Modeling Policy Pathways to Carbon Neutrality in Canada

by

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Abstract

The Canadian government has made commitments to transition Canada to a carbon neutral economy by 2050, but to date have yet to announce a policy pathway to achieve its goal. This study uses the CIMS energy-economy model to assess two policy packages that could help Canada achieve carbon neutrality by 2050: one focusing on carbon pricing and the other on flexibly designed regulations. Each were modeled in two scenarios, which represented different levels of global climate action. Both policy packages are likely to achieve significant emissions reductions, though reductions will likely come from different sectors of the Canadian economy depending on how aggressively the rest of the world acts on climate change.

Keywords: climate policy; carbon neutral; energy-economy modeling; energy; economics

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CCS	Carbon Capture and Storage
DAC	Direct Air Capture
EITE	Emissions Intensive and Trade Exposed
EV	Electric Vehicle
GHG	Greenhous Gas
HDRD	Hydrogenation Derived Renewable Diesel
OBPS	Output Based Pricing System
RPP	Refined Petroleum Product

Chapter 1. Introduction and Background

Over the last several decades the dangers associated with climate change have become increasingly clear and the need for action ever more pressing. While natural cycles continually shift global climate regimes, the anthropogenically driven changes earth's climate is currently experiencing are unprecedented in modern times. These recent changes are largely driven by the burning of fossil fuels which release greenhouse gasses (GHGs) into the atmosphere, creating a warming effect. Scientific assessments by the Intergovernmental Panel on Climate Change (2018) indicates this warming leads to a number of disastrous effects including species extinction, increased risk of forest fires, and the disappearance of polar ice sheets. Prompted by these dire warnings many countries, including Canada, have committed to cutting GHG emissions.

During the 2019 Canadian federal election, the Liberal Party of Canada (2019) pledged to introduce legislation that would ensure Canada achieves carbon neutrality by 2050, meaning that any residual emissions in that year would be completely offset by processes that extract emissions from the atmosphere. Few nations have put themselves on a course towards carbon neutrality and there is no beaten path Canada can follow to achieve this promise. For a country with emissions per capita in the top 20 worldwide, this will be no small feat (World Bank, 2019). Carbon neutrality will require a concerted effort that addresses all aspects of the Canadian economy and takes international policy developments into consideration.

In 2016, Environment and Climate Change Canada released the Pan - Canadian Framework on Clean Growth and Climate Change, which outlined a plan intended to help Canada reduce greenhouse gas (GHG) emissions in 2030 by 30 percent as compared to 2005 levels. Policies within the framework include emission pricing, the phase-out of coal from use in electricity generation, and clean fuel standards in transportation. As of 2017, Canada had managed a 2% reduction below 2005 levels (Environment and Climate Change Canada, 2020a). While these gains may seem small, it will take time for their full effects to play out and current emissions may have been significantly higher without some of the more important policies that have already been implemented. For example, the phase-out of coal for electricity generation in Ontario, completed in 2014, has contributed significantly to the province's 22% reduction in emissions compared to 2005 levels (Environment and Climate Change Canada, 2020a). However, emission increases from the oil and gas (23%) and transportation (7%) sectors have wiped out much of the gains. Figure 1 shows emissions from the different economic sectors in Canada from 1990 through to 2018.

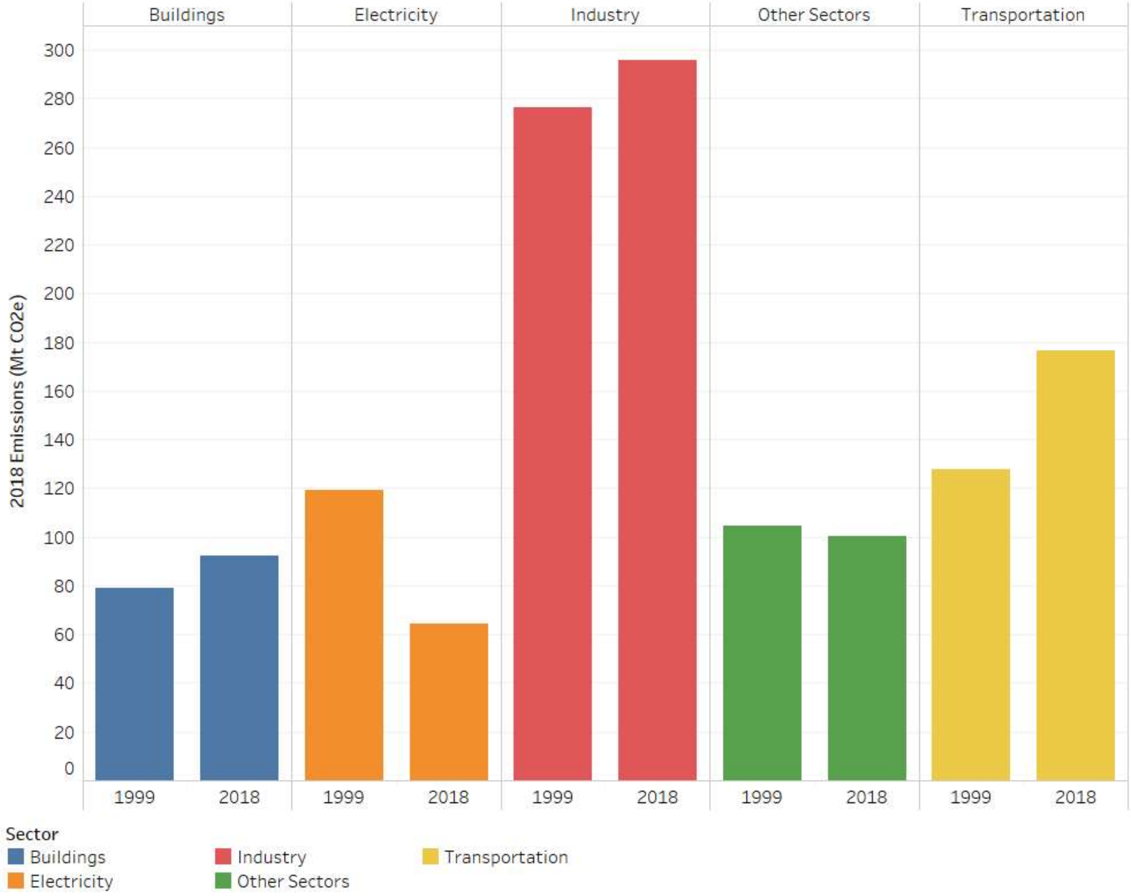

Figure 1: Canadian GHG emissions by sector in 1990 and 2018

There are important differences in the economic sectors that produce GHG emissions in Canada, with a portion of emissions being tied to domestic consumption and others to emissions-intensive trade-exposed (EITE) industries that compete with foreign firms for sales of their products in Canada and foreign markets. Non-EITE emissions are those produced by the commercial, residential, transportation, and electricity sectors while EITE emissions come from industries including the petroleum, mining, and manufacturing sectors. Emissions produced by non-EITE sectors should be addressed differently than those produced by EITE sectors as any increases in the cost of exported products could cause their production to leave Canada for jurisdictions with weaker climate policies, in what is known as carbon leakage (Aichele & Felbermaer, 2015). This would not only hurt Canada economically but may not decrease global emissions if production shifts to a jurisdiction with an equal or greater carbon intensity. This makes decreasing emissions for EITE sectors challenging, especially without a global coalition of countries acting together on climate change.

The difference in emissions between economic sectors reflects the regional resource heterogeneity in Canada. Some provinces, such as British Columbia, are naturally endowed with huge amounts of non-emitting hydropower, while others, like Alberta, have access to some of the largest reserves of hydrocarbons in the world (National Energy Board, 2018). This access to resources has shaped the development of their economies and energy systems, leading to the dramatically different levels of emissions illustrated by Figure 2. Because of this divide, the burden of reducing emissions on the path to carbon neutrality will fall disproportionately to those regions that rely most heavily on fossil fuels. To further complicate the matter, this issue has spilled into the political sphere and generated disagreement regarding how emissions should be reduced.

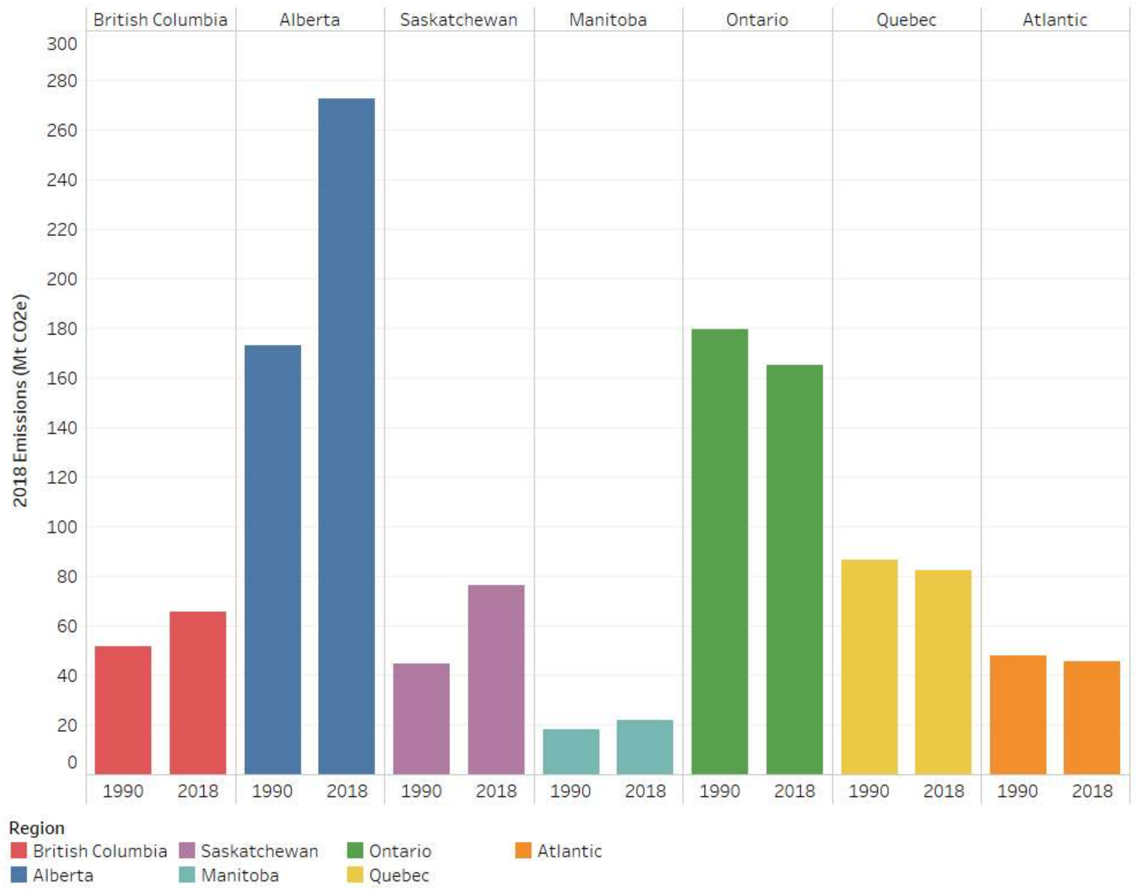

Figure 2: Canadian GHG emissions by province in 1990 and 2018

If Canada is to achieve carbon neutrality by 2050, one of two things need to happen: a) the emission of all GHGs in Canada must stop, or b) for every tonne of GHGs Canada emits, one tonne will need to be captured and stored underground in what is known as carbon capture and storage or offset in another way. While neither of the scenarios is impossible, it may prove very difficult to eliminate all emissions by 2050, since some regions of Canada, such as Alberta, rely heavily on fossil fuels energy sources. Recent investment into direct air capture technology has also dramatically reduced costs in recent years and could prove to be an important aspect of decarbonization efforts (Keith, et al., 2018). Of course, without any policies inducing the switch to low carbon technology, the role of carbon capture and storage and offsets would be limited to a select few situations. The following section will outline some of the policy options available to ensure emissions reductions occur.

