards in those sectors. Additionally, given the Alberta government's already promised 100 Mt emissions cap on oil sands, it was not necessary to apply an additional more stringent federal policy on this highly trade-exposed industry in order to meet the 2030 target; instead, a federal performance standard was applied after 2030 to drive the sector to achieve low emissions levels by 2050 in line with long-term deep decarbonization objectives. The industrial regulations were modeled in CIMS using emissions prices applied to each sector, since a sector-wide tradeable performance standard would result in similar outcomes as a sector-wide emissions price.

Chapter 5. Results and Discussion

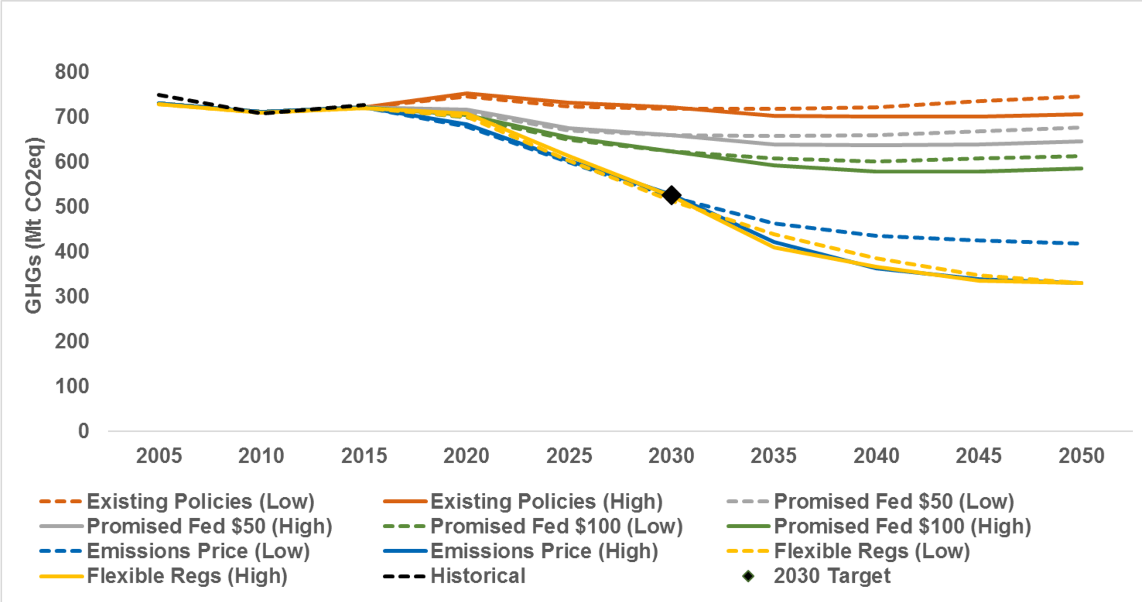
After the scenarios were run, I compared them in terms of national emissions, provincial emissions, and sectoral emissions. I also analyzed technology and energy cost outcomes in the electricity and transportation sectors. I focused in particular on comparing the results of the carbon pricing and flexible regulations scenarios, in order to get a sense of the relative efficiency of the two approaches. Similar outcomes in terms of technology market shares and energy costs were considered to be a crude proxy indication of similarities in economic efficiency.

5.1. National results

Emission results from the existing policies scenario show little progress towards achieving the 2030 Paris commitment (30% reduction), with emissions levels at only 4% below 2005 levels (Figure 2). This is not to say that current policies are having no impact on reducing emissions. Due to economic and population growth, Canada's emissions would likely be on a path to exceed 2005 levels in 2030 in the absence of current policy measures (Environment and Climate Change Canada, 2014). However, current measures are far from sufficient to meet Canada's 2030 target.

Furthermore, by 2050, the existing policies scenario shows emissions reductions of 0 to 6% relative to 2005 levels, far from the deep reductions needed by countries like Canada if humanity is to prevent temperatures from rising by more than 1.5 degrees Celsius in this century. Emissions are slightly lower under the high oil price by 2050, as increasingly high gasoline and diesel prices drive more fuel switching in transportation in comparison to the low oil price. Meanwhile, Alberta's provincial policy of a 100 Mt emissions cap for the oil sands prevents a large increase in emissions under the high oil price, despite much higher oil sands production.

Figure 2 National GHG emissions in each scenario



* Low = low oil price, High = high oil price.

In the promised federal policies scenario in which the carbon price remains at $50 beyond 2022 (Promised Fed $50), national emissions fall by 12% below 2005 levels by 2030, and by 10 to 14% by 2050. These results are only a moderate improvement over the existing policies scenario and again far from sufficient to meet Canada's 2030 commitment. For the version in which the carbon price continues increasing to $100 by 2030 (Promised Fed $100), national emissions fall by 17% below 2005 levels by 2030, and by 18 to 22% by 2050. While this version does get Canada over halfway to its 2030 target, the target is still not met. The federal government's promised carbon price is far too low to drive the necessary emission reductions, even if we assume that it continues to increase beyond 2022, which the government has not yet stated it will.

As for the federal government's funding and subsidies for low carbon technologies, the model shows high free-ridership rates, exceeding 50% in many cases. This means that subsidies go towards technologies that were already being adopted in the existing policies scenario, due to a combination of other policies and the heterogeneous market choices of consumers and industry. The promised federal methane emissions regulation for the oil and gas sector drives some emission reductions, but mainly in British Columbia and Saskatchewan since the provincial Alberta methane regulations are already in the existing policies scenario. Overall, if the policies announced as of October 2016 constituted the federal government's entire climate strategy, the strategy would be inadequate to meet Canada's targets. Again, the federal government acknowledges this, which is why it plans to announce additional policies in late 2016 and in 2017.

In contrast with the first two scenarios, the second two are specifically designed to achieve the 2030 Paris target. In the emissions pricing scenario, I simulated increasingly higher carbon price paths until I found one that achieved the necessary 30% reduction. In the flexible regulations scenario, the stringencies of the regulations were adjusted so that together they would also meet the target.

Emissions continue to fall after 2030 under the emissions pricing and flexible regulations scenarios to reach 45% to 55% below 2005 levels by 2050. While this is considerable progress towards achieving deep emission reductions by mid-century, the trajectories fail to achieve either the 65% reduction by 2050 that Canada committed to at Copenhagen in 2009 or the more recently announced target of 80% reductions by 2050. Achieving a specific target by 2050 was not a primary objective of the study, given that the government's 2050 target has recently changed and modeling results several decades into the future become increasingly uncertain. It is difficult to forecast long-term technological change, particularly if a strong policy effort is made to reduce emissions. Costs of low emission technologies may fall more than anticipated, and unanticipated innovations could lead to greater than expected uptake of technologies that are currently in their infancy or perhaps haven't even been invented yet. Thus, emissions may fall substantially more by 2050 than what the modeling results show. Depending on the rate and direction of technological change, adjustments could be made to the post-2030 stringency of the carbon price path and flexible regulations to help achieve the desired 2050 target.

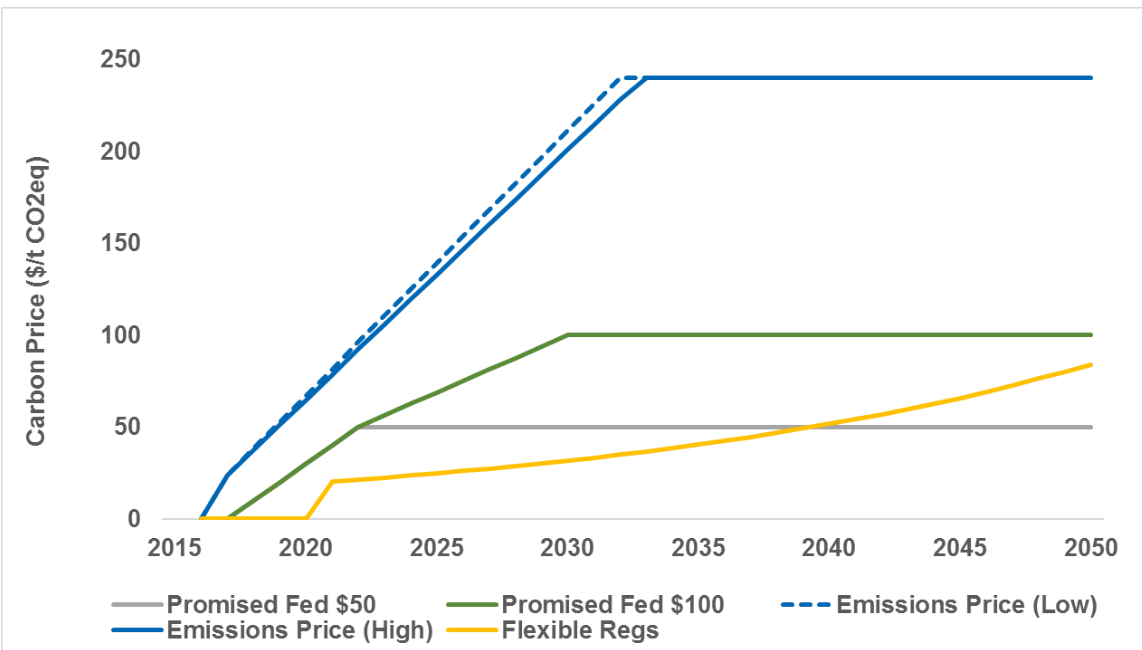
Reductions by 2050 are sensitive to the global oil price in the emissions pricing scenario, while they are insensitive in the flexible regulations scenario since the given regulatory requirements must be achieved regardless of external factors. Theoretically, total emission reductions from an emissions price would be sensitive to external factors only if applied as an emissions tax and not if applied through cap-and-trade, since the cap sets a quantity of emissions that cannot be exceeded. However, in this instance where I am only modeling domestic emission reductions, cap-and-trade would not provide certainty about the amount of domestic emission reductions if assuming that emissions permits could be purchased from jurisdictions outside of Canada, such as California in the case of the Quebec-Ontario-California cap-and-trade system. Thus, emissions pricing provides certainty about the cost of emission reductions but not the quantity of emission reductions, whereas regulations provide the opposite.