1.1. Evaluating Policies

When selecting and implementing policies, it is important to remember that they are not all created equal. Policies vary across a variety of criteria including a) economic efficiency, b) environmental effectiveness, c) political acceptability, and d) administrative feasibility. An economically efficient policy will achieve emissions reductions at close to the lowest cost per tonne. These policies are generally broad-based and allow for flexibility in how they are met, which allows emitters to make reductions in the way that is the lowest cost for them. Environmental effectiveness refers to the ability of a policy to reduce emissions to the desired level. Policies that do well on this criterion generally act directly on pollution through either taxes or regulations. Policies that do poorly on this criterion, such as information programs, provide no economic incentive to reduce emissions. Political acceptability is how popular or unpopular the policy is with the general public. This is an important criterion, as politicians are unlikely to implement significantly unpopular policies and, even if they do, subsequent administrations may repeal them to appease voters. Policy continuity is especially necessary to address long-term problems like climate change, as the shift to a zero-emission energy-economy system will take decades. To enhance continuity, policies should also be designed in a way that makes them robust and less at risk of repeal should political leadership change. Administrative feasibility refers to the ability of the government to implement a policy and consists of two important parts. The first is jurisdictional, which means any proposed policy must fall within the powers of the government implementing it. Since achieving net zero is a federal initiative, most of the policies outlined in this study fall within federal jurisdiction, although important provincial ones are also included. The second important part is the capability of the government to effectively implement the policy. Emissions reduction policies that are similar to functions the government already performs are more administratively feasible to implement.

1.1.1. Carbon Pricing

Carbon pricing is either cap-and-trade or carbon taxes and is often touted as the most economically efficient means of reducing carbon emissions (Canada’s Ecofiscal Commission, 2019). These mechanisms fall into a category known as Pigouvian pricing, which is designed to correct for the effects of negative externalities (Sandmo, 2008).

Pigouvian pricing is used when the consumption of a product or service inflicts harm on a third party to the transaction and is not accounted for in the market price. This results in the over-consumption of the good or service compared to what is socially optimal. Adding a tax will increase the market price and decrease demand to a more socially optimal level. In this case, any good or service emitting GHGs during its use or production would be subject to such a tax.

Research shows that increasing the cost of emitting GHGs through carbon pricing is effective at reducing emissions and has shown promise in British Columbia (Murray & Rivers, 2015). While emissions have not fallen since the tax was first implemented, they would have likely been even higher without it. Rather than signaling carbon pricing is ineffective, this indicates the carbon tax needs to be raised for emissions to be reduced. However, raising carbon taxes to the point where they are stringent enough to cause substantial decarbonization may be difficult, as evidence has shown carbon pricing to be unpopular even at low levels (Rhodes, Axsen & Jaccard, 2014). This makes it a daunting prospect for any government to rely on carbon pricing for the bulk of its emissions reductions, especially over the several election cycles needed to achieve carbon neutrality.

While carbon taxes tend to be unpopular, steps can be taken to make them more robust and resistant to repeal. For example, British Columbia’s carbon tax was designed to be revenue neutral, with revenues generated by the tax being offset by cuts to personal and business income taxes. (Murray & Rivers, 2015). In the event an incoming government wanted to repeal this carbon tax, they would have to either increase taxes or make budget cuts elsewhere, or run a budget deficit, which may prove unpopular. So, while the carbon tax itself is not popular, its revenues are used in a way that may make the policy more politically resilient.

Under a carbon tax, every tonne of GHG emissions is taxed at a uniform rate, but in an internationally integrated economy, such as Canada, this may not be feasible for EITE industries. These industries, including steel, iron, cement, and chemical production, are sensitive to increases in the pricing of GHGs. Even modest increases in the price of emissions could hurt these industries’ international competitiveness and may result in production shifting out of Canada to other judications that have weaker carbon policies in place, creating carbon leakage (Aichele & Felbermayr, 2015). An output-based pricing system (OBPS) attempts to prevent leakage by allocating companies credits for a specified level of emissions based on how emissions-intensive their production process is compared to the industrial average (Bohringer et al., 2017). Companies that emit less than their allotment are allowed to sell their credits to those who emit over the limit, which provides an extra incentive for them to reduce emissions. Companies that emit more than the limit must either pay the carbon price on emissions over the limit or purchase credits. The allotment is then gradually decreased over time to ensure industries are continually reducing emissions. The result of this system is the marginal cost of the carbon price is preserved, but the average carbon price paid by all companies in the sector is lower due to the allocated credits.

OBPS style policies exist both on the federal and provincial levels in Canada and have been implemented by parties across the political spectrum, with early Canadian examples of the policy being introduced by a politically conservative party in Alberta (Government of Alberta, 2021). While they have been successfully implemented, this does not mean these systems have been effective at reducing GHG emissions. Despite implementing its own OBPS in 2004, and having differing versions of it in place since, emissions from Alberta industries have continued to rise (Environment and Climate Change Canada, 2020a). Rather than indicating OBPSs are ineffective policies this seems to suggest higher stringencies are needed to achieve meaningful emission reductions. An OBPS fares similarly to carbon pricing on all criteria, except it appears to be more politically acceptable than traditional carbon pricing. However, this may be due to a general lack of awareness of the policy rather than actual public support of it or the weak stringencies at which they have been implemented so far, and the fact that the policy only applies to corporations and not voters.

1.1.2. Regulations

Compared to carbon pricing regulations tend to be less economically efficient, although this varies depending on how they are designed (Liu et al., 2014). Prescriptive regulations are inflexible in how they are met and include policies such as the mandated use of a specific technology. Flexible regulations allow the regulated party to choose how to meet the requirement. This includes policies such as those requiring that a certain amount of electricity generated in a region be from non-emitting sources but allowing firms to decide how this is met. The distinction between these two types of regulations is not a sharp divide, and so it is better to think of them as two ends on a spectrum rather than separate entities.

Flexible regulations are commonly used in climate policy regimes, including Canada's and California's (Jaccard, 2020; State of California, 2019). The Clean Fuel Standard, which is under development in Canada, provides a good example of a flexible regulation (Environment and Climate Change Canada, 2019). The goal of the program is to decrease the life cycle carbon intensity over time of carbon emitting fuels used in Canada. Each fuel regulated under the Clean Fuel Standard has a benchmark life cycle carbon intensity set; flexibility is provided by using a credit trading system that awards producers whose fuels fall below this benchmark with credits that can be sold to producers who do not meet it. Producers who wish to reduce the carbon intensity of their fuels can go about it in a number of ways including blending low carbon fuels, such as biodiesel, with their product or lowering the emissions of the production process – in other words, reducing emissions anywhere in the entire life cycle of the form of energy. For example, a refinery producing gasoline and diesel could equip their natural gas boilers with carbon capture technology and store the CO2 underground to lower the lifecycle emissions of their products.

In contrast, regulations like those requiring catalytic converters be installed in vehicles allow little in the way of flexibility as each vehicle must meet an exact specification before it can go on sale. A prescriptive regulation such as this may be less economically efficient than more flexible ones. But as a system, it does still have appeal. In the case of catalytic converter installation, it may be more administratively feasible to simply set requirements rather than trying to institute a more complicated credit system or some other flexible regulation.

The low visibility of costs is one of the greatest strengths of both flexible and prescriptive regulations and gives them a leg up over carbon pricing in the criterion of political acceptability (Harrison, 2012). Regulations not only tend to be less unpopular with the general public than carbon pricing measures, but they also are perceived as being more effective (Rhodes, et al., 2016). This holds true most of the time, but governments should be careful when implementing regulations, as describing them with language that can be interpreted as restrictive significantly hurts their popularity (Cherry, Kallbekken & Kroll, 2011).

1.1.3. Offsets and Carbon Capture

A carbon offset is a credit purchased by one party from another with the agreement the seller will decrease their emissions by a specified amount. For example, someone who flies with an airline and wishes to offset the emissions from their flight may purchase carbon offsets from owners of forested land with the agreement that the trees on it will not be cut down. On paper, this sounds like a good idea for reducing carbon emissions, however, it falls victim to problems, which potentially dramatically reduces the effectiveness of offsets (Bushnell, 2012). The first of these problems is the difficulty of determining whether or not pollution would have occurred if the offset was not purchased. In the case of the forest, the owner may never have intended to cut it down but sells offsets anyway. The second problem has to do with maintaining the offset. For the preservation of a forest to be an effective offset, there has to be some way to ensure it is preserved in perpetuity. If it was cut down after a few years, the offset would be negated.

While most types of carbon offsets suffer from significant problems one type, direct air capture (DAC), presents an alternative that may prove an effective tool in achieving carbon neutrality. DAC works by removing carbon dioxide from the ambient air. Carbon capture and storage (CCS) is a similar process to DAC, although emissions are instead removed at the point of emission, such as coal-fired power plants. When DAC and CCS are used in combination, captured emissions can be sealed in underground geological formations, which makes the process carbon negative, and can be used as a permanent offset (Szulczewskia, MacMinn, Herzog & Janues, 2012). If DAC was used as part of a carbon offset program, it could offer a useful method for negating the effects of emissions from areas of the economy that prove expensive to decarbonize. Currently, costs for this technology are still high, although it is an area of ongoing research and has attracted the interest of high-profile investors such as Bill Gates (Brigham, 2019).

1.1.4. Subsidies

Compared to other environmental policies, subsidies are quite popular among voters and it is easy to see why (Cherry, Kallbekken & Kroll, 2011). Rather than punishing consumers for carbon emissions, subsidies reward those who take steps to lessen their environmental impacts with monetary compensation in the form of rebates or tax credits. This does not mean though, that they are effective or efficient at reducing greenhouse gas emissions, as they end up suffering from the free-rider problem. The intention of subsidies is to induce GHG emission reductions by paying people to take actions they would otherwise not have, like buying an electric car or using a more efficient home heating system. The problem arises when the government has no way of knowing who would have changed their behaviour in the absence of the subsidy and ends up paying anyone who takes the action. Those who would have reduced their emissions without the subsidy, but still receive compensation, are known as free riders and can capture over half of the total amount paid out by the government (Alberini, Gans & Towe, 2016). To further complicate matters, the funding for subsidies has to be paid by the government in some way, which often leaves only the unsavoury options of cutting spending in other areas, taking on debt, or raising taxes.

1.1.5. Border Carbon Tariffs

Climate change is a global problem requiring long-term collective action to address. Nations unilaterally enacting emissions reduction policies can help to slow temperature changes, but these measures are unlikely to achieve meaningful results unless there is universal global participation. There are also problems when acting alone, as measures like carbon taxes can raise the cost of production for companies and may result in carbon leakage. Even when a country successfully reduces emissions, other countries cannot be excluded from enjoying the improved atmosphere, which encourages free riding. Thus far, voluntary international pacts like the Kyoto Accord and Paris Agreement have failed to reverse the trend of increasing global emissions. This must happen soon if the warming of the planet is to be kept to 1.5 or even 2 degrees above pre-industrial levels (Intergovernmental Panel on Climate Change, 2018).

For countries disillusioned with the ineffectiveness of global agreements, an alternative exists in carbon tariffs. These tariffs can be implemented by jurisdictions that have rigorous climate plans and would be imposed on imports from countries that have weaker emission reduction measures in place. This will raise the cost of imports from jurisdictions without stringent climate policies and allow local industries to compete on even footing. Countries with sufficiently strict climate measures in place would be exempt from paying this tariff, which provides laggard countries with incentives to reduce their emissions (Morris, 2018). Currently, no country has a border carbon tariff in place and there is some uncertainty on whether this would violate World Trade Organization rules (Condon & Ignaciuk, 2013). However, there are indications the European Union is considering the measure and it may be implemented in the coming years (von der Leyen, 2019).

1.2. The Transition to Carbon Neutrality

There is currently little work detailing the policy stringencies Canada may need to reach carbon neutrality by 2050, despite indications the federal government will implement legislation ensuring this occurs. This gap in the literature provides an opportunity for my work to meaningfully contribute to the conversation going forward. While there is a lack of studies looking directly at the policies needed for Canada to achieve carbon neutrality by 2050, there are several studies looking at the possible technological pathways (Bataille et al. 2015; Canadian Institute for Climate Choices, 2021; Government of Canada, 2016; Langlois-Bertrand et al., 2018; Trottier Energy Futures Project, 2016). These five studies offer differing views of what the future may hold, although there are some important commonalities I will discuss below.

1.2.1. Widespread Electrification

It could be argued the most important trend observed across these deep decarbonization studies are the changes occurring in electricity generation and use. There are two important aspects: the decarbonization of the electricity sector itself and the electrification of Canadian energy demand.

Bataille et al. (2015) note the Canadian electricity sector is already less carbon intensive than the average of the countries that comprise the Organisation for Economic Co-operation and Development. In all five studies, areas where electricity generation is carbon-intensive could see their emissions fall as GHG emitting facilities are either replaced by low carbon alternatives, such as renewable and nuclear, or retrofitted with CCS. The Canadian Institute for Climate Choices (2021) views hydroelectric, solar, and wind resources as “safe bets” to replace emitting technologies, meaning they are likely to be significant substitutes in all scenarios[1]. Currently, Alberta and Saskatchewan have carbon intensive grids, but also access to some of the largest unexploited wind and solar resources in the country that could be used to replace existing coal and natural gas generation (Government of Canada, 2016). The replacement may be especially rapid for coal, which in most studies is removed from the electricity generation mix earlier than natural gas facilities and sees a total phase-out by 2050 (Langlois-Bertrand et al. 2018; Trottier Energy Futures Project, 2016). Natural gas combined-cycle units equipped with CCS could persist longer than coal according to these two studies, although they only make up a maximum of 5% of total generation in net-zero cases. The demise of coal generation is an extension of a current North American trend, which has seen the share of electricity provided by coal generation drop in both the United States and Canada because of policies and relative costs (Canada Energy Regulator, 2019; United States Energy Information Agency, 2020).

As GHG producing fuels such as diesel, gasoline, and natural gas are phased out of the energy mix, electricity may replace them in functions such as home heating, passenger transport, and some industrial thermal applications (Bataille et al. 2015). The increased demand has the potential to be so large that the Trottier Energy Futures Project (2016) estimates net-zero could require a three-fold increase of Canadian electricity supply. As of 2018, approximately half of Canada relied on electricity for home and commercial heating, with natural gas providing a similar amount of energy to these sectors (Langlois-Bertrand et al. 2018). Net-zero scenarios in all five of the studies discussed is this section find that natural gas' share may shrink to near zero, being largely replaced by electricity. However, the Canadian Institute for Climate Choices (2021) notes that replacing natural gas with biomethane in buildings could accelerate the decarbonization of the building sector compared to relying on electrification alone.

Electrification is also projected to play a large role in decarbonizing the Canadian transportation sector. As of 2019, over half of the energy consumed by the transportation sector was supplied by gasoline with much of the rest being split between other refined petroleum products, such as diesel and aviation fuel (Canada Energy Regulator, 2020).

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[1] The Canadian Institute for Climate Choices (2021) categorizes the climate solutions in their study as either "safe bets" or "wild cards". Safe bets are solutions that have already seen use in some places and face no scalability problems. Wild cards are solutions whose future is more uncertain and are either in the early stages of development or may face issues to scalability.

As the transportation sector decarbonizes, the five net-zero studies I reference all project electric vehicles (EVs) could be important in replacing gasoline motors. The Canadian Institute for Climate Choices (2021) study gives a range of how much market share could be captured by EVs which varies from 47% to 96% across their cases. Langlois-Bertrand et al. (2018) project the penetration of EVs may rise above 80% of market share with the Bataille et al. (2015) analysis estimating they could reach 100% by 2050. Where EVs do not reach 100% market penetration, the remaining share could be captured by internal combustion engine vehicles using biofuels or hybrid gasoline-electric vehicles.

The Government of Canada (2016) notes that about 70% of emissions in the industrial sectors come from the combustion of fossil fuels for heating purposes in boilers and furnaces. Electrification is possible in these areas, as heat pumps and electric furnaces can be used as substitutes for low-temperature technologies fueled by coal or natural gas in many situations. Other processes, such as the production of steel, can move away from GHG intensive methods and use low carbon options, such as electric arc furnaces (Bataille et al. 2015).

1.2.2. Uncertainty Around Carbon Capture and Storage

Different studies surrounding deep decarbonization in Canada tend to vary significantly in their projected use of CCS technology. The report by the Trottier Energy Futures Project (2016) does not project CCS to play a role in Canadian decarbonization, noting the abandonment of many CCS pilot projects and the cost overruns associated with the Boundary Dam coal CCS project in Saskatchewan. Other reports are more optimistic on the prospect of CCS contributing to Canadian decarbonization, with Bataille et al. (2015) stating it could play an important role, especially in industrial sectors. In this study, the authors suggest CCS may be used in a number of industrial applications including to capture carbon dioxide produced alongside natural gas and oil in the hydrocarbon extraction sector. It could also play an important role in other industrial sectors, such as the cement and chemical sectors, where emissions are released through chemical reactions during production. These process emissions are often harder to reduce as they may be tied to a critical step of the production process where no low-emissions substitute exists at a comparative cost.

The Canadian Institute for Climate Choices (2021) is quite optimistic on the role of CCS, considering it one of its safe bets, when used on concentrated emissions sources. Its report also notes captured carbon could be used to produce useful products such as concrete in what is know as carbon capture and utilization. The Government of Canada (2016) study finds CCS might play a similar role in the industrial sector, as well as in the decarbonization of the electricity sector. Most of the electricity sector CCS in the study is tied to natural gas generation facilities rather than coal, as it was determined to be too costly for the latter. Of the five studies detailed here, none go into great detail on the potential role of bioenergy carbon capture and storage (BECCS) in Canadian decarbonization, although it is touched upon briefly in the Canadian Institute for Climate Choices (2021), Government of Canada (2016), and Langlois-Bertrand et al. (2018) studies. While focusing on the global system rather than Canada's, recent work produced by Buntar et al. (2020), asserts BECCS may play an important role in global decarbonization.

1.2.3. Different Pathways to Freight Decarbonization

Unlike the personal transportation sector, which could rely on electric vehicles (EVs) for most emissions reductions, the studies referenced here are mostly in agreement that EV trucks are unlikely to play a large role in a decarbonized freight transportation sector. This is due to the relatively low energy density of currently available EV batteries, meaning they would have to be scaled up to an unfeasible size in order to deliver the same range as those offered by internal combustion engine vehicles. Of the five examined deep decarbonization studies, only Langlois-Bertrand et al. (2018) projects electric trucks could capture the majority of the market share. Other reports suggest this market share could be split between hydrogen and biofuels, although there is variation between cases within the studies. This uncertainty is highlighted by the Canadian Institute for Climate Choices (2021) who project hydrogen fuel cell freight trucks could capture between 36% and 64% of the market share, with internal combustion engine vehicles accounting for most of the rest. The Trottier Energy Futures Project (2016) is less optimistic on the future of hydrogen vehicles, with a possible 33% of freight energy consumption coming from hydrogen and the rest split between biofuels and fossil fuels. Hydrogen uptake varies significantly in the Government of Canada (2016) study across cases with different cost assumptions leading to hydrogen possibly capturing a maximum of one-third of the total market share by 2050 to 5% at the minimum. The Bataille et al. (2015) study does not give a precise estimate of how large of a role hydrogen might play in the decarbonization of the freight sector, but it is implied to be smaller than that of biofuels.

1.3. Need for Analysis

The transition to carbon neutrality by 2050 will require drastic changes to the Canadian economy and a re-evaluation of current climate policies. Previous outlooks on Canadian deep decarbonization have shown understandable disagreement on how this can be achieved, as 2050 is a long-range projection with many unknown variables. Current research has mainly focused on what the technology and energy mixes may look like in a carbon-neutral future, rather than on the level of policy stringencies needed to hit those targets. The purpose of my research is to address this gap and develop policy packages that can achieve carbon neutrality in Canada by 2050.

Without this type of guiding research, governments run the risk of implementing ineffective or needlessly costly policies. In the absence of energy-economy modeling, it may be very difficult for policymakers to know whether their policies are likely to achieve the desired levels of emissions reductions. This can be further clouded by well-funded interest groups who advocate for rules designed to their benefit or advocating for voluntary self-monitoring programs[2]. Without proper policy modeling, overlapping policies may also be implemented. Overlapping policies may seem to be effective reduction strategies at first glance, but are rendered mostly or completely ineffective by existing regulations. Recent research has explored this policy overlap problem and found it may serve as a barrier preventing the Clean Fuel Standard from achieving the promised emission reductions (Hoyle, 2020).

An additional benefit of energy-economy modeling is that it can help to quantify the cost of various emissions reduction policies. Without it, well-meaning politicians run the risk of implementing policies able to achieve significant emissions reduction, but that come at significant economic costs. These inflated costs may not only hurt economic

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[2] Professor Mark Jaccard discusses effects of industry lobbying and the problems of voluntary policies in Chapter 5 of his book *The Citizens Guide to Climate Success: Overcoming Myths that Hinder Progress* (Jaccard, 2020)

development, but could also result in backlash against the environmental policies. In turn, this could result in their repeal by a successive government that may be less willing to implement effective climate policy.

To guide the design of the policy packages in this study, I referenced work by Jaccard, Hein, & Vass (2016), who simulated how two different policy packages may be used to achieve emissions reductions in line with Canada's Paris commitments. In their study, two cases were used to simulate how policy may induce emissions to fall 30% by 2030 compared to 2005 levels. The first of these was a case which relied on carbon pricing to drive the majority of reductions and was intended to illustrate an economically efficient reductions path. The second was a flexible regulations case designed to achieve the same 2030 economy-wide target, with reductions mimicking those achieved in the carbon tax scenario, where possible. This was done to illustrate that emissions reductions can be achieved in a way that is both politically acceptable and economically efficient.

The intent behind my work is the same as Jaccard, Hein, & Vass (2016), and I follow the same blueprint laid by their study in an effort to provide two policy pathways that are able to achieve carbon neutrality in Canada by 2050. Through this research, the following questions are examined:

1. What are the needed policy stringencies to ensure Canada reaches carbon neutrality by 2050?
2. What are the differences in needed policy stringency if Canada is acting alone in addressing climate change compared to acting as part of a global effort?
3. What impact does the status of global climate action have on the emissions from the different sectors of the Canadian economy?
4. Which sectors offer the cheapest decarbonization options, and which are the most expensive?

Chapter 2. Methods

2.1. Overview of the CIMS Model

The model chosen for this project was CIMS. CIMS is an energy-economy model developed in the Energy and Materials Research Group at Simon Fraser University under the supervision of Professor Mark Jaccard (Jaccard, 2009). The model is designed to show how stocks of energy-using and energy-producing technologies change over time in response to changing market conditions. Differing conditions include changes in energy prices, availability of new technologies entering the market, and the introduction or removal of government policies. For my research, a national scale version of CIMS was used, which groups Canada into seven separate economic regions: British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, and the Atlantic Region and Territories. The Atlantic provinces and Territories are grouped together due to their smaller energy and emissions profiles compared to the other Canadian provinces.