When uncertainty exists as to the benefits and costs of a particular action, such as climate change policy, the nature of the benefits and costs will influence whether a pricing or a quantity instrument is a better choice (Weitzman, 1974). If marginal costs of abatement rise sharply, small inaccuracies in estimated costs could lead to abatement costs that are much higher than expected, and thus a price instrument that provides price certainty may be optimal. Conversely, if the marginal benefits of abatement rise sharply, small inaccuracies in estimated costs could lead to fewer emission reductions than expected and in turn much higher climate damages than expected, and thus a quantity instrument that provides certainty about emission reductions may be optimal. While it is beyond the scope of this study to compare the steepness of the marginal cost and marginal benefit curves for reducing Canada's emissions, the advantages and disadvantages of price versus quantity certainty is one of many factors that policymakers may want to consider when choosing between emissions pricing and regulations to reduce emissions.

Returning to the modeling results, for the emissions pricing scenario, I started the emissions price in CIMS at $30 in 2017, increasing it linearly to meet the 2030 target. In order to meet Canada's Paris commitment, a carbon price (in $2016) rising to $250/t$CO_2$ by 2030 was required under high global oil prices assumptions. Under low global oil price assumptions, the 2030 carbon price was slightly higher at $265. As noted, however, the carbon price path using just the CIMS model is likely an overstatement of the required carbon price path because CIMS, used without a CGE model, under-represents the full macro-economic response and also likely under-represents technological change to some degree. As noted earlier, for this study, I have made a judgement-based assumption that

CIMS overestimates the required carbon price by approximately 25%. Thus, after the appropriate downward adjustment is made, the more likely carbon price path would start at about $25 in 2017 and rise to $200 in 2030 with high oil prices and $210 with low oil prices (Figure 3). This is equivalent to increasing the carbon price by approximately $13 each year. While this carbon price path might still seem very high, it is consistent with the findings of other researchers. Using a CGE model, Bataille and Sawyer (2016) estimated that Canada would need a carbon price of $110 by 2030 just to reduce emissions to 15% below 2005 levels. The additional reductions required to be 30% below would require a much higher carbon price. While there is some uncertainty about the precise carbon price trajectory needed to achieve the Paris target, it almost certainly needs to be much higher than the federal government's promised carbon price, regardless of whether it remains at $50 or rises to $100 in the 2030 timeframe.

Figure 3 Carbon prices under policy scenarios (with downward adjustment)



* Low = low oil price, High = high oil price.

For the flexible regulations scenario, the carbon price path was set the same for high and low oil prices. It is much lower than the price trajectory required under the emission price scenario and somewhat lower than the promised Federal price (although it does exceed $50 towards the end of the simulation around 2040). As noted, this scenario treated carbon pricing and flexible regulations as substitutes in the 2017 to 2030 period, but increasingly as complements in the 2030 to 2050 period. While the flexible regulations undoubtedly have fairly high implicit carbon prices to 2030, the explicit carbon prices are kept low. After 2030, these prices rise more rapidly. By this time, low- and zero-emission technologies and energy forms would be more established and many consumers and firms would have already taken steps to reduce emissions. Thus, with lower emissions, the high carbon prices would be less of a financial burden on consumers and firms. From a political acceptability perspective, although the flexible regulations approach would not necessarily be easy, it appears that it would be less difficult than relying primarily on a rapidly rising explicit emissions price from the outset.

As noted above, estimating domestic emissions reductions is significantly complicated when some provinces, or the entire country, belong to a cap-and-trade system with non-Canadian partners, as is currently the case with Quebec, Ontario and California. If well-designed, linking of cap-and-trade systems can enhance efficiencies by helping achieve the least cost reductions over a larger area. However, if reductions in other jurisdictions would have occurred in the absence of linking cap-and-trade systems (such as reductions in California due to other domestic regulatory policies), crediting permits bought outside of Canada towards Canada's emissions targets is problematic. To avoid assessing this potential loophole, I have focused my analysis on emissions reductions in Canada and did not model permit trading among jurisdictions within the Quebec-Ontario-California cap-and-trade system.

However, a simple exogenous assessment demonstrates that even if permit purchases from other jurisdictions by Quebec and Ontario were counted toward Canada's target, Canada would still not achieve its Paris target with the existing and promised provincial and federal policies in place (Table 16). I substituted the Ontario and Quebec emissions cap for my modeling results for those two provinces to exogenously represent purchasing permits to meet their caps. Then I looked at the effect of the caps on national emissions in 2030, under both high and low oil price assumptions. For the existing policies scenario, emissions reductions were only 13 to 15% below 2005 levels, and in the promised federal policies scenarios, emissions reductions were 20 to 25% below 2005 levels. While giving credit to purchased permits does get Canada closer to its target, a gap still exists. Furthermore, it remains unclear whether purchasing permits from California would constitute a loophole or would actually lead to new emission reductions that wouldn't have otherwise occurred. That question is a potential area for future research. The results presented in the remainder of this study do not account for permit purchases by Quebec and Ontario.

Table 16 Emission reductions with and without permit purchases under linked Quebec-Ontario-California cap-and-trade system

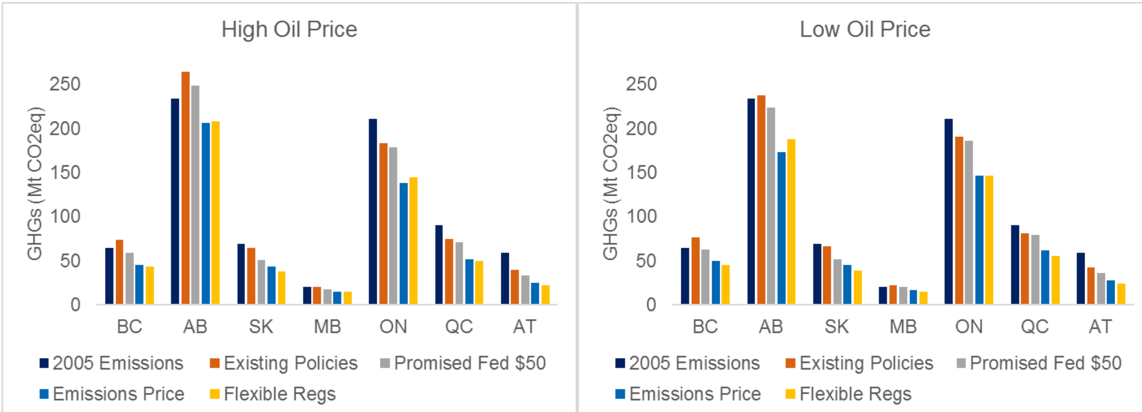
	Emission Reductions in 2030 below 2005 Levels	
	Without Permit Purchases	*With Permit Purchases*
Existing Policies	4%	13 to 15%
Promised Fed $50	12%	20 to 22%
Promised Fed $100	17%	23 to 25%
Emissions Price	30%	30 to 33%
Flexible Regs	30 to 31%	31 to 33%

*A range is provided where outcomes differed with high and low oil price assumptions.

5.2. Provincial results

Emission reductions in 2030 in each province are similar in the emissions pricing and flexible regulations scenarios (Figure 4). In some provinces, there are small differences between these two scenarios, and this occurs largely due to the less stringent treatment of trade-exposed sectors in the regulatory scenario. For example, emissions in Alberta are higher in the regulations scenario under low oil prices relative to the emissions pricing scenario, due to the prominence of the trade-exposed oil and gas sector in Alberta. Of course, an emissions pricing approach could also be applied that provides favorable treatment to trade-exposed sectors under low or high oil prices. Therefore, the small differences are simply a result of the particular design of the two scenarios. Overall, the two approaches require similar levels of effort from the provinces in achieving the Paris commitment.

Figure 4 Provincial emissions in 2030 under each scenario

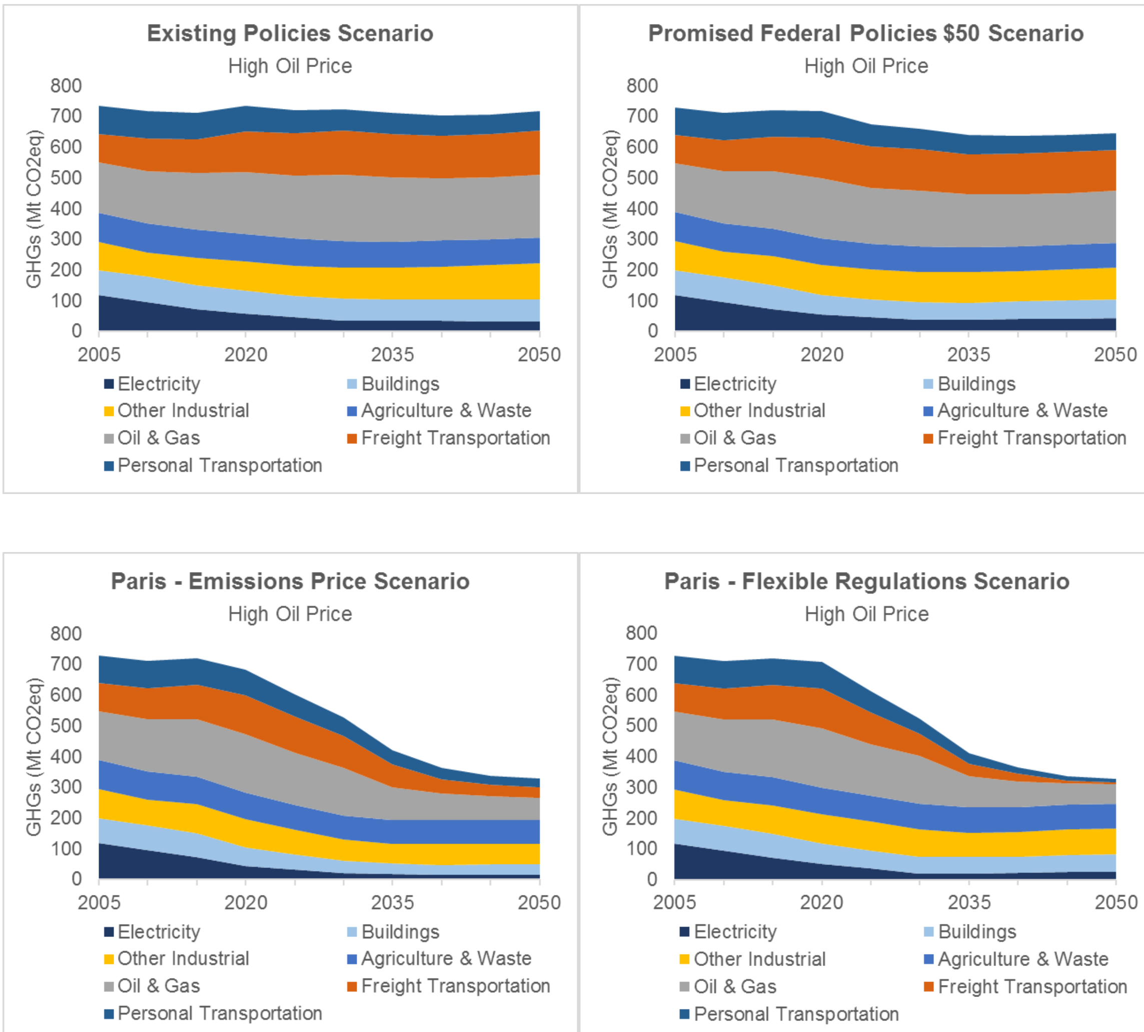


5.3. Sectoral results

In the existing policies scenario, oil and gas and freight transportation remain the two largest sources of emissions through to 2050 (Figure 5). By 2030, oil and gas emissions have grown by 17 to 32% above 2005 levels, while freight transportation emissions have grown by 52 to 75% and other industrial emissions have grown by 12%. (The ranges are due to different outcomes under high and low oil price assumptions.) The largest reductions from 2005 levels occur in the electricity sector, due to the various existing and promised provincial and federal policies targeting emissions from electricity generation. In 2030, electricity sector emissions are 69 to 74% below 2005 levels. Reductions by 2030 in the range of 4 to 24% also occur in each of the personal transportation, buildings, agriculture, and waste sectors.