Individual regions are further broken down into economic sectors that either demand or supply energy. Demand sectors in CIMS output non-energy goods and services, such as transportation, housing, and industrial products. Energy inputs for these sectors are either provided exogenously through a specified price curve or by a supply sector. Prices that are set on international markets, such as the price of crude oil, can be set exogenously while those that are set at a provincial or near provincial level are calculated endogenously through supply sectors. Supply sectors produce energy products used by demand sectors and other supply sectors. In the version of CIMS used for this research, the supply sectors are the biodiesel, electricity, ethanol, and hydrogen sectors.

2.1.1. Market Share and Capital Cost Equations

Using capital stocks calibrated to a base year, which is currently set to 2000, CIMS simulates how these stocks change over time in five-year simulation periods from 2005 until 2050 (EMRG, 2007). The first main factor that determines the evolution of this stock is the demand for new technologies, which is calculated at the beginning of every simulation period. To find new demand, old technologies are retired and removed from the existing capital stock, which is then compared to forecasted total demand to find the demand gap which needs to be met with new technologies. The second factor is the relative life cycle costs (LCCs) of the technologies competing to meet demand, with technologies that have lower LCCs capturing greater market share (MS) as described by the equation below:

Equation 1: CIMS market share equation

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

In Equation 1, MS is a function of the capital cost (CC), maintenance cost (MC), energy cost (EC), intangible cost (i), discount rate (r), average life (n), and market heterogeneity (v) of the technology (j).

- CC, MC, and EC represent the different financial costs associated with a technology.
- The r variable represents the time preference that consumers or firms have for money and places a greater weight on present cash flows and less on ones further into the future.
- The intangible costs captured by the i parameter represent all factors a consumer may take into account that are not captured by the other cost terms. This can include elements like familiarity with a product, risk preference, or visual appeal.
- The v variable in the MS equation represents the heterogeneity of the market. A lower value for v means the consumers in a market have a greater diversity in

preferences and each competing technology will be allocated a more equal market share compared to a higher v, all else constant[3].

The numerator of the MS equation represents the LCC of a technology to the power of negative v. The denominator of the MS equation takes the LCC every competing technology, puts it to the power of negative v, then sums them. This equation gives the relative MS each technology captures in a competition as a percentage.

The MS equation is solved for every demand node in CIMS to ensure total demand is filled by technologies. Once demand for all energy-using services is met, a total energy demand is calculated. This same MS allocation process is then applied to the supply side of CIMS, where technologies compete to fill the demand for energy. Through this competition, energy prices are calculated and are fed back into the demand side of the model, which adjusts the market shares of technologies based on the new prices. CIMS then iterates through this process until it reaches a cut-off point where market shares and prices only change a small amount with each iteration. CIMS then finalizes the energy prices and market shares and moves onto the next time period. Once CIMS has moved through all five-year periods, the run is completed and the simulation ends.

In the MS equation, the CC and i terms are not fixed and can change over time. Capital costs fall through innovations and operation improvements in technologies, as well as economies of scale. For example, prices of electricity generated from wind and solar have decreased significantly over the past decade due to improvements in technology and the scaling up of production (IRENA, 2019). Intangible costs fall as buyers become increasingly familiar with a technology, thereby lowering its associated risk perception. The declining capital cost equation (Equation 2) is of particular importance to this study and became important in defining the climate action scenarios created in this project.

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[3] See Appendix A, Figure A1 for illustration of the interaction between technology price and the v parameter.

Equation 2: CIMS capital cost equation

$$CC_t = GCC_t * \left[\left(\sum\nolimits_1^p \frac{CumulNS_{2000,p} + \sum_{j=2005}^{j=t-5} NS_{jp}}{CumulNS_{2000,p}} \right)^{log_2(PR)} \right]$$

In Equation 2, CC_t is the capital cost of a given technology in period t. GCC_t is the capital cost of a technology adjusted for cumulative stock in other countries. NS_{jp} is the new stock of a technology added from 2005 to the previous time period in each province, p. $CumulNS_{2000,p}$ is the cumulative new stock of a technology for all years up to and including the year 2000 in each province, p. PR is the progress ratio which is the amount cost should decrease in response to a doubling of cumulative production. The GCCt term has been adjusted for certain technologies in this study, which will be discussed later in the methods section.

2.1.2. Simulation Settings

CIMS has several important functions governing simulation behaviour that can be adjusted based on the needs of the modeler. One such function is energy supply and demand, which determines if output from selected sectors follows an exogenously specified trajectory or if they are endogenously calculated based on demand from other sectors. In my study, I turned this function on for sectors whose outputs I assumed would not be significantly influenced by international trade, as they were mostly confined to trade within Canada. These are the electricity, biodiesel, ethanol, and hydrogen sectors. Most of the electricity produced by the Canadian electricity sector is consumed within Canada. Although there are interconnections with grids in the United States that allow international trade to occur, I determined it was beyond the scope of this study to include international trade.

The production of the ethanol, biodiesel, and hydrogen sectors was set to be calculated endogenously because I assumed most of the future Canadian production of these low carbon fuels would be consumed domestically and exports would be minimal. Since these fuels still make up a small portion of the total liquid fuels consumed in Canada, production and emissions from these supply sectors could vary significantly from case to case depending on how much market share their fuels capture. By calculating the production from these sectors endogenously, I hope to get a better idea of the net emissions reductions achieved by fuel switching than I would if they were exogenously specified.

Prices for coal, oil, natural gas, and refined petroleum products (RPPs) were exogenously specified because these products are global commodities whose prices are set by international markets and not determined by Canadian demand. Along with the aforementioned fuels, I also set the price of biomethane and biomass exogenously. Biomethane and biomass may have benefited from endogenous price calculations for the same reasons as ethanol, biodiesel, and hydrogen, but the version of the model I used for this study does not have separate biomass and biomethane sectors to simulate these dynamics. The exogenous prices set for all the above fuels do not include carbon pricing, which is added as part of my scenario parameters.

Many of the goods produced in Canada are exported internationally and are subject to competition from other jurisdictions. This competition is captured by Armington elasticities, which are parameters that describes how readily similar products, produced in different countries, are substituted with one another. Armington elasticities help in simulating the effects of policy on international trade as measures like tariffs and taxes can create price changes which in turn affect demand (Welsch, 2006). These elasticities are presented as ratios and describe how much the demand for a product changes based on a 1% change in price. For example, the Armington elasticity for bricks produced in Canada may be -0.15, which means that for every 1% increase in price, demand for that product would fall by 0.15%. Some of the policies I have implemented in this study impact these internationally traded goods, especially in EITE sectors. Since these policies have the potential to increase the production costs of these products, we should not expect demand to stay the same.

Sectors existing within Canada are also subject to similar elasticity dynamics even though they are not traded on a global market. To illustrate this effect, I chose to turn on macroeconomic feedbacks. These are not general equilibrium feedbacks and do not simulate how investment or employment may change in response to policy, but rather partial equilibrium effects that make adjustments across sectors (Bataille et al., 2006; Bergman, 2005). Demand from the building and transportation sectors have activity elasticities that respond to changes in manufacturing production, where a fall in manufacturing output leads to a fall in building and transportation demand. A fall in manufacturing output can be driven by either an exogenously specified fall in production or through the Armington elasticities reflecting the substitution of Canadian produced goods with foreign ones.

The revenue recycling function in CIMS was also enabled for this study. Revenue recycling works by returning all of the funds collected through emissions pricing and returning them to the sector they were collected from. This in effect means the price of the carbon tax is not included in the final output cost calculations, which is instead only based on the lifecycle costs of each technology in that sector and how much market share it captures. However, the market shares captured by each technology within that sector will still reflect the effects of the emissions price as emitting technologies will lose market share to low emissions technology, all else equal. In reality, governments may choose not to return carbon tax revenue to the sector it was collected from and spend it elsewhere. So far, the federal government has implemented forms of revenue recycling in its policies, such as the climate action incentive payment which returns carbon tax revenue in lump sums to residents of provinces where the backstop carbon price is in place (Government of Canada, 2021). Another is the OBPS, which allocates credits to EITE industries to cover part of the cost they would otherwise have to pay for their emissions (Government of Canada, 2018).

Emissions pricing was implemented using the emissions charges function in CIMS which allows the user to specify how emissions should be priced in every five-year simulation period beginning in 2005. CIMS has the option to enter pricing for eight different types of emissions, though not all of these were utilized in this study. The amount a technology pays on emissions is calculated by multiplying the quantity of GHG’s emitted by that technology in the provision of a service by the specified emissions price in the current simulation year. This same calculation is done whether the emissions from a technology are positive or negative. If a technology has negative emissions, the price of those emissions will be subtracted from the cost of the technology rather than added. The result is negative emissions technologies receive payments for the emissions they store at a rate equal to the carbon price. Under a cap and trade system, this can be thought of as a mechanism whereby credits are generated by the sequestration of GHGs, which can then be sold for the credit market price.

CIMS also offers several ways for future carbon pricing to be accounted for in the market share equation. These are accessed through the GHG precognition function which can be set to either current, average, or discounting and set to begin at a specified year. Current means future carbon pricing is not taken into account in the market share equation and may reflect a situation where carbon pricing has not yet been announced. Average calculates the average cost of carbon emissions over the technology's lifetime, which assumes carbon pricing is taken into account when making purchasing decisions, but not in a perfectly rational way. Discounting takes the total cost of emissions over the lifetime of the technology and discounts them back to present values, representing the perfectly rational decision-maker. For this study, I used the average method, because I believe it represents more realistic purchasing behaviour than either of the other two options as it reflects some degree of consumer foresight of future carbon pricing when making decisions, but avoids having consumers act as perfectly rational economic actors. GHG precognition was set to begin in the 2021-2025 period, as beginning it earlier would cause choices made in the past to react to future policies.

2.2. Changes Made to the CIMS Model

Through the course of modeling how Canada might reach net-zero emissions by 2050, I made several changes to the CIMS model, which reflect the implementation of policies, changes in commodity prices, and new technologies entering the market. The following section will detail how I implemented these changes and what purpose they served.

2.2.1. Coal to Bioenergy with Carbon Capture and Storage

Despite progress being made towards decarbonization of the Canadian electricity grid, CO2 intensive coal plants still make up a sizeable share of the power generated in Alberta and Saskatchewan (Canada Energy Regulator, 2019). Many of these facilities still have years left of useful life, but are scheduled to shut down due to federal regulations. Instead of closing the plants, another option would be to retrofit them so they are fueled by biomass rather than coal. The carbon contained in biomass is taken from the atmosphere by organic plants (through photosynthesis), therefore the combustion of this fuel is considered carbon neutral. Although emissions may be generated when the raw plant material is converted into usable fuel if hydrocarbons are consumed in the production and transportation processes. In my modeling, I have provided an option for these coal plants to be retrofitted so that they are fueled by biomass equipped with CCS technology, known as bioenergy with carbon capture and storage (BECCS). This turns these coal plants, which were once a high emissions intensity electricity source, into emissions negative facilities. I did not include an option for these facilities to be retrofit to biomass without CCS.

As part of the Ontario government's initiative to phase out coal from its electricity generation mix, the Atikokan Generating Station and Thunder Bay Generating Station were converted from using coal to wood pellets (Cox, 2018). I used conversion costs of the Atikokan Generating Station to parametrize my model. In my modeling, I limited the amount of market share the converted plants could capture to the 2015 share of electricity generation provided by coal in each province to ensure the number of converted units is less than or equal to the number of coal plants currently available for conversion.

2.2.2. Biomethane and Biodiesel

To ensure there were as many realistic options for decarbonization as possible in my model I added the option to use biodiesel and biomethane in a number of different markets. I added the option to use biomethane into the residential and commercial sectors for home heating and the freight transportation sector as fuel for liquid natural gas engines. I added biodiesel to the agricultural sector as a low carbon alternative to diesel tractor fuel. Perhaps due to its current limited use, there are few detailed forecasts available for the price of biomethane. The prices used in this study were based on those charged by Fortis BC for biomethane (Fortis BC, 2021). Currently, Fortis BC biomethane prices are about double that of fossil fuel natural gas. I assume biomethane prices remain this high then gradually fall until they are one and a half times the price of fossil fuel natural gas by 2050 due to improvements in technology and economies of scale.

Since they are chemically identical, biomethane can be blended with natural gas in the current distribution system and even completely replace natural gas with no adverse effects. The blending of biomethane with natural gas for home heating is already available in jurisdictions such as British Columbia, where consumers can choose to offset up to 100% of the fossil fuel natural gas they consume with biomethane[4]. The option to use biomethane for residential and commercial heating also provides an important alternative to electrical heating which was previously one of the few low carbon options available in these sectors. While most of the natural gas consumed in Canada is currently sourced from fossil fuels, mandates such as those proposed under CleanBC seek to increase the blended share of biomethane through government regulations (Government of British Columbia, 2018).

Biodiesel currently makes up about 2% of the total diesel consumed in Canada, although its share has been growing on an annual basis (Wolinetz, Hein & Moawad, 2019). As Canada moves towards economy-wide decarbonization, this share may grow and biodiesel may become an important low carbon fuel source. My work added the option to use biodiesel as a fuel source in the agricultural sector. I also imported segments from other versions of CIMS that included greater detail in the biodiesel production sector. The option to use biodiesel in place of fossil fuel diesel was already in use in the personal and freight transportation sectors of CIMS.

Biodiesel in CIMS is broken down into two different types: conventional biodiesel and hydrogenation-derived biodiesel (HDRD), with the important difference between the two being their chemical composition. Conventional biodiesel is chemically similar but not a perfect substitute for fossil fuel-derived diesel, whereas HDRD is chemically identical to its fossil fuel counterpart. This means that in currently available diesel engines, HDRD can be blended up to 100% with fossil fuel diesel. Conventional biodiesel can only be blended in quantities of up to 20% before engine modifications need to be made (U.S. Department of Energy, 2020). In this study, I assume the diesel engines sold in Canada will be capable of running on higher percentage blends of conventional biodiesel through continuous technological improvement and the tightening of government regulation on freight motors. This dynamic was captured by phasing out standard efficiency diesel motors and replacing them with more advanced options.

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[4] When a customer chooses a biomethane blend this does not actually result in that blend being delivered to their homes. Instead, the amount of biomethane the consumer purchases will be blended into the delivery system and distributed to all homes connected to the main supply line. For example, if a residence chose a 100% biomethane option and consumed 10 GJ of natural gas in a month then an additional 10 GJ of biomethane would be blended into the distribution system.

2.2.3. Agriculture

While the version of CIMS used in this study is technologically detailed in most energy-using and emissions-producing sectors of the Canadian economy, its representation of the agriculture sector is limited. This is mainly related to non-energy emissions such as those produced by livestock. There are a variety of options for how the sector may be decarbonized on both the animal and crop production fronts, but the incorporation of those pathways is beyond the scope of this study (Aggarwal, et al., 2018). Instead, I have assumed the emissions from the agricultural sector fall at the same rate as emissions from the rest of the economy in each case in each 5-year period. This means if emissions were to fall by an average of 5% across all other sectors of the Canadian economy between 2030-2035, I would assume emissions from the agriculture sector also fall by 5% in the same period.

2.3. Scenarios

In this study, I have created three distinct cases that differ on their level of climate action and the types of climate policies implemented. Each of these cases has been modeled in two scenarios which represent different levels of global action on climate change: the Global Action scenario, which assumes the rest of the world tackles climate change along with Canada, and the Global Inaction scenario, which assumes Canada is acting alone. These two states of global climate action have important implications for how Canada may need to go about reducing its carbon emissions. I do not presume one of these two scenarios to be more likely than the other and, as such, I think it important to assess policies needed to achieve carbon neutrality under both sets of assumptions.

2.3.1. Oil Price and Production Assumptions

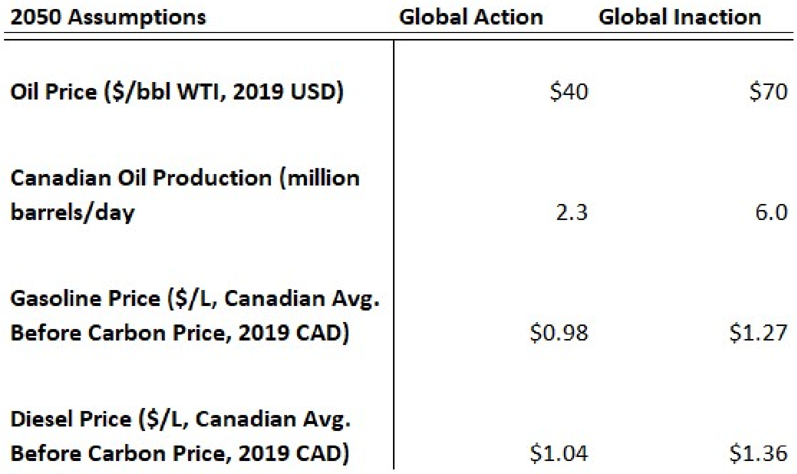
Perhaps the most important difference between these two global scenarios is in the global price of oil. The Global Inaction scenario assumes oil consumption proceeds as it has in the past with demand around the globe rising and continued demand for Canadian oil exports. This level of oil consumption is reflected in a higher global oil price, which stays constant at $70 per barrel US WTI from 2030 until 2050. The Global Action scenario assumes the trend of increasing oil demand is reversed and falls over time, resulting in a lower oil price. For my study, I have assumed this price to be $40 per barrel US WTI from 2030 until 2050. These oil price assumptions are based on the *Canada's Energy Future 2018* report (Canada Energy Regulator, 2018).

The differences in oil prices impact my model in two main ways: the difference in refined petroleum product (RPP) prices and oil production. RPPs include fuels such as gasoline, diesel, and fuel oil, which provide energy for many Canadian economic sectors. The price of these RPPs is in part determined by the price of crude oil, but also by refining, distribution costs, taxes, and other market factors, which leads to differential pricing even within provinces. For this project, I have calculated different RPP prices for each province, but I have assumed within provinces all RPP prices are the same. The RPP prices entered into the model include all provincial factors impacting prices but exclude any carbon pricing. This instead is applied and calculated endogenously within CIMS.

The differences in demand for oil and RPPs globally will not only impact the price Canadian's pay for their hydrocarbon derived fuels, but also the output of the Canadian oil sector. I assume oil-related sector output in the Global Inaction scenario is based on projections from *Canada's Energy Future 2018* and rises by 15% in 2050 compared to 2020 levels (Canada Energy Regulator, 2018). The increased production amounts to an extra 0.8 million barrels of oil produced per day, bringing total Canadian production to 6 million barrels per day, with Alberta alone accounting for 5.7 million barrels of daily production. Implicit in this assumption is that current pipeline export capacity constraints are relieved. These constraints have resulted in the Western Canadian Select, the benchmark for heavy oil produced in Alberta, trading at a significant discount to WTI and at times resulted in government-imposed oil production curtailments (Government of Alberta, 2021).

Due to supply and demand dynamics, lower worldwide demand for RPPs in the Global Action scenario is expected to significantly lower production from the Canadian oil sector. I have assumed production from the Canadian oil sector in 2050 will be half of 2020 levels, with production beginning to fall in 2025 and continuing to fall smoothly through to 2050. This results in Canadian oil production reaching 2.6 million barrels per day by 2050, which is similar to the levels seen in 2005. The projected production numbers are based on trigger prices estimated by Heyes et al. (2018), who found new oil sands mining would require a WTI price of $85 per barrel, and in-situ projects would need $58 per barrel WTI. With the price of WTI sitting well below both of these values in the Global Action case, I would not expect to see any capacity expansion of oil sands projects and the more expensive ones may even be shut in early. Table 1 summarises the oil-related assumptions I have made in my two scenarios.

Table 1: Oil production, oil price, and RPP price assumptions made in this study



2050 Assumptions	Global Action	Global Inaction
Oil Price ($/bbl WTI, 2019 USD)	$40	$70
Canadian Oil Production (million barrels/day	2.3	6.0
Gasoline Price ($/L, Canadian Avg. Before Carbon Price, 2019 CAD)	$0.98	$1.27
Diesel Price ($/L, Canadian Avg. Before Carbon Price, 2019 CAD)	$1.04	$1.36

2.3.2. Accelerated Cost Declines

As the world works together to reduce emissions in the Global Action scenario, the market for low carbon technologies is expected to get larger as their adoption becomes more widespread. Greater adoption would likely lead to faster declines in the cost of these low carbon technologies and drive more investment to help improve production techniques and create economies of scale. To illustrate this effect, I have increased the declining capital cost parameter for certain key technologies. Rather than including all the low emission technologies that may see faster cost declines under the Global Action scenario, I selected a few to cover areas of the Canadian economy. The chosen technologies were deemed to be the most suitable for my study, as they are not fully mature in their development leaving room for their costs to fall. At the same time, they are beyond the theoretical development stage and are proven to work, even if some of them have only seen limited adoption.

Electric vehicle (EV) cars are perhaps the most notable technology on the list, as they have caught much public attention in recent years due to the success of EV companies, such as Tesla, and their increasing rate of adoption. A major factor in this trend has been the rapidly falling EV costs in recent years, which could be further accelerated with the implementation of favorable climate policy worldwide (Lutsey & Nicholas, 2020). Much of the recent decline in EV costs can be attributed to the rapid improvements in battery technology, since most other components of electric vehicles are similar to those in those outfitted with internal combustion engines. While there are several different kinds of EV batteries on the market, the most prominent are lithium-ion batteries, which are used by EV many manufactures including Tesla, Nissan, and Chevrolet. Though popular currently, there is no guarantee lithium-ion batteries will retain top position as research into alternate battery chemistries may prove fruitful. In my modeling, I use a generic EV car that represents trends in EV battery cost in general, rather than having separate chemistries or EV components compete for market share. In the Global Action scenario, I have accelerated the exogenously specified part of the capital cost equation (GCC_t in Equation 2) which results in capital costs being 25% lower than in the Global Inaction scenario by 2050. EV cost declines are based on projections from the Rapid Advancement case of the National Renewable Energy Laboratory's (2017) *Electrification Futures Study*.

Since I have accelerated the cost decline of EV cars, I have also accelerated the capital cost decline of EV trucks, as they rely on the same battery technology. EV trucks are a zero-carbon technology serving as short-haul transportation in CIMS' freight transportation sector. In CIMS, EV trucks are kept out of the long-haul freight market as battery sizes of current chemistries would need to get impractically large before they could compete with internal combustion engines fueled by diesel or biodiesel. New, more energy-dense, battery chemistries may allow EV trucks to enter the long-haul freight market in the future, but for now, I have confined them to serving short-haul demand. Sales of EV trucks have thus far been very small with an estimated 6000 units sold in 2019 (International Energy Agency, 2020). However, these vehicles are still a relatively new technology and could benefit from quickly falling costs as they are more widely adopted by the global market. In the Global Action scenario, capital costs for EV trucks are 27% lower in 2050 compared to the Global Inaction scenario and are again based on the *Electrification Futures Study* (National Renewable Energy Laboratory, 2017).