In the promised federal policies scenario, sectoral emissions follow similar trends as in the existing policies scenario, although with somewhat lower emissions in some sectors. Meanwhile, moderate to substantial emission reductions occur in most sectors in the emissions price and regulations scenarios. In the emissions price scenario, it is worth noting that freight sector emissions have grown by 14 to 42% in 2030 relative to 2005 levels, with high and low oil prices respectively, although this growth is still substantially lower than with existing policies and more substantial reductions do occur after 2030 with high oil prices.

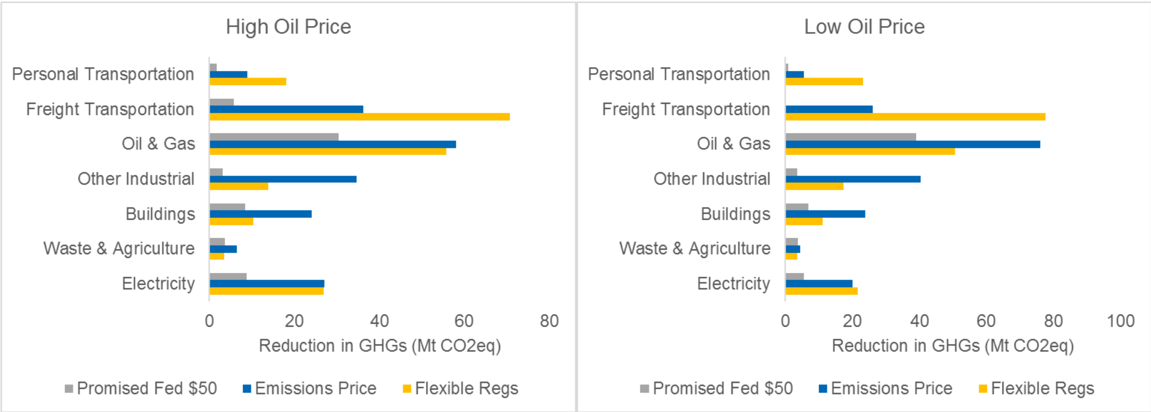
Figure 5 Sectoral emissions under each scenario



*Emissions by sector follow similar trends under low oil price assumptions.

In the promised federal policies scenario, the largest reductions in 2030 relative to the existing policies scenario occur in the oil and gas sector, resulting from the combined influence of promised federal policies (Figure 6). Significant although relatively small reductions occur in buildings and electricity, due to my assumption that much of the government's investment in low carbon technologies may end up being used for building efficiency measures and low carbon electricity generation. Reductions relative to the existing policies scenario in most other sectors are small.

Figure 6 Changes in sectoral emissions in 2030 relative to existing policies scenario



For the emissions price and flexible regulations scenarios, emission reductions are very similar in the electricity sector. By design, the results show greater reductions in industry in the carbon pricing scenario, contrasted with greater reductions in transportation in the flexible regulations scenario. As explained earlier, the regulatory approach was designed to be less stringent with trade-exposed industries in order to reduce GDP and structural impacts. To compensate, since both scenarios achieve the Paris target, sectors with less trade-exposure, particularly transportation, are required to make up the difference in emission reductions. Again, a carbon pricing approach could also be designed with less stringency for trade-exposed industries, and thus a carbon price-dominant approach applied in the real world might end up resulting in sectoral emissions results closer to those of the flexible regulations scenario.

Note that the flexible regulations scenario achieves fewer reductions in buildings in comparison to the emissions pricing scenario, since regulations for buildings were not included in the regulatory scenario. As mentioned earlier, while this study focused on a smaller list of regulatory policies that target the areas with the largest emissions reduction potential, a comprehensive regulatory approach would likely also include policies targeted at buildings, which would reduce the difference in emissions between the carbon pricing and regulatory scenarios.

5.4. Technology and fuel outcomes

5.4.1. Electricity generation technology shares

Given that already existing provincial and federal policies are likely to lead to substantial decarbonization of electricity generation, all the scenarios have similar technology outcomes in that sector (Figure 7). In 2030, British Columbia, Manitoba, Quebec, and the Atlantic region are almost entirely dominated by hydropower in all scenarios, a result that largely reflects a continuation of their already existing circumstances, as well as Nova Scotia's existing policies in the case of the Atlantic region. In Ontario, nuclear remains an important source of generation, complemented by a mix of other generation sources.

Alberta and Saskatchewan show some of the largest differences among the scenarios. In 2030, coal generation without carbon capture and storage still plays a substantial role in Saskatchewan in the existing policies and promised federal policies scenarios, while its role is substantially diminished in the emissions pricing scenario and eliminated in the flexible regulations scenario. Natural gas without carbon capture and storage accounts for a large proportion of generation in both Saskatchewan and Alberta in the existing policies and promised federal policies scenarios, whereas carbon capture and storage and wind account for substantial amounts of generation in the emissions pricing and flexible regulations scenarios. Keep in mind that uncertainty exists surrounding future costs of technologies. While carbon capture and storage and wind are the low-carbon technologies that dominate in Alberta and Saskatchewan in my scenarios with stringent policy, different assumptions about technology costs may lead other low-carbon technologies to play a larger role.

Figure 7 Electricity generation in 2030 by technology in each region

*Results follow similar trends for under low oil price assumptions.

The dominance of natural gas in Alberta and Saskatchewan in the existing policies and promised federal policies scenarios points to the value of policies that have adequate

1) coverage and 2) stringency. In terms of coverage, while the Alberta provincial government has a regulation requiring coal plants to be shut down by 2030, complementary policies do not fully cover emissions from the entire sector, and thus natural gas replaces much of the retired coal generation. Natural gas is lower-emitting than coal, but it is not the type of near-zero emission generation that would need to become dominant to achieve a low-carbon electricity system. Furthermore, the large amount of industrial cogeneration in Alberta indicates the importance of policy that covers all electricity generation as opposed to only generation by utilities and dedicated electricity plants. If policy does not cover electricity fed into the grid from industrial cogeneration, it is possible that power previously generated by coal plants could be replaced with power cogenerated in industry by natural gas or even coal-fired boilers. Policy also covering industrial cogeneration could help ensure that cogeneration is from zero or near-zero emission fuels and technologies such as biomethane or natural gas with carbon capture and storage.

In terms of stringency, the federal government's carbon price is not stringent enough to drive investment in Alberta and Saskatchewan predominantly towards zero and near-zero emission generation instead of in cheaper natural gas generation. Considering that the lifespan of a natural gas power plant is several decades, a strong policy signal early on is important to guide investment decisions and prevent lock-in of emitting technologies. Note that while Alberta and Saskatchewan both have provincial policies that aim to increase renewable electricity technologies, both policies are weaker than they may initially sound due to their focus on renewable *capacity*. Since renewable technologies like wind and solar tend to have much lower capacity factors (in the range of 10 to 35%) in comparison to natural gas (could be approximately 85% for baseload generation), the focus on capacity means that these policies will likely result in a much smaller proportion of renewable *generation* than the proportion of *capacity* that they are aiming for.