While I did not allow EV trucks to compete in the long-haul section of the freight market, hydrogen vehicles were used to provide a low carbon technology. Like EV trucks, hydrogen truck sales are very low at present with the International Energy Agency

(2019) estimating that only a few hundred have been purchased in recent years worldwide. However, this does not mean sales will not pick up in the future, especially with nations such as Canada and the European Union releasing strategies intended to increase the use of hydrogen within their borders (Natural Resources Canada, 2020; European Commission, 2020). Strategies such as these are assumed to be effective in the Global Action scenario. Using the same method that was applied to EVs, I accelerated the decline in capital costs of hydrogen trucks leading to them being 33% lower than in the Global Inaction scenario.

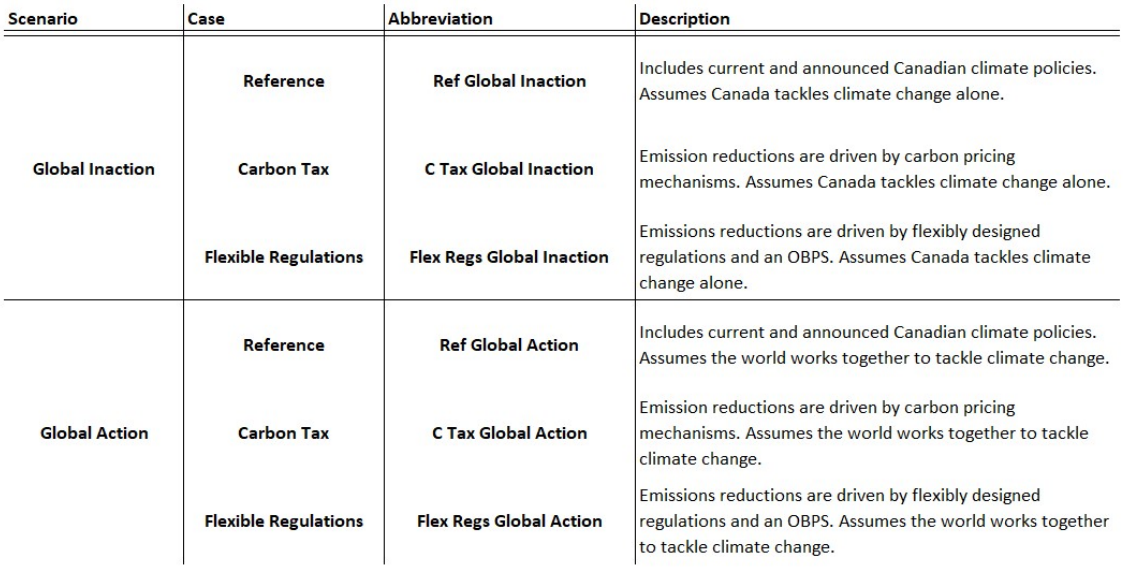
To go along with the accelerated decline of hydrogen truck capital costs, I have also accelerated the capital cost decline of electrolysers, which use electricity and water to produce hydrogen. Although most hydrogen used today is produced through the reformation of fossil fuels, 2019 was a record year for the installation of electrolysers and a continuation of this trend will likely lead to decreasing costs. Currently, the chemical products and petroleum refining sectors are the main sources hydrogen demand, although the widespread adoption of hydrogen vehicles could shift this balance (International Energy Agency, 2019). The exogenously specified part of the capital cost decline function for electrolysers in the Global Action scenario was increased leading the capital cost to be 33% lower compared to the Global Inaction scenario.

Both wind and solar energy generation have seen large increases in their share of electricity generation in recent years due to improvements in generation technology and assistance from government policy (IRENA, 2019). In the Global Action scenario, I expect this trend to accelerate further and will decrease the capital costs of solar installations by 40% and wind installations by 20% by 2050. This acceleration was done using the same method that was applied to the other technologies in this section. These declines are based on estimates from the *Canada's Energy Future 2018* report (Canada Energy Regulator, 2018). Solar energy costs fall more quickly than those of wind because solar is a less established technology. Being less established provides solar with more room to achieve greater cost reductions as techniques in its production improve and increased adoption results in economies of scale. While wind power is by no means a fully matured technology, it has had been present in electricity markets for several decades and projections suggest improvements will come more slowly. Tied in with this is the assumption the storage costs for wind and solar will also decrease at the same rate. At higher market penetrations, variable renewable resources benefit from being paired with energy storage options like batteries or pumped storage hydro. This is done so energy produced at times of low demand can be stored and later used during high demand periods. CIMS does not have explicit technologies that compete to provide energy storage in the electricity sector, but these are simulated through the use of higher capital costs attached to variable (or non-dispatchable) renewables at higher levels of market penetration.

2.4. Cases

I modeled six cases to reflect different levels of global action on climate change and different policy paths the Canadian government could pursue through to 2050. The case names and their basic characteristics are displayed in Table 2:

Table 2: Matrix of cases modeled in this study



Scenario	Case	Abbreviation	Description
Global Inaction	Reference	Ref Global Inaction	Includes current and announced Canadian climate policies. Assumes Canada tackles climate change alone.
	Carbon Tax	C Tax Global Inaction	Emission reductions are driven by carbon pricing mechanisms. Assumes Canada tackles climate change alone.
	Flexible Regulations	Flex Regs Global Inaction	Emissions reductions are driven by flexibly designed regulations and an OBPS. Assumes Canada tackles climate change alone.
Global Action	Reference	Ref Global Action	Includes current and announced Canadian climate policies. Assumes the world works together to tackle climate change.
	Carbon Tax	C Tax Global Action	Emission reductions are driven by carbon pricing mechanisms. Assumes the world works together to tackle climate change.
	Flexible Regulations	Flex Regs Global Action	Emissions reductions are driven by flexibly designed regulations and an OBPS. Assumes the world works together to tackle climate change.

I created the Reference (Ref) cases to illustrate what Canadian emissions may look like by 2050 if further policy action is not taken. The cases in this study designed to achieve carbon neutrality by 2050 are the two Carbon Tax (C Tax) cases and the two Flexible Regulations (Flex Regs) cases. Collectively these cases are referred to as “net-zero cases”. The C Tax cases are designed to achieve emissions reductions in the most economically efficient way possible, while not worrying about political acceptability. The Flex Regs cases are designed in a way that trades off some of the economic efficiency of the C Tax cases for policies expected to be more politically acceptable. Since emissions reductions differ between the two C Tax cases, some of the policies are set at different stringencies in the two Flex Regs cases. The policies in the Flex Regs and C Tax cases are mainly implemented in addition to those in the Ref cases. The exception to this is in the Flex Regs cases which have had the Ref case carbon price removed.

In the context of this research, net-zero does not mean emissions from the Canadian economy fall to zero, but rather that all remaining emissions are offset through the capture and storage of CO2 with direct air capture (DAC) technology. Cost estimates for commercial DAC put the price of capturing a tonne of CO2 between about $130 and $320 CAD (Keith et al., 2018). However, this range does not include transportation and storage costs which should be included in a full life cycle cost assessment and would likely lead to higher costs. While pilot projects have been built the technology is still only in the early stages of deployment and it is yet to be seen whether it can be effective on a large scale. To compensate for these unknowns, I chose to use a more conservative price of $450 per tonne for DAC in my modeling. This price also acts as a price ceiling for the carbon tax since emitters would choose to use DAC rather than pay the carbon tax if it was raised beyond $450 per tonne. If DAC is deployed at large scales its cost may fall as the technology matures and it benefits from economies of scale in production. At the same time however, it may become more expensive to store CO2 as the most suitable geological reservoirs would likely be filled first. Because there is significant uncertainty in how this dynamic may play out, I believe a DAC plus storage cost of $450 per tonne is a reasonable assumption to make.

2.4.1. Reference

The Ref policy package assumes Canada pursues measures similar to those already in place or announced in sufficient detail to model, such as federal carbon pricing and vehicle emission standards. It has been designed to serve as a baseline and show what Canadian emissions may look like if additional GHG mitigation measures are not taken. The case does not seek to model every Canadian climate-related policy as they are numerous and the addition of many of the smaller ones would only serve to complicate the model. I have also opted to not model detailed city-specific GHG policies as the version of CIMS used for this study functions at a provincial level and there is no way to separate emissions by municipalities. The two Ref cases are identical in their policy composition and contain policies implemented at both the federal level and provincial levels. They are outlined below:

- Federal: While there are several provincial carbon pricing plans in Canada along with a federal plan, I have chosen to lump them all together under the federal backstop program. The backstop price is set to follow the announced federal plan outlined in *A Healthy Environment and a Healthy Economy* reaching $170/tonne by 2030 and then remaining there until 2050 (Environment and Climate Change Canada, 2020b). It is important to note this price on GHGs is expressed in nominal dollars and is lower after being adjusted for inflation. For transportation, I have included vehicle fuel efficiency standards like those applying to light-duty vehicles and heavy vehicles. The electricity sector is covered by federal regulations which limit the emissions intensity of electricity production to 420 tonnes of carbon dioxide emissions per Gigawatt hour. This measure is designed to phase out non-CCS coal generation by 2030 along with higher emission intensity natural gas units.

- British Columbia: The electricity sector in BC is governed in part by the 2010 Clean Energy Act which requires 93% of the electricity in BC to come from non-emitting energy sources. This has been modeled and is assumed to hold constant throughout the projection period. The personal transportation sector in BC is subject to two separate regulations designed to lower its carbon intensity. The first is a zero-emissions vehicle mandate, which requires that 30% of vehicles sold within the province must be non-emitting by 2030 and increase to 100% by 2040 as per the *Zero-Emission Vehicles Act* (2019). The second is a low carbon fuel standard, which is designed is to decrease the life cycle carbon intensity over time of carbon emitting fuels used in Canada. In addition to these fuel regulations, I implemented a measure that requires 15% of methane used in British Columbia to be renewably sourced by 2030 as stipulated by CleanBC.

- Alberta: For Alberta, I modeled the Renewable Fuels Standard, which applies to gasoline and diesel and requires they be blended with renewably sourced fuels. I also modeled the planned phase-out of coal for electricity generation, which is set to occur by 2030. Additionally, I have included measures to reduce methane emissions from Alberta's oil and gas sector which are designed to achieve reductions of 45% by 2025.

- Saskatchewan: In Saskatchewan, I implemented the CCS retrofit of the 115 MW Boundary Dam coal power plant, which was completed in 2014. I also included their target of having 50% of their electricity capacity come from renewables sources by 2030.

- Manitoba: I included the phase-out of coal from Manitoba's electricity sector, which was completed in 2010.
- Ontario: I included the Ontario coal phase-out for electricity generation in my modeling, which was completed in 2014.
- Quebec: In Quebec, I modeled the zero-emissions vehicle standard, which came into effect in 2018. This standard applies at different stringencies depending on the size of the automaker, but all levels come with the requirement that an increasing number of vehicles sold in Quebec be zero-emission. I have represented the requirement as 15.5% of new light-duty vehicles sold be zero emissions by 2025.
- Atlantic: My modeling of the Territories and Atlantic Provinces included Nova Scotia's electricity sector regulations, which put an emissions cap on the sector that falls to 2.5 Mt CO2 by 2050 and mandates that at least 40% of electricity generated in the province come from renewable sources by 2020.

All provinces with biofuel blending mandates for gasoline and diesel were also modeled and can be seen in more detail in Appendix A2. I also included any energy efficiency and building regulations that were important in each of the provinces. Subsidy programs were not included in this case, as they often change quickly and may not deliver much in the way of emissions reductions due to the free-rider effect.

2.4.2. Carbon Tax Cases

The Carbon Tax (C Tax) cases rely on carbon pricing applied to all emissions in the Canadian economy to achieve reductions, with the intention of hitting net-zero emissions by 2050. While I call these Carbon Tax cases, they could just as easily be thought of as cap and trade systems, since they are modeled the same in CIMS. Under a cap and trade regime, the carbon price would represent the credit trading price, which would apply equally to all credits traded assuming efficient market functioning. The price trajectory follows the one set out in the Ref cases until 2025, after which the price begins to rise at $100 every five years until 2045. The price then rises $50 more to reach $450 by 2050. The described carbon pricing applied to both combustion emissions from the burning of fossil fuels and process emissions produced through chemical reactions in both C Tax Global Action and C Tax Global Inaction. Revenues collected through emissions pricing are returned to the sectors they were collected from within each province by enabling the revenue recycling function in CIMS. This was done to prevent carbon pricing from acting as a method for facilitating interprovincial or inter-sectoral transfers of revenues. Figure 3 shows the carbon tax schedules for the C Tax cases and the Ref cases.

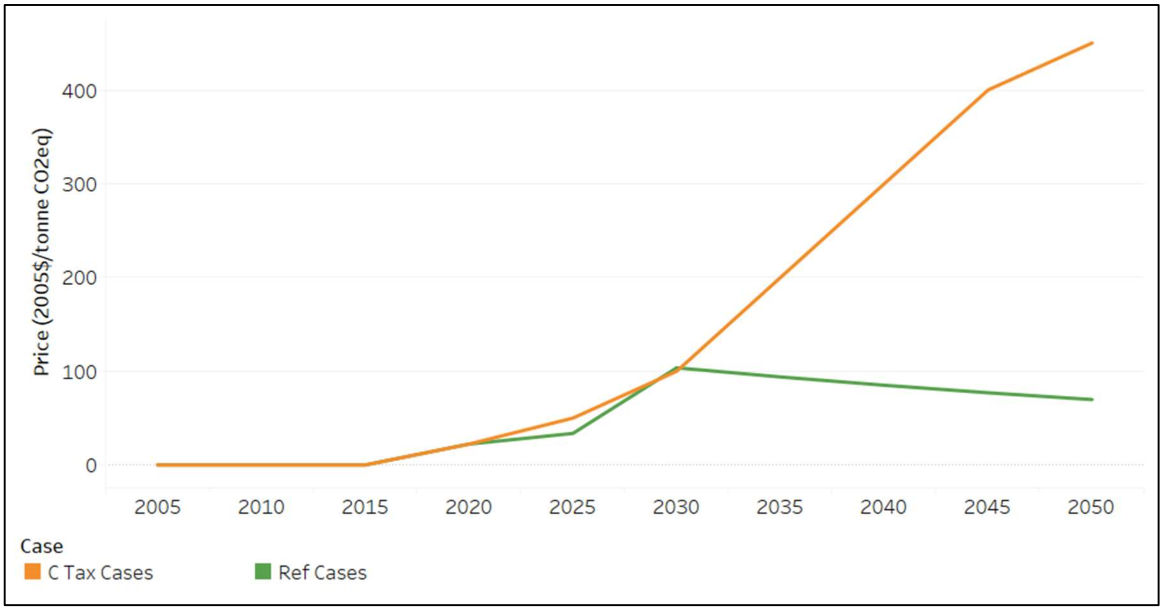


Figure 3: Carbon price in the C Tax cases and Ref cases

As suggested by their name, products produced by emissions intensive trade exposed (EITE) industries contain a high level of embodied emissions and are subject to competition from other countries. If the production cost of these goods were to rise in any one country, that nation would likely lose market share to international competitors. This presents a challenge to decarbonization, as countries earnestly trying to decarbonize these industries may have their efforts defeated by competitors who lack strong climate regulations.

In the Global Action scenario, this is not an issue as I assume all of the nations who compete with Canadian EITE industries will have equally stringent climate policies, which eliminates the risk of carbon leakage. This could be the result, for example, of a global agreement that includes a stringent carbon tariff mechanism to ensure universal compliance. Or, it could be the result of ad hoc carbon tariffs by groups of countries who bind together in “climate clubs” such that eventually their trade pressures cause near-universal adoption of equally stringent climate policies (Nordhaus, 2013; Victor, 2011). In this scenario, I cover all EITE industries with a carbon price, which rises to $450 per tonne, in an effort to drive decarbonization. In my modeling, I do not adjust the exogenously specified demand for any of these industries and I assume global demand for the products remains unchanged regardless of how much the price increases. One assumption embodied in this decision is the production costs of competing nations will rise at the same rate as they do in Canada, which was done to prevent EITE industries from moving away from Canada to regions with lower production costs. This dynamic may occur in the real world if competitor nations already have low emission intensity production or zero-emission production options cheaply available. But the shift could also go in the opposite direction since, because of its low-cost, low-emission hydropower endowment, Canada has low carbon intensity relative to competitors with some of its industrial products such as aluminum, metal smelting, pulp, and forest products. However, modeling such interactions would require detail on the EITE industries of competing nations and is beyond the scope of this study.

In the Global Inaction scenario, I have taken measures to protect Canadian EITE industries from carbon leakage through the introduction of a three-tiered OBPS, which has different levels of carbon pricing based on how sensitive industry production costs are to emissions pricing. Carbon prices are applied to all emissions from these sectors, with the revenues collected being recycled back into the sectors they were taken from. The goal behind this decision was not to prevent any rise in the average production cost of EITE industries, but to hold the rise to below 15% through 2050 compared to the reference case of the Global Inaction scenario. Pricing schedules were created through an iterative process. I began by simulating a $450 per tonne carbon price on all EITE sectors then calculated the difference in production cost between the two policy Global Inaction cases and the Ref Global Inaction case. Next, I determined if any of the sectors saw a rise in production cost greater than 15%. I found most sectors saw rises in production costs less than 15%, with the two exceptions being the “other manufacturing” and “industrial minerals” sectors. Based on these findings I created a tiered system where sectors more sensitive to carbon pricing were covered by a lower carbon price. These prices are illustrated in Figure 4.

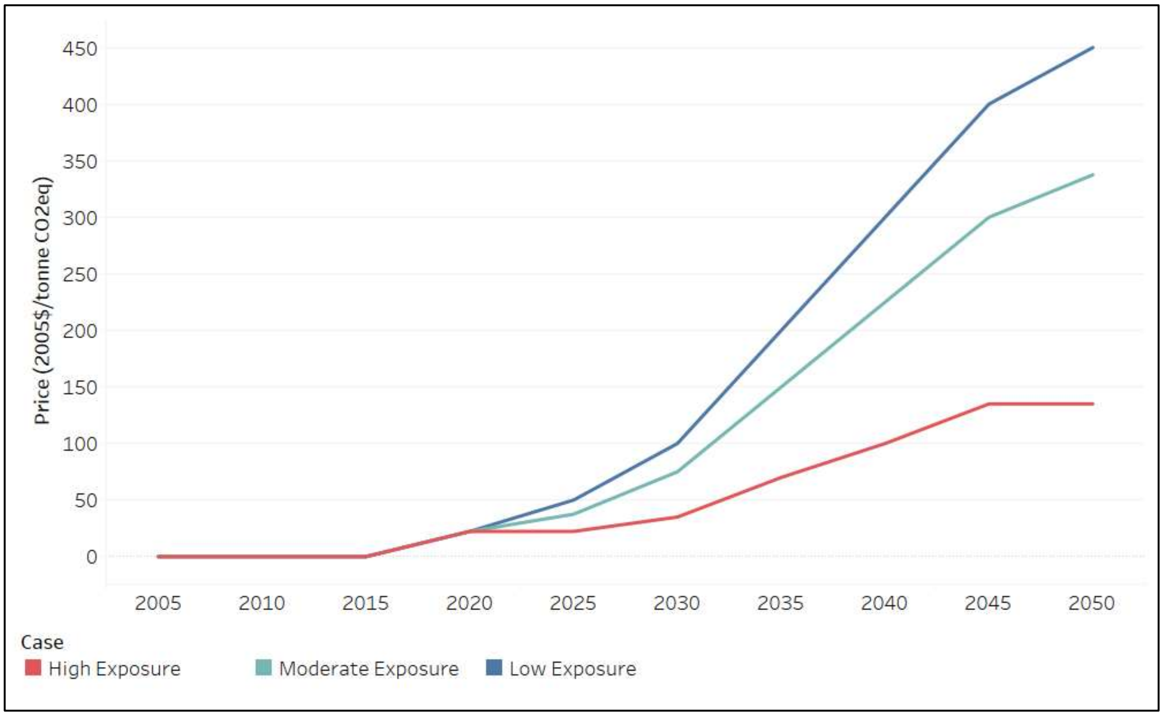


Figure 4: OBPS price tiers in the Global Inaction case

The industrial minerals sector is in the High Exposure tier with the lowest price, which rises at a steady rate from 2025 to 2045, before plateauing at $135 per tonne. The other manufacturing sector is in the Moderate Exposure tier and faces a price that steadily rises to $340 per tonne in 2050[5]. The pricing in the Low Exposure tier follows the same schedule as the regular carbon tax and covers the rest of the EITE industries rising to $450 per tonne by 2050. Table 3 outlines the price of each OBPS tier and which industries they apply to.

Sectors like iron and steel, and chemical products that I placed in the Low Exposure tier may be less sensitive to carbon pricing than those in the higher tiers because they have lower cost decarbonization options available. These technologies may not be commonly used at present or may be expected to become commercially available in the near

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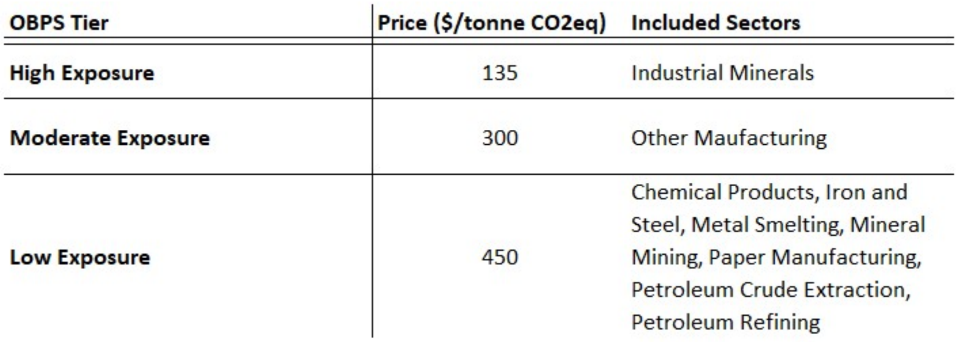
[5] The Other Manufacturing sector lacks the same level of technological detail as other industrial sectors in CIMS. This lower resolution may explain why it is more sensitive to carbon pricing than more detailed sectors like the Iron and Steel.

future. Alternatively, this low sensitivity to carbon pricing could be an indication that CIMS lacks sufficient detail in these sectors which results in technological change occurring too easily.

The tiered OBPS was designed to prevent high-intensity industries from shifting overseas to jurisdictions with weak climate policies through carbon leakage. If this were to occur, global emissions would not be reduced and Canada would suffer economic losses. Another option for addressing the carbon leakage concern would be to implement carbon border tariffs on products coming from jurisdictions without sufficiently stringent climate policies. While this would protect domestic sales, it still leaves Canadian products at a disadvantage when competing against carbon intensive alternatives on international markets. In my study I have opted to not model carbon border tariffs as they have not yet been implemented anywhere in the world and would require assumptions about the carbon intensity of imported products.