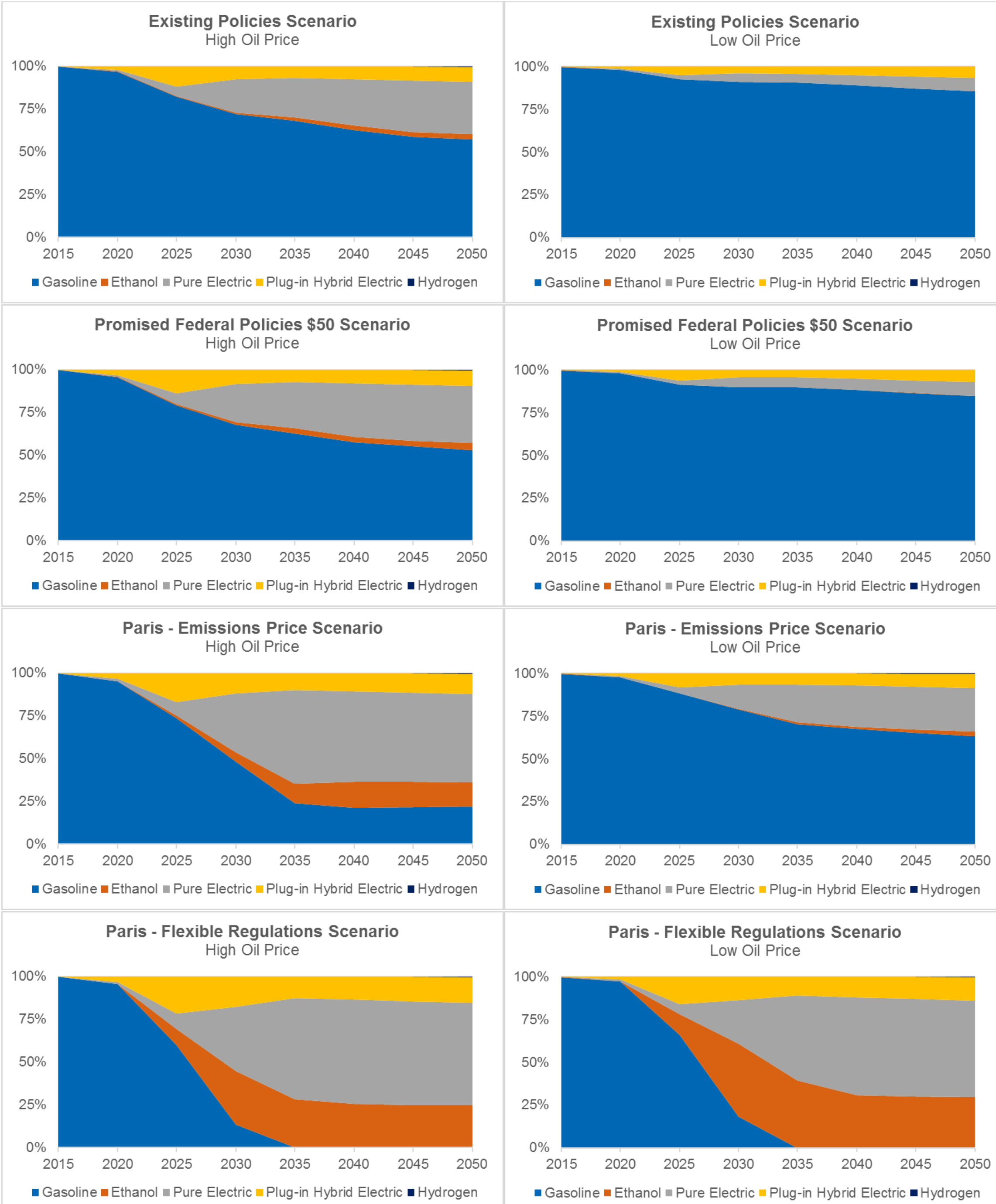
5.4.2. Personal vehicles shares

In the existing policies and promised federal policies scenarios, new personal vehicle sales continue to be largely dominated by gasoline vehicles through to 2050 (Figure 8). (Note that Figure 8 shows *new* vehicle sales; due to stock turnover, the *total* proportion of gasoline vehicles on the road would be even higher). Under high oil price assumptions, rising gasoline prices do drive increasing sales of zero and partial-zero emission vehicles. Only a small amount of zero and partial-zero emission vehicle sales occur with low oil prices, and these sales can be largely attributed to the forthcoming zero-emission vehicle mandate in Quebec. The federal carbon price leads to little change in vehicle purchases. A $50/tonne emissions price equates to a $0.12/L increase in the price of gasoline, which is too low for most people to decide to purchase an alternative fuel vehicle, especially considering that gasoline prices fluctuate by more than that amount on a regular basis.

A larger amount of zero and partial-zero emission vehicle sales occur in the emissions price scenario. However, sales are greatest in the flexible regulations scenario, which by design achieves 100% zero and partial-zero emission vehicle sales shortly after 2030. In the emissions price scenario, fewer zero and partial-zero emission vehicles are sold with low oil prices. The $200/tonne carbon price equates to a $0.48/L increase in the price of gasoline, which will likely still not be enough for some people to switch to alternative fuel vehicles if the price of gasoline otherwise remains low. This highlights one potential advantage of regulations if certainty about emission reductions is considered important – as mentioned earlier, the regulatory requirements must be achieved regardless of external factors, and thus similar emission reductions will occur in transportation with either high or low global oil prices.

The results also show the importance of starting policy early and ramping up over time. For the flexible regulations scenario, although the regulations start prior to 2020, the biggest transition doesn't occur until the 2025 to 2035 period. Starting the partial zero-emission vehicle mandate and low carbon fuel standard early gives consumers, manufacturers, and fuel distributors time to adjust – manufacturers widen the range of vehicle options and move to mass production, while expansion of alternative fuel infrastructure lowers the intangible costs of alternative fuel vehicles.

Figure 8 New personal vehicle sales by technology in each scenario



*E85 flex-fuel vehicles are attributed to the gasoline and ethanol categories in proportion to their average use of the two fuels.

In my flexible regulations scenario, electric and ethanol-85 flex fuel vehicles dominate the market for zero and partial-zero emission vehicles. This occurs due to the cost and consumer preference assumptions in the model. Although these assumptions were guided by research and calibrated to historical data, they are uncertain given that the future is uncertain and that some degree of judgement goes into setting the assumptions. With different assumptions, it is possible that plug-in hybrids or hydrogen fuel cell vehicles could capture a larger portion of the market share than occurred in my model simulations.

It should be kept in mind when looking at these results that switching to alternative fuel vehicles is not the only way to achieve emission reductions in personal transportation. Some amount of reductions can also be achieved by purchasing more efficient gasoline vehicles and by switching to public transit, cycling, or walking. A high emissions price is more likely to achieve emission reductions in a greater number of ways than a regulation. For example, a high carbon price might encourage a person who currently owns a gasoline vehicle to occasionally take the bus, while a partial-zero emission vehicle regulation would not affect her behaviour. In this way, the emissions price is theoretically more economically efficient. However, my results for all the scenarios do not show a significant amount of emission reductions from more efficient vehicles and mode switching. This occurs based on the current behavioural assumptions in CIMS and the limited ability to represent continuous improvement in vehicle efficiencies; different behavioural assumptions and representation of efficiency improvements might have led to different results. Still, most people will likely continue to drive personal vehicles, and thus switching to zero and partial-zero emission vehicles will likely be paramount to achieving substantial emission reductions in personal transportation. For this reason, regulations targeted at vehicles may not lead to a substantial loss in economic efficiency compared to emissions pricing.

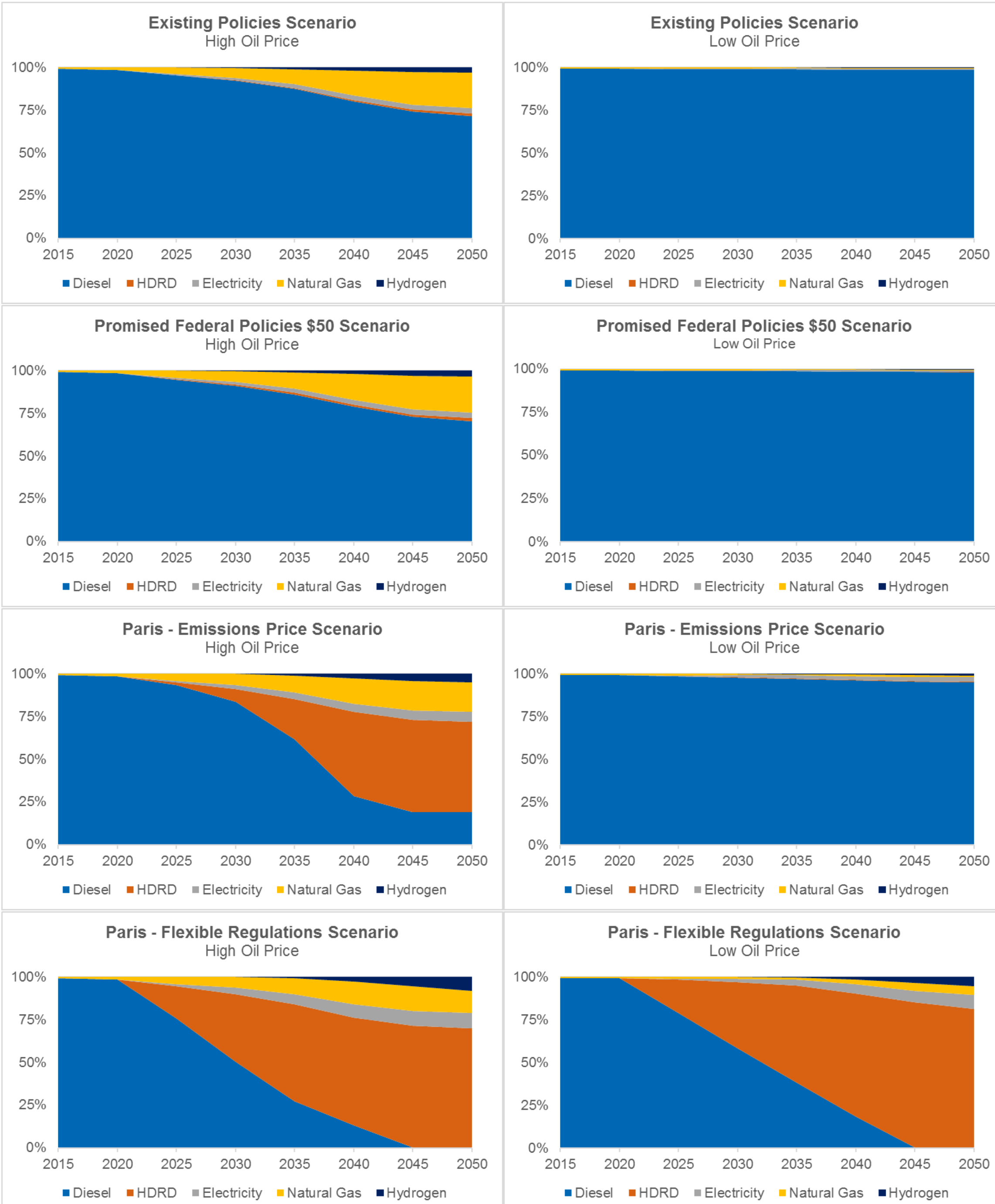
5.4.3. Freight truck fuel use shares

The results for freight truck fuel use follow somewhat similar trends as the results for personal transportation (Figure 9). (Note that Figure 9 shows *total* fuel shares, as opposed to sales of *new* vehicles as was shown for personal transportation). In the existing policies and promised federal policies scenarios, there is little movement away from diesel use in freight. With high global oil prices, rising diesel prices do motivate some switching towards trucks running on liquefied and compressed natural gas. Although natural gas is less emitting than diesel, it is far from being a near-zero emission fuel and thus is not a long-term solution on a path towards deep decarbonization by the middle of the century. Similar to personal transportation, the federal carbon price of $50/tonne, which equates to a $0.14/L increase in the price of diesel, is too low to drive substantial fuel switching in freight.

For the emissions price scenario, considerable fuel switching does occur after 2030 with high oil price assumptions, while fuel switching remains relatively limited under low oil price assumptions. Meanwhile, a large amount of fuel switching occurs in the flexible regulations scenario with both high and low oil price assumptions, with diesel eliminated entirely by 2045, as per the design of the regulations. Achieving substantial fuel switching in freight requires one or more of the following major transformations: greatly increased production and distribution of HDRD, major technological gains in hydrogen fuel cell technology to bring down costs, or substantial technological gains to increase battery energy density to make electric trucks a feasible option. My emissions price scenario shows that with low diesel prices, even a $200/tonne carbon price that results in a $0.54 increase in the price of diesel is unlikely to generate sufficient demand for alternative fuels to undergo any of the required transformations. The $200 carbon price along with otherwise high diesel prices might create enough of an incentive to push development of alternative fuels. Meanwhile, the regulatory scenario requires fuel switching, and thus emission reductions, regardless of the global oil price.

In my flexible regulations scenario, while electric, natural gas and hydrogen vehicles capture some market share, HDRD dominates the market for low carbon fuels. Since HDRD can be blended into conventional diesel in any mixture, this fuel works with existing technologies and could be highly competitive in the transition to low-emission transportation. Since I have also included regulations on biofuel production, the HDRD has very low lifecycle emissions. In the flexible regulations scenarios, the low carbon fuel standard results in a rather dramatic shift from conventional diesel to HDRD in the 2025 to 2035 period. Again, this outcome occurs due to the cost and behavioural assumptions I used in CIMS, all of which are uncertain. Different assumptions could have led to different outcomes, such as electricity or hydrogen playing a larger role.

Figure 9 Total share of fuel use by freight trucks in each scenario



As with personal transportation, fuel switching is not the only way to achieve emission reductions in freight. Reductions could occur from increases in efficiency of diesel trucks and by switching some freight to be transported by rail, although the amount of switching to rail may be relatively limited given that trucks have a substantial flexibility advantage over rail. Given that the barriers to fuel switching may be greater in freight than in personal transportation, efficiency gains in diesel trucks may make a more important contribution to emission reductions, particularly in the near-term. Even if emissions pricing is not high enough to drive fuel switching in freight, it may be able to drive substantial emission reductions through truck efficiency gains. Meanwhile, a regulation focused only on the carbon intensity of fuels will not achieve these lower cost emission reductions. To improve the economic efficiency of the flexible regulations approach, I also included an average emissions performance standard for new freight trucks applied to truck manufactures to complement the low carbon fuel standard. If we were to assume that HDRD will play a large role in decarbonizing freight, more efficient trucks would have the advantage of 1) reducing increases in the total fuel costs for trucking companies, even as the cost per litre of diesel increases with increasing blends of HDRD, and 2) requiring less conversion of agricultural land since the total amount of HDRD used would be less.

5.5. Energy cost changes

As noted, the GDP effects of policies cannot be calculated using CIMS alone. However, I am able to calculate the effects on energy prices, which provides an indication of some of the cost implications of different policy approaches. Similarities in energy costs, after netting out tax transfers, can provide a proxy for similarities in economic efficiency. Note that below, I have netted out tax transfers in the prices calculated for electricity but not for transportation liquid fuels, and thus the former may provide a proxy for economic efficiency while the latter does not[19].

[19] An emissions price signal would likely work differently for electricity and transportation. For electricity, the emissions price is intended to affect the technology acquisition decisions of electricity-generating utilities rather than the choices of electricity-consuming firms and individuals. Thus, the emissions price revenue from electricity could be recycled in lump sum payments directly back to utilities so that the emissions price itself does not lead to a net increase in average consumer electricity prices. In contrast, in transportation, the emissions price is intended to affect the technology and fuel choices of individuals and trucking companies, and so the price signal should be maintained in the prices of fuels. The emissions price revenue from transportation fuels could then perhaps be recycled through rebate cheques of tax breaks to households and trucking companies.

5.5.1. Electricity prices

Relative to the existing policies scenario in 2030, the promised federal policies scenario results in little change in electricity prices, which is expected given that it results in little change in greenhouse gas emissions relative to with existing policies (Figure 10)[20,21]. In the emissions pricing and flexible regulations scenarios, Alberta and Saskatchewan see the largest increases in electricity prices above the existing policies scenario in 2030 because they currently rely the most on fossil fuel electricity generation. However, these increases are relatively small: in Alberta, 18% and 15% in the emissions pricing and flexible regulations scenarios, respectively, (equivalent to 2.7 and 2.3 cents per kWh); and in Saskatchewan, 12% and 13% in the emissions pricing and flexible regulations scenarios, respectively (equivalent to 2.6 and 2.7 cents per kWh). This represents increases above the existing policies scenario of about 1% per year in real terms.

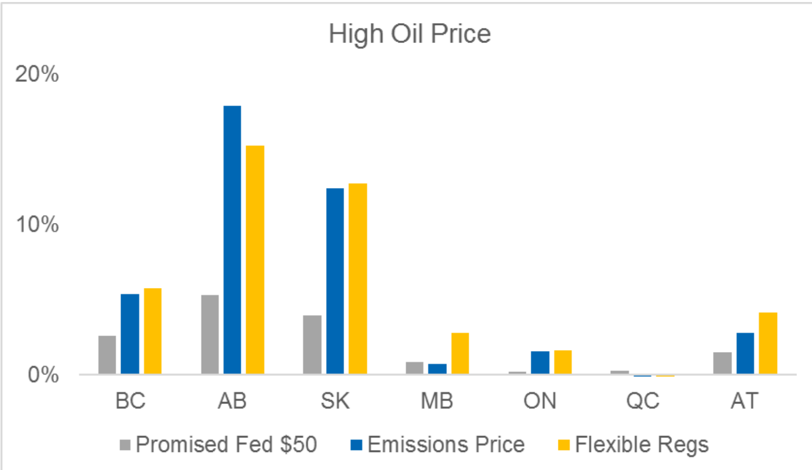
The increase in Alberta is slightly higher in the emissions pricing scenario due to greater emission reductions relative to the regulatory approach. This demonstrates that the regulations as designed result in a small loss of efficiency in comparison to emissions pricing, since the regulations could have required more emission reductions in the Alberta electricity sector instead of achieving the same reductions at a higher cost elsewhere in the economy. In practice, small losses in economy-wide efficiency may be justifiable when policies are designed to intentionally reduce the burden on provinces and sectors that would have otherwise seen the largest impacts, as was the case here with the differentiated electricity standards for provinces currently dominated by fossil fuel versus hydro electricity generation. Overall, though, the cost impacts are not greatly different

[20] Electricity prices were calculated based on the average levelized cost of generation. I assumed that a 1% increase in the average levelized cost of generation would result in a 0.5% increase in electricity price, given that electricity prices include substantial fixed costs, such as distribution infrastructure and overhead costs, in addition to costs of generation. Revenue collected through carbon pricing was assumed to be returned to the sector in lump sum payments and therefore carbon prices were assumed to not be directly included in electricity prices.

[21] Note that with existing policies, most provinces will likely see some increase in electricity prices above current prices by 2030, due to already existing policies and the need to build new generation to meet increased demand; the price changes discussed here are the additional increases in prices relative to existing policies resulting from additional policies.

between the two scenarios, indicating that they may achieve similar levels of economic efficiency.

Figure 10 Electricity price change in 2030 relative to existing policies scenario by province



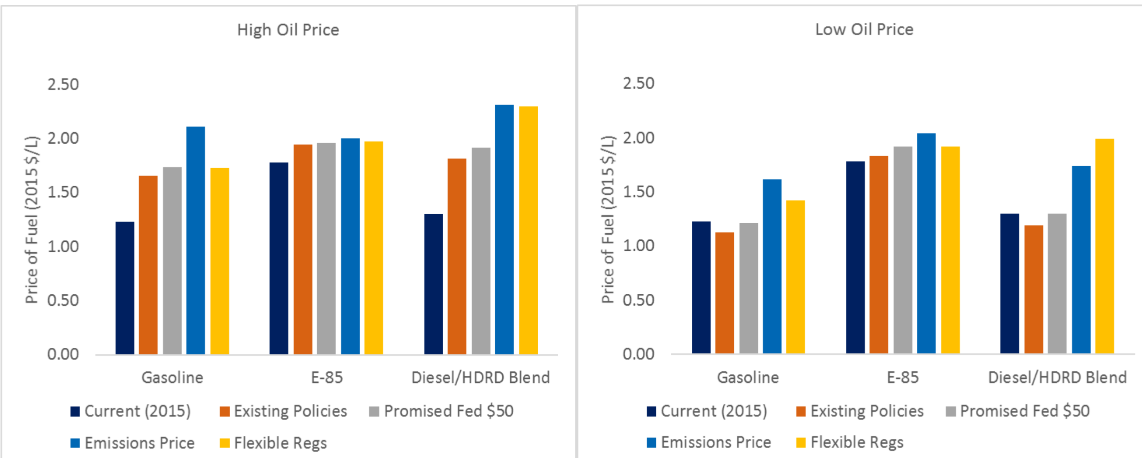
*Results are similar for low oil price assumptions.

In the emission pricing and flexible regulations scenarios, there is also a notable increase in the average electricity price in the Atlantic region. Given that Nova Scotia and to a lesser degree New Brunswick currently have considerable reliance on fossil fuel generation, a lot of the increase is likely happening in these two provinces and is being hidden to some degree due to the grouping of the Atlantic provinces together and averaging of their electricity prices. In British Columbia, the increases in 2030 electricity prices above the existing policies scenario occurs largely due to increased demand for electricity, a large portion of which is coming from growth in the natural gas industry. As policy – either carbon pricing or regulations, depending on the scenario – requires emission reductions in industry, there is a greater shift from fossil fuels to electricity. As lower-cost existing large hydro generation becomes increasingly unable to meet demand, higher cost new sources of generation – including new hydro and wind generation – are required to meet demand and lead to the observed increase in electricity prices.

5.5.2. Transportation liquid fuel prices

Under the promised federal policies scenario, the average Canadian prices of gasoline and diesel in 2030 are slightly higher than in the existing policies scenario (Figure 11)[22,23]. The increases occur primarily due to the federal government's promised minimum carbon price requirement, and thus the increases are largest in provinces that did not have emissions pricing policies with existing policies.

Figure 11 Average Canadian retail prices of transportation liquid fuels in 2030



*E-85 prices are in $/L of gasoline equivalent, to account for the lower energy density of ethanol.

For gasoline, the emissions pricing scenario resulted in greater price increases by 2030 than the regulatory approach – on average, 46 and 49 cents per litre above the existing policies price compared with 8 and 29 cents in the case of regulations, under high

[22] The retail prices of liquid fuels include emissions prices. For gasoline, the price for the flexible regulations scenario includes the retailer mark-up of gasoline in order to cross-subsidize E-85 or to cover externally purchased low carbon fuel credits to meet sales requirements under the low carbon fuel standard. The diesel/HDRD blend was calculated as one price based on the assumption that HDRD would be blended into regular diesel since this can be done without need for truck engine adjustments. The price was calculated as the average cost of conventional diesel and HDRD, weighted by each fuel's share within the dispensed diesel. Again, in the flexible regulations scenario the price of the diesel/HDRD blend includes retailer mark-up to cover externally purchased low carbon fuel credits to meet requirements under the low carbon fuel standard. Intangible costs of renewable fuels are not included in the calculated retail prices.

[23] Note that under high oil price assumptions, the existing policies scenario shows, as expected, significantly higher gasoline prices than current prices. With low oil price assumptions, gasoline prices are not much different, if anything slightly lower once accounting for the effects of inflation.

and low oil price assumptions respectively. The greater increase under the emissions pricing scenario occurs because the carbon price is being applied to all carbon emissions from gasoline, whereas in the regulations scenario the price of gasoline is only increasing to the extent needed for retailers to cross-subsidize their own sales of ethanol-85 to make it competitive with gasoline and/or to pay for low carbon fuel credits from external sources.

The difference in price between the two scenarios is more dramatic with high oil price assumptions. In the emission pricing scenario, on the one hand, the increase in the retail price of gasoline above existing policies is similar under low and high oil price assumptions, since the carbon price is only marginally higher with low oil prices. On the other hand, in the flexible regulations scenario, with low gasoline prices, gasoline retailers must significantly mark-up the price of gasoline in order to make ethanol-85 cost competitive, and perhaps to also cause some switching to electric vehicles, to meet their quotas under the low carbon fuel standard. Such a substantial mark-up was not required with high oil prices.

Even with the dramatically higher emissions price in the emissions pricing scenario, ethanol-85 is used to fuel only 5% and 1% of internal combustion engine vehicles nationally, with high and low oil prices respectively. In the regulatory scenario, ethanol-85 fuels 25% and 28% of vehicles, with high and low oil prices respectively. This result highlights several potential advantages of the low carbon fuel standard in that it 1) mandates a shift towards increased low carbon fuel infrastructure that the carbon price is still not high enough to cause and 2) results in less increase in the price of gasoline, an advantage in terms of political acceptability. On the other hand, this result may also point to a deficiency of the regulatory approach. By mandating a minimum percent of low carbon fuels, the regulation cannot be met by other potentially less-expensive ways of reducing emissions that might be spurred by carbon pricing, such as shifting to greater use of public transit and active forms of transportation. Additionally, the regulatory scenario achieves more emission reductions in the personal transportation sector than the emissions pricing scenario, which would be positive if the sole objective were to achieve emissions reductions in transportation, but from an economy-wide perspective means that those same reductions could have been achieved outside of the personal transportation sector at a lower cost, as occurred with emissions pricing.

For the diesel/HDRD blend, the retail price in 2030 is comparable in the emissions pricing and flexible regulations scenarios under high oil price assumptions - on average, 45 and 42 cents per litre above the existing policies price, respectively. Under low oil price assumptions, the retail price of diesel increased most by 2030 in the flexible regulations scenario – 70 cents per litre above the existing policies price as compared to 49 cents in the emissions pricing scenario. For the regulatory approach, the price increase over the existing policies scenario is substantially greater with low oil prices than with high oil prices. Since the price of diesel is much lower with low oil prices while the price of HDRD is the same regardless of global oil prices, blending in HDRD results in a greater price differential when assuming a low global oil price.

The regulatory approach results in a much higher HDRD blend (44% and 40% with high and low oil price assumptions, respectively) as compared to emissions pricing (8% and 1% with high and low oil price assumptions, respectively). Thus, the increase in the diesel/HDRD blend price occurs largely due to payments to the government in the emissions pricing scenario but due to blending more HDRD and reducing more emissions in the flexible regulations scenario. This may result in an advantage in terms of political acceptability for the regulatory approach, since people would likely be less opposed to higher prices if these were due to emission reductions rather than payments to the government. On the other hand, the regulatory approach is again likely less economically efficient, since it requires more emissions reductions in freight transportation when the same reductions could have occurred in other sectors at a lower cost; however, the regulatory approach was intentionally designed this way in order to be more lenient on trade-exposed industrial sectors. The regulatory approach is also likely less economically efficient in that the low carbon fuel standard requires emission reductions within freight to be achieved through fuel switching, when those same emission reductions could have been achieved, at least to some extent, from more efficient trucks or to some degree from switching from trucking to rail.

Chapter 6. Conclusion

6.1. Summary of key findings

This study has evaluated Canadian climate policy options for achieving the commitment at Paris in 2015 to reduce national emissions in 2030 by 30% relative to their 2005 levels. The modeling results show that federal and provincial climate policies adopted and announced as of October 2016 will likely fall far short of that commitment. Even the federal government's promised minimum national carbon price, which would rise to $50/tonne by 2022, will be insufficient. My results show that if the carbon price remains frozen at $50 after 2022, national emissions would fall by approximately 12% by 2030. If the carbon price continues to increase to $100 by 2030, emissions would fall by approximately 17%. Thus, a significant gap exists between Canada's emission target and the emissions levels likely to be achieved with current policies.

If the federal government were to rely solely on emissions pricing to close the policy gap, my results suggest that the carbon price would need to start in 2017 at $25 and rise by approximately $13 each year to reach $200 by 2030. This price trajectory was obtained after adjusting downwards the price required in CIMS in order to account for macroeconomic effects that would likely occur as a result of climate policy but are not captured by this model, with its micro-economic focus, and to account for a likely underestimation of technological change in CIMS. Research suggests that implementing a carbon price this high would be extremely difficult, if not impossible, from a political acceptability perspective. People tend to be resistant to policies that impose visible, short-term costs for less tangible long-term benefits. Taxes or policies that can be framed as taxes, such as carbon taxes and cap-and-trade, tend to face the highest levels of opposition. Essentially no governments in the world have adopted or seriously proposed carbon prices on the order of $200/tonne. Even the federal government's modest $50 carbon price announcement faced substantial objections from some provinces.

As an alternative policy approach, I outlined a package of flexible regulations that could also achieve the Paris target. The policy approach was dominated by regulations, but also included a low but rising explicit carbon price. The regulations included a phase out of coal-fired electricity generation and an emissions performance standards for the electricity sector, a partial zero emission vehicle standard and low carbon fuel standard for personal transportation vehicles, a low carbon fuel standard and vehicle emission standards for freight trucks, performance standards for biofuel and hydrogen production, and performance standards for other industrial sectors. As designed, most of the regulations offer a considerable degree of flexibility in that they allow the technology requirements and emissions standards to be achieved in multiple ways. Most also allow trading of emissions permits among regulated entities so that emission reductions are undertaken by those who can do so at the lowest cost. The policies were designed to partially protect trade-exposed industries by imposing less stringent emissions requirements on them, and thus more reductions were required from other sectors, particularly the transportation sector. The regulations would likely have an implicit price in the range of $200/tonne or higher by 2030. However, research and experience show that regulations like those included in this policy package would likely face less public opposition than explicit emissions pricing.

The modeling results show that relatively comparable results occurred whether achieving the Paris target through emissions pricing or flexible regulations. The level of ambition required from each province was comparable under the two scenarios. For the electricity sector, both scenarios led to very similar outcomes in terms of the amount of emissions reduced, technology market shares, and electricity prices. There were some differences in other sectors. The flexible regulations led to more emission reductions in transportation and less in industrial sectors. This occurred as a result of the intentional design of the regulations to protect trade-exposed industries. Emissions pricing can also be designed to provide favourable treatment to trade-exposed industries, which would likely lead to more comparable sectoral emissions outcomes under the two approaches. Market shares for personal vehicle technologies and fuel types in freight were relatively similar with high oil prices, although differed considerably with low oil prices. This points to one advantage of regulations, in that emission reductions are less sensitive to global oil prices than with carbon pricing. Also, with high oil prices, gasoline prices increased more with carbon pricing than with flexible regulations. This is another advantage of regulations, in that they can achieve comparable emissions reductions without as dramatic increases in fuel costs, thus reducing a potential source of public opposition. Despite a number of differences, the two scenarios did not lead to drastically different outcomes in terms of technology market shares and energy costs changes (after netting out tax transfers), suggesting that the two approaches may be at least somewhat comparable in terms of economic efficiency and impacts on GDP.

Nonetheless, emissions pricing would likely be somewhat more economically efficient than flexible regulations. First, emissions pricing presents more available response opportunities for firms and households, some of which could be lower cost. For example, in the transportation sector, while both a PZEV and an emission price allows people to respond by choosing any low-emission vehicle, an emissions price also enables people to respond by driving less. However, the wider availability of options may not actually have a large effect on the costs of reducing emissions since many of those options may not be widely chosen anyways. In the case of transportation, even with stringent policy most people will likely continue to drive their vehicles at similar rates. Second, the revenue collected with emissions pricing could be used to reduce other growth-inhibiting taxes, having a countervailing effect on GDP, whereas no such revenue is collected with regulations. However, most governments that have adopted emissions pricing, apart from BC, have used the revenues in ways other than solely to reduce other taxes. Thus, this 'double-dividend' possibility with emissions pricing may not be large. Overall, although emissions pricing does have an economic efficiency advantage over flexible regulations, in real-world applications the difference between the two approaches may not be large.

In summary, either emissions pricing or flexible regulations could be used to achieve Canada's 2030 Paris commitment. There may not be a large economic efficiency loss from a flexible regulations approach relative to emissions pricing, and the literature suggests that regulations could have an advantage over emission pricing in terms of political acceptability. This study has shown that an emissions price would need to rise to levels on the order of $200/tonne by 2030 to reach the Paris target, a price that would be very politically challenging to implement and is much higher than the promised minimum federal price of $50. If politicians are serious about meeting their emissions targets but are unwilling or unable to reach a high enough emissions price to drive the required reductions, flexible regulations could offer an alternative approach. A low but rising emissions price along with the flexible regulations could serve as a complement to drive deeper emissions reductions in a decade or two after the regulations have brought down the costs and increased the availability of low carbon technologies.

All effective climate policy is difficult, and policy-makers will likely need to make trade-offs when choosing an approach. In the past, policy-makers have tended to trade-off policy effectiveness in order to prevent public opposition, which has resulted in decades of stagnancy in reducing greenhouse gas emissions. This study has sought to present a different path. With careful policy design, options are available to policy-makers that may enable them to trade-off a modest amount of economic efficiency to gain greater levels of public acceptance, thus offering improved chances of achieving the substantial emission reductions that are needed to maintain a safe and liveable climate.

6.2. Limitations and recommendations for future research

This study had a number of limitations, from which I draw recommendations for future research. Modeling is a simplification of reality, in which the modeler must make informed decisions about how to represent a wide variety of complex dynamics occurring in the real world. All modeling studies involve uncertainty, since we do not know for sure how the future will unfold. When modeling using CIMS, the outcomes depend on the structure of the model itself and on the interaction of a large number of parameters. The parameters are based on data and assumptions about technological availability and innovation, current and future costs of technologies, sectoral growth rates that are a function of both economic and population growth, human preferences and behaviour, and a variety of other factors. Given that modeling is a simplification and involves uncertainty, modeling results should be viewed as a way to explore system dynamics and to gain insights into the possible outcomes under contrasting circumstances, in this case with contrasting policy approaches.

Uncertainty and sensitivity analyses can be useful ways to better understand how outcomes may change under different assumptions about uncertain parameters, and thus how robust outcomes are to these changing assumptions. For this study, I ran all scenarios with both low and high global oil price assumptions, given that the global oil price was a key uncertainty that could influence outcomes. To maintain a reasonable scope to my study, I did not conduct sensitivity analyses on any of the multitude of other uncertain parameters in CIMS. Future research could explore how outcomes would change with alternative assumptions about the future evolution of technology and fuel costs, the behavioural parameters, sectoral growth, etc. It could be particularly useful to look at uncertainty using probabilistic Bayesian statistics techniques, such as Monte Carlo analysis. Future research could also look at how changes to the structure of the model would affect outcomes. For example, there are drawbacks to the way I represented intermittent renewable electricity generation, in that I did not incorporate detailed information on how electricity load and generation by different technologies vary over time. Outcomes could be assessed using an alternative representation of the electricity sector, such as by linking CIMS to a more detailed electricity dispatch model.

As discussed, this study used CIMS alone rather than in conjunction with a computable general equilibrium model, which means that I was unable to compare my scenarios in terms of impacts on economic growth. While I did compare the technological and energy cost outcomes of my scenarios as a proxy for economic efficiency, I lacked a formal method for evaluating the economic efficiency of alternative policy approaches. Future research could run similar scenarios using CIMS linked to a CGE in order to explore GDP outcomes and formally compare the economic efficiency of the alternative policy approaches. Even without a CGE, other approaches could be developed to gauge the difference in efficiency between scenarios, such as through policy cost calculations. In particular, it would be interesting to compare the economic efficiency of the emissions pricing and flexible regulations scenarios, both of which achieved Canada's Paris commitment. If future research arrived at an estimation of the economic efficiency of the alternative approaches, a decision analysis framework could be used to formally explore the trade-off between economic efficiency and political acceptability. Such an analysis would involve 1) assigning probabilities to each policy approach based on the likelihood that the policy would actually be implemented, 2) using the probabilities to calculate expected values for both emission reductions and economic objectives, and 3) comparing the different policy approaches based on those expected values.

For the flexible regulations scenario in this study, I focused on regulations in the electricity and transportation sectors, and also included regulations for industrial sectors.

As mentioned, a comprehensive policy package would also likely include regulations in other sectors, including buildings, agriculture, and waste. Future research could design other flexible regulations approaches that also addressed these other sectors. It could be interesting to compare a number of different flexible regulations scenarios with each other, perhaps including different assumptions with regards to how much leniency is afforded to trade-exposed industries. If a measure of economic efficiency were being calculated, the different flexible regulations packages could also be compared in terms of efficiency with a pure emissions pricing approach.

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Appendices

Appendix A.

Behavioural parameters used for this study

Note that for the market heterogeneity parameter, a low value results in more market heterogeneity and a high value results in less market heterogeneity. I.e. if the value is about 3 or 4, technologies can capture similar market shares even if they have very different costs; if the value is 25 or 30, the lowest cost technology will capture almost the entire market.

Sector	Technology Node	Market Heterogeneity Parameter	Discount Rate
Electricity	Generation technologies	10	10%
Personal Transportation	Urban transportation modes (personal vehicle vs. bus vs. walk/cycle)	6	N/A
	Personal vehicle type (small vs large, car vs. truck)	7	25%
	Personal vehicle motor (gasoline vs. hybrid vs. electric)	10	25%
	Personal vehicle flex-fuel fuel (gasoline vs. ethanol)	10	N/A
	Transit bus type (diesel vs. natural gas vs. electric trolley)	20	25%
	Inter-city transportation (bus vs. rail vs. vehicle; type of bus; type of rail)	10	25%
Freight Transportation	Heavy freight - trucks vs. rail	4	N/A
	Light freight truck motors (diesel vs. electric vs. hydrogen)	12	25%
	Heavy freight truck motors (diesel vs. natural gasvs. hydrogen)	20	25%
	Diesel blend for truck fuel (diesel vs. HDRD)	15	N/A
	Rail type (diesel vs. HDRD vs. electric)	10	25%
	Marine freight type (diesel vs. HDRD vs. hydrogen)	15	12.5%
Biofuel production	Ethanol production method (corn vs. cellulosic)	25	20%
	Tractor fuel (diesel vs. HDRD)	10	N/A
	Fuel production boilers	10	20%
Other sectors	Industrial	Most are 10. A small number are 15 or 25.	20%
	Buildings	10	25 to 30%
	Waste	Less than 1	20 to 35%
	Agriculture	10 to 15	30 to 40%

Appendix B.

Modeling method for existing policies

Jurisdiction	Start Year	Policy Description	Explanation of How Policy was Modeled
Carbon Pricing			
BC	2008	**Carbon tax**: started at $10 in 2008, rising to $30 by 2012, where it has remained since. Applies to combustion emissions but not process emissions.	Applied as an emissions price. Since it isn't indexed to inflation, it was modeled as decreasing in real terms. Applied to combustion emissions in all sectors except waste.
AB	2007	**Specified Gas Emitters Regulation (SGER)**: facilities emitting 100,000+ tonnes must reduce emissions to meet intensity targets: 12% reduction ($15/tonne over), increasing to 15% ($20/tonne over) in 2016, 20% ($30/tonne over) in 2017. Does not cover process emissions. **Sector and product based performance standards**: will replace the SGER after 2017. Details have not yet been made public.	Applied as a $2 emissions price up to 2015 ($2 = $15 x 12%, to approximate $15 applied to 12% of emissions). Increases in 2016 and 2017. A $30 carbon price was applied after 2017 to 100% of industrial emissions to approximate the forthcoming performance standards. Applied to combustion emissions in all industrial sectors, including the electricity sector but excluding agriculture and waste.
AB	2017	**Carbon levy**: $20 in 2017 and $30 thereafter. Applies to combustion fuels (diesel, gasoline, natural gas, propane); does not apply to purchases of electricity, heating fuels on sites subject to SGER, natural gas produced and consumed on site by conventional oil and gas products (until 2023), nor the agricultural sector.	Applied as an emissions price. Since it isn't indexed to inflation, it was modeled as decreasing in real terms. Applied to combustion emissions in transportation, residential, and commercial sectors.
ON	2017	**Cap-and-trade**: very similar to Quebec cap-and-trade (see immediately below). Cap is 15% below 1990 levels by 2020, 37% by 2030, and 80% by 2050.	Modeled same way as Quebec cap-and-trade (see below), except starting in 2017.
QC	2007	**Levy on fossil fuels**: (from 2007-2014): $3.2 levy on fossil fuels.	Modeled as $3.2 carbon price.

QC	2013	**Cap-and-trade:** began in 2013, linked with California's cap-and-trade system in 2014. Applies to business that emit 25,000+ tonnes/year. Started out applying to only industrial and electricity sectors; in 2015 also extended to fossil fuel distributors. Includes an offset scheme. Cap is 20% below 1990 levels by 2020, with future caps not specified. Floor price of $10.75 in 2013 and increases by 5% plus inflation each year until 2020, with future increases not specified.	Modeled as an emissions price set at 10% above the floor price and adjusted to assume an ongoing exchange rate of 1 CAD = 0.75 USD. The floor price is assumed to continue increasing at the same rate beyond 2020. Applied to combustion and process emissions in all sectors except agriculture and waste.
Electricity Policies			
Federal	2015	**Coal performance standard**: intensity standard of 420 tonnes of CO_2 per GWh (emissions intensity of an efficient natural gas combined cycle plant); applies to new (after 2015) and end of life coal-fired electricity generation units (45-50 years of age).	Set new market share maximum of 0 for coal plants without CCS after 2015.
BC	2010	**Renewable portfolio standard**: 93% of electricity generation must be from clean electricity. Updated in August 2016 to 100%, with exceptions to address reliability.	Set new market share maximum to 0 for all fossil fuel generation without CCS, except for allowing a very small amount of diesel.
AB	2016	**Coal phase out**: all coal plants must be closed by 2030. *(Announced but not yet legislated.)*	Set retirement age on coal plants without CCS so all would retire by 2030. New market share maximum of 0 for coal plants beginning in 2015 already set under federal policy.
AB	2016	**Renewable generation increase**: two-third of phased out coal capacity will be replaced by renewable energy. (As of 2015, AB had 6300 MW of coal capacity. Thus, about 4200 MW of renewables capacity should be added.) (*Announced but not yet legislated.)*	Set new market share minimums for wind, solar, and biomass to achieve 4200 MW new capacity. Approximately 2800 MW will be from wind, with the remainder split between solar and biomass.

SK	2014	**Carbon capture and storage retrofit**: a 115 MW generating unit at the Boundary Dam coal plant was retrofitted with carbon capture and storage technology.	Forced 115 MW of existing coal capacity to retrofit to carbon capture and storage.
SK	2015	**Renewable electricity target**: sets a target of 50% renewable electricity capacity by 2030. (*Announced but not yet legislated.)*	Made new baseload natural gas generation unavailable from 2015 to 2025 so that new baseload market share is captured by renewables, which results in 50% renewable capacity by 2030. To ensure a mix of renewable types, set minimum new market share of solar and hydro generation at 10% each, with remainder of new market share captured by wind and biomass.
MB	2010	**Coal phase out**: by 2010, coal plants can only be used in emergencies.	Forced existing coal generation to be replaced by hydro (using retrofit function in CIMS).
ON	2007	**Coal phase out**: all coal plants must be closed by end of 2014.	Set retirement age on coal plants so all would retire by 2015. Set new market share maximum of 0 for coal plants after 2010.
ON	2009	**Feed-in-tariff (FIT) and large renewable procurement (LRP)**: FIT offers fixed contract prices for renewable generation, which transitioned to include a procurement process for larger projects. Second and most recent LRP is set to procure 600 MW of wind, 225 MW of solar, 30 MW of biomass.	Set minimum new market share of 25% for wind, 15% for solar, and 10% for biomass to approximate the addition every few years of the amount of new capacity being added under the second LRP.

NS	2009/ 2010	**Electricity sector emissions cap**: GHG Emissions Regulation requires that the combined emissions of all electricity-producing facilities in the province (that emit greater than 10,000 metric tonnes of CO_2 per year) must be no greater than 7.5 million tonnes CO_2 by 2020 and 4.5 million tonnes CO_2 by 2030. **Renewable portfolio standard**: requires minimum amount of generation from renewables: 5% in 2011, 10% in 2013, 25% in 2015, 40% in 2020.	Set new market share maximum to 0 for all coal without CCS after 2010. With no new coal allowed, capital stock turnover largely achieves these two regulations, as coal naturally retires and is replaced largely with hydro. Additionally, a small amount of existing coal generation (2-3%) in each period is forced to be replaced by wind, using the CIMS retrofit function (so that coal generates approx. 2.5TWh in 2030 in NS, as compared to 7TWh currently; this leaves room for some new natural gas generation while still staying under the 2030 cap).
Transportation: Low Carbon/Renewable Fuel Standards			
BC	2010	Requires 5% renewable content in gasoline, 4% in diesel; 10% reduction in carbon intensity by 2020,15% by 2030.	Set new market share maximum to 0 for pure gasoline and diesel (starting in year policy starts), so that gasoline and diesel with the required ethanol or HDRD blend must capture all new market share. Federal policy applied in Quebec and Atlantic region only, as the rest of the provinces have provincial policies of equal or greater stringency.
AB	2011	Requires 5% renewable content in gasoline, 2% in diesel.	
SK	2007/ 2012	Requires 7.5% renewable content in gasoline, 2% in diesel.	
MB	2008/ 2009	Requires 8.5% renewable content in gasoline, 2% in diesel.	
ON	2007/ 2014	Requires 5% renewable content in gasoline, 2% in diesel rising to 4% by 2017.	
Federal	2011	Requires 5% renewable content in gasoline, 2% in diesel.	
Transportation: Other Regulations			
Federal	2013	**Heavy-duty vehicle emissions standard**: sets minimum standards in terms of CO_2/tonne-mile for different classes of freight vehicles. One set of standards for 2014-2016 vehicles, another set of vehicles for 2017 and beyond.	Made standard efficiency heavy freight truck unavailable after 2015. Standard for light-medium freight is achieved in CIMS without adding policy. Average standard estimated directly from the regulations. (Modeled this way because the standards are not very stringent and are liking to be met mostly through efficiency gains in diesel trucks.)

Federal	2012	**Light-duty vehicle emissions standard**: sets minimum standards in terms of CO_2/km for passenger cars and trucks. One set of standards for 2012-2016 vehicles, another set of vehicles for 2017-2025.	Applied an emissions price on personal vehicle motors and found a price trajectory that led to achieving the average CO_2/km targets for new vehicles. Targets were based on summary data from the International Council on Clean Transportation, as opposed to calculated directly from the regulations. (Modeled this way because the standards are more stringent than freight and are likely to lead to some amount of fuel switching, for example from gasoline to electric vehicles, and so are modeled differently from freight.)
QC	2016	**ZEV mandate**: will require automakers to sell a minimum number of ZEVs: 3.4% in 208, 7% in 2020, 15.5% in 2025; electric, plug-in hybrid, and hydrogen vehicles qualify, but biofuel or E85 flex fuel vehicles do not qualify.	Set new market share minimum of 1.5% for each of EVs and PHEVs for the 2020 period, rising at a rate of 1.75% per year. (So 3% total ZEV new market share in the 2020 period – average of the minimum standard over the 5 years from 2016 to 2020.) Assumed approximately half of mandate will be met with EVs and half PHEVs, since biofuel vehicles do not qualify and hydrogen vehicles currently remain very expensive.
Building Codes and Energy Efficiency			
BC, AB, MN, ON, QC, NS	2008 to 2016	**Energy-related building codes**: set standards for new (but not existing) buildings. Standards vary among provinces, but many roughly require the following: - Residential: meet standards set by National Building Code 2012 Revision (Part 9.36) OR EnerGuide 80 - Commercial: meet standards set by ASHRAE 90.1-2010 or NECB 2011 (National Energy Building Code)	Set new market share max of 0 beginning in the code start year for the following: - Residential: low efficiency air conditioning; low efficiency natural gas and oil furnaces; standard building shell; standard efficiency natural gas and electric water heating. - Commercial: standard building shell; standard efficiency oil, natural gas, and electric water heating; low efficiency HVAC; least efficient lighting; low efficiency motive power; standard efficiency plugload.

			Given the technicality of the building codes and the flexibility in how the standards can be met, precise requirements are difficult to model. The method used here was considered a sufficient approximation of a requirement for new buildings to be more efficient but not built to a zero-emission standard. (Note that although only NS has adopted an energy building code, the policy was applied to the whole Atlantic region for simplicity.)
Fed	1992	**Energy efficiency regulations**: sets minimum standards for a wide variety of energy using products. Updated regularly.	Use declining market share maximum to make the following technologies unavailable to capture new market share by 2015 or 2020: incandescent lightbulbs, inefficient natural gas water heaters, and inefficient natural gas and oil HVAC systems. This method serves as an approximation of standards for some of the key technologies covered by the regulations.
Landfill Gas Regulations			
BC	2009	Requires landfills to create a landfill gas management facilities design plan and to install the designed facilities at the landfill site, including landfill gas management systems that address ghgs. Deadline for installing system is 2016 for larger waste producers.	Set new market share max of 0 for all landfills without methane control; forces retrofit of 50% of existing large and medium landfills with no control. (Note that the 50% retrofit requirement for all landfill gas regulations was chosen to approximate that the regulations require efforts to reduce methane emissions but do not require methane emissions to be reduced to near-zero levels.)
MN	2009	Requires the province's three largest landfills to capture or flare excess methane by 2010.	Set new market share max of 0 for large landfills without methane control; forces retrofit of 50% of existing large landfills with no control
ON	2008	Requires landfills larger than 1.5 million cubic meters to have methane collection systems in place by 2010 (utilization or flaring).	Set new market share max of 0 for all landfills without methane control; forces retrofit of 50% of existing large and medium landfills with no control

QC	2005	Requires that landfills that process more than 50,000 tons will be required to capture methane and, ideally, recover it or, if this is not feasible, burn it.	Set new market share max of 0 for all landfills without methane control; forces retrofit of 50% of all existing landfills with no control
Oil and Gas Policies			
AB	2016	**Oils sands emissions limit**: sets a cap on oil sands emissions of 100 MT per year. *(Announced but not yet legislated.)*	Applied an emissions price to oil sands processes and technologies, and found a trajectory that kept emissions under the cap. For the high oil price version, a relatively high emissions price was required for emissions to remain under the cap; for the low oil price version, emissions remained under the cap without applying an emissions price.
AB	2016	**Methane regulations**: requires methane emissions from oil and gas operations to be reduced by 45% by 2025 through minimum facility, equipment, and operations standards at new and existing facilities. *(Announced but legislation not yet passed.)*	Set new market share max of 0 for processes and technologies without leak detection and repair (LDAR) after 2015 and forced retrofit of existing processes to LDAR by 2025. Applied to conventional oil, oil sands, and natural gas for all exploration, drilling, processing, and production processes and technologies.

Appendix C.

Modeling method for federal budget subsidies

In CIMS, subsidies used to approximate federal budget funding were applied only in the 2016-2020 period using a ‘proxy fuel’ method. A fuel was added to the technologies as a proxy for the subsidy. Demand for the fuel was set to equal to the technology’s levelized costs. The price of the fuel in the period the subsidy is applied was set as a negative cost, in proportion to the percent of levelized costs to be subsidized. For example, if the subsidy is 25% of levelized costs, the price of the proxy fuel in the 2016-2020 period would be

-0.25.

The following table outlines the technologies subsidized and which federal budget items the subsidies were intended to represent. The technologies were chosen as a rough approximation of the types of low carbon technologies that could receive support due to federal funding commitments. The number of technologies subsidized and the subsidy amounts were chosen judgementally considering the nature of the funding commitment and so that the total amount of funding used up by the model was reasonable, taking into consideration that 1) in many instances these technologies will be adopted but federal funding will not be provided to the adopter, 2) in some cases federal funding will be provided to adopters who would have adopted the technologies in the absence of the funding (free-rider effect), and 3) some portion of the funding amounts will go to purposes other than direct technology subsidies. My assumptions erred on the side of being generous in terms of the degree to which federal funding will translate into direct technology subsidies.

Sector	Federal Budget Items Represented	Subsidy Amount (% of technology's levelized costs)	Technologies Subsidized
Electricity	- Low carbon economy fund/ Pan-Canadian Framework on Clean Growth and Climate Change: support provincial actions that reduce ghgs ($2 billion over 2 years) - Clean tech activities by regional development agencies ($100 million annually) - Off-grid renewable energy projects in northern communities reliant on diesel ($10.7 million over 2 years)	30%	biomass, solar, geothermal, wind, run of river hydro, carbon capture and storage
Personal Transportation	- Alternative fuels infrastructure investment ($62.5 million over 2 years) - Tax breaks for EV charging stations and electrical energy storage ($19 million over 5 years)	5% (of capital and operating costs)	electric vehicles and plug-in hybrid vehicles

Residential	- Energy & water efficiency retrofits for social housing ($573.9 million over 2 years) - Funding for municipalities to address climate change – ghg reduction, assessing local climate risks, asset management plans ($75 million)	25%	low flow hot water devices, solar panels, LEED building shells, heat pumps for water and space heating
Commercial	- Federal infrastructure investment: repair and retrofit government properties and buildings, greening government operations ($2.1 billion) - Post-Secondary Institutions Strategic Investment Fund: infrastructure projects that enhance and modernize facilities and reduce ghgs/improve sustainability ($2 billion over 3 years) - Green Municipal Fund: innovative municipal green infrastructure projects like Halifax's Solar City and net-zero library in Quebec ($125 million over 2 years)	50%	heat pumps for HVAC; building shells: LEED Gold and Silver for Information and Cultural Services and Arts Entertainment and Recreation (all provinces to represent municipal funding), Education (all provinces to represent university funding), and Offices (in Ontario only to represent government building upgrades)
Oil and Gas	- Low carbon economy fund/ Pan-Canadian Framework on Clean Growth and Climate Change: support provincial actions that reduce ghgs ($2 billion over 2 years) - Developing cleaner oil and gas technologies ($50 million over 2 years)	20%	more efficient extraction processes with leak detection and repair, efficient natural gas boilers, efficient compressor engines and gas turbines