Table 3: OBPS tiers used in the Flex Regs and C Tax Global Inaction cases, with 2050 emissions prices



OBPS Tier	Price ($/tonne CO2eq)	Included Sectors
High Exposure	135	Industrial Minerals
Moderate Exposure	300	Other Maufacturing
Low Exposure	450	Chemical Products, Iron and Steel, Metal Smelting, Mineral Mining, Paper Manufacturing, Petroleum Crude Extraction, Petroleum Refining

2.4.3. Flexible Regulations Cases

Rather than using a single policy tool, the two analyzed Flexible Regulations (Flex Regs) cases rely on a mixture of regulations and an OBPS to achieve emissions reductions. The design of Flex Regs focused on improving political acceptability compared to the C Tax case, while also trying to minimize any reductions in economic efficiency. The regulations are designed in a way that gives emitters as much choice as possible in how they are met, rather than mandating the use of specific technologies. This was done to improve the economic efficiency of the policy package and to avoid restricting purchasing decisions unnecessarily. A key design aspect of these regulations is that they target the source of GHG emissions as directly as possible in an attempt to mimic the precision of a carbon tax. Part of the reason why carbon pricing is an effective method of abatement is because it puts a price directly on the pollutant, which increases its cost and corrects for externalities. With regulations, we lack the same level of precision, but we can try to get as close as possible. In following this principle, I chose to target GHG emitting fuels where I could and set regulations that limited their use. These regulations are applied to all GHG fuels in the sectors where they were implemented. If only one emitting fuel source was regulated, consumers may substitute the regulated one with a non-regulated one, thereby defeating the spirit of the regulation. In instances where it was not possible to implement regulations on carbon-intensive fuels, I instead regulated emitting technologies.

Rather than design a new set of regulations for the electricity, hydrogen, and industrial sectors for these cases, I instead chose to regulate their emission through the same OBPS used in the C Tax cases. This choice was made because the current OBPS has so far proven both politically acceptable and economically efficient. Replacing it with an alternative may decrease either political acceptability or economic efficiency, which leaves little motivation to replace it in the two Flex Regs cases.

Commercial and Residential

The majority of emissions from the residential and commercial sectors come from the use of natural gas in heating applications. To reduce emissions in these sectors, I implemented a regulation requiring an increasing amount of biomethane to be blended with natural gas. This requirement is based on a similar blending mandate being created under the CleanBC policy package in British Columbia, although the one used in my is applied to all provinces. Required blending begins at 20% in 2030 and rises smoothly until it reaches 100% in 2050. Flexibility is provided because the regulation does not prescribe the use of biomethane in a building, but rather it disallows the use of natural gas. Building owners and operators have the option of using biomethane for heating or instead using electric devices, like heat pumps and resistance heaters, or perhaps fuel cells that use hydrogen produced in zero-emission processes. A portion of residential and commercial emissions also come from the use of propane and fuel oil. Rather than require these fuels to be blended with a low carbon alternative, I instead phase out their use through a regulation mandating they can no longer be sold past 2025.

Transportation

In the personal transportation sector, I modeled regulations requiring an increasing amount of gasoline to be blended with ethanol. This mandate requires 20% ethanol blending by 2030, rising to 100% by 2050 in both Flex Regs. Because regular gasoline motors cannot use blends with higher levels of ethanol, I disallow their sale after 2025. While they may not achieve the same level of cost-effectiveness as a carbon tax, research indicates these types of regulations can provide relatively low-cost emissions reductions (Vass & Jaccard, 2017; Rivers & Wigle, 2018).

Buses and rail, which provide public transit services, have regulations designed to phase out emitting technologies rather than target their fuel sources directly. To model this, I mandated new sales of public transit options running on fossil fuels fall to zero by between 2030 and 2035. Zero-emission vehicles running on electricity, biodiesel, or hydrogen were allowed to compete for market share, which provides flexibility in how this regulation was met. In my study, I did not model regulations applying to aircraft or ships due to the international nature of their travel and the risk of carbon leakage. However, a comprehensive net-neutral carbon plan would include policies targeting these sources of emissions.

In the freight transportation sector, heavy-duty vehicles running on diesel account for the majority of sectoral emissions. To drive reductions, I modeled regulations requiring an increasing share of the diesel sold to the sector to be blended with biodiesel or HDRD. In the Flex Regs Global Action case, this value reaches 60% by 2050 and in the Flex Regs Global Inaction case 100% by 2050. While conventional biodiesel cannot be blended with regular diesel in excess of 20% in many modern engines, I assume next-generation diesel engines will be able to tolerate these higher blending rates. To model this evolution, I disallowed the sale of standard diesel engines beginning in 2025. Similar regulations are also applied to freight vehicles fueled by compressed natural gas, but for these I require an increasing share of their fuel to be provided by biomethane. This rises at the same rate in both Flex Regs cases, beginning at 20% in 2030 and reaching 100%

in 2050. With the phasing out of diesel and natural gas as fuel options, flexibility is still available as purchasers can choose to use biomethane, biodiesel, hydrogen, or electrically powered vehicles.

Biodiesel and Ethanol Production

With regulations in place to induce switching away from fossil fuels towards low carbon fuels, it is important to ensure these low carbon fuels are produced with as few emissions as possible. In ethanol and biodiesel production, I implemented regulations requiring the boilers and cogeneration units providing heat not to use coal beginning in 2025 in both Flex Regs cases. I also added a requirement where biomethane had to account for an increasing share of the methane used in the sector resulting in biomethane completely replacing natural gas by 2050. In addition, I also regulated the use of diesel in the production process of these biofuels, with the share of biodiesel needing to be blended with conventional diesel reaching 10% in the Flex Regs Global Action scenario and 20% in the Global Inaction scenario by 2050. These values were chosen to mimic the biodiesel blending rates achieved under the two carbon pricing scenarios.

Chapter 3. Results and Discussion

The purpose of this study was to explore two possible policy pathways Canada could take in efforts to achieve domestic carbon neutrality by 2050. My analysis compares four net-zero cases which are designed to hit net zero (C Tax Global Action, C Tax Global Inaction, Flex Regs Global Action, Flex Regs Global Inaction) with two reference cases (Ref Global Action, Ref Global Inaction) and assesses technological change, energy change and GHG emissions depending on scenarios, regions and sectors. I focus especially on differences in the results between the cases I modeled in the year 2050. Similar results in terms of technology shares and sectoral emissions between the Flex Regs and C Tax cases were created intentionally, with a greater degree of similarity between the two indicating that my regulatory packages would not diverge dramatically from carbon tax in terms of the economic impacts.

3.1. National Results

In all six of the cases, my policy simulations indicate significant declines in emissions may occur by 2050 compared to 2005 levels, with their trajectories illustrated by Figure 5. My simulation indicates emissions from the Ref Global Action case may fall to 26% below 2005 levels (544 Mt) and the Ref Global Inaction may fall to 19% below 2005 levels by 2050 (599 Mt). This suggests the accelerated cost declines for low emissions technologies combined with lower output from the Canadian oil sector could induce 55 Mt of additional emissions reductions. At the same time, these effects could offset any increases in demand for RPPs induced by the $40 per barrel oil price in the Global Action scenario. While these cases show improvement from 2005 levels, they are both likely fall well short of the carbon neutrality goal[6].

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[6] All cases in this study miss Canada’s Paris Agreement commitment to reduce 2030 emissions to 30% below 2005 levels. Meeting this target was not part of my study and as such will not be discussed further.

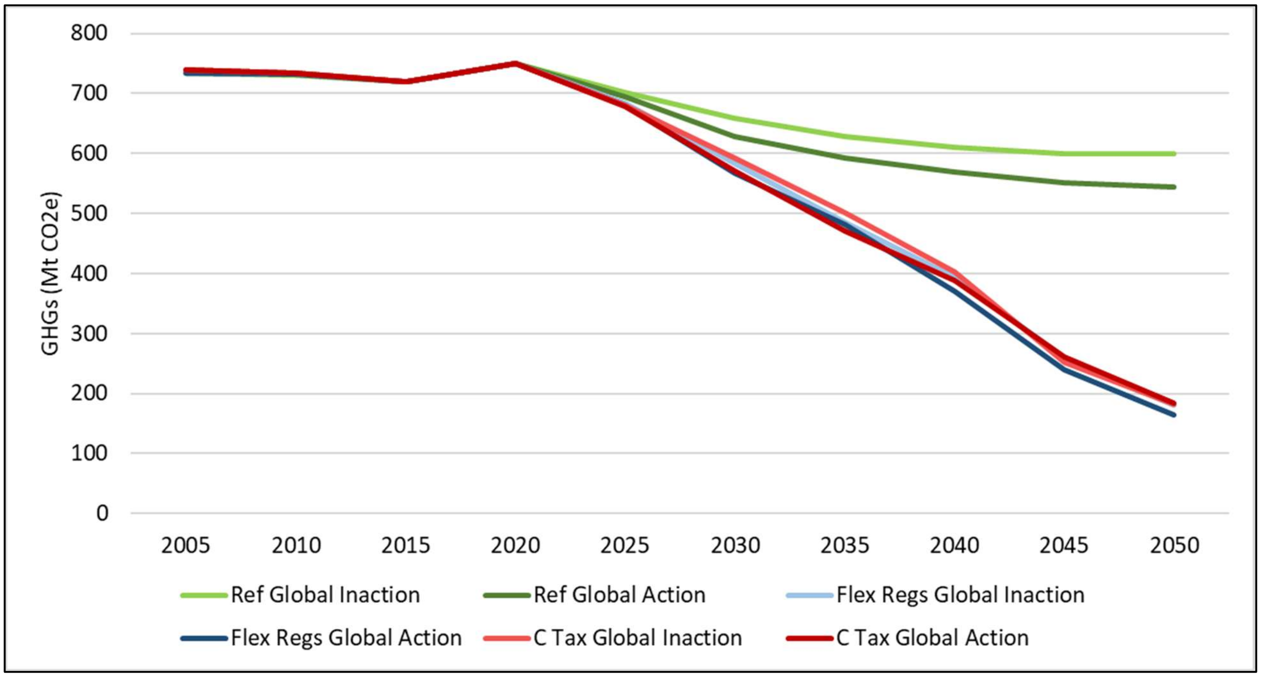


Figure 5: Net GHG emissions by case

Unlike the two reference cases, the four net-zero cases in the study are specifically designed to approach carbon neutrality by 2050 and unsurprisingly my simulation generates far greater reductions. Emissions in the net-zero cases could fall by between 78% (160 Mt) in the Flex Regs Global Inaction case and 74% (189 Mt) in the C Tax Global Action case by 2050. It appears the lower price for RPPs in the Global Action scenario may be able to completely offset any additional reductions induced by lower Canadian oil production and the accelerated cost decline of low carbon technologies. While none of these simulated cases reach zero total emissions, I assume the remaining emissions could be offset by negative emissions technologies such as DAC, which, as noted, I did not explicitly model in this study.

3.2. Provincial Results

As we would expect, emissions from my simulated net-zero cases are lower than those from the Ref cases across all regions of Canada. My modeling suggests all regions could see emissions decrease by at least 48% in the net-zero cases compared to the Ref cases by 2050. Of all the provinces, British Columbia may see the smallest decrease in total emissions in the net-zero cases compared to the Ref cases, with total emissions 48% lower in the net-zero cases. My simulations indicate Alberta may see the largest difference between the net-zero and Ref cases, with sector differences ranging from 89% to over 100% in instances where emissions in the sector become net negative. Alberta is likely to be the region most impacted by the lower oil production, with simulated emissions much lower in the Ref Global Action case than the Ref Global Inaction case. Some other provinces, such as Ontario, could see small increases in emissions in the Global Action cases, which is likely due to the lower price for RPPs leading to higher consumption of gasoline and diesel. All net-zero cases indicate Ontario could replace Alberta as the largest GHG emitter, followed by British Columbia and Quebec, while Alberta goes from being one of the largest emitters to one of the smallest. This change of roles may seem odd, but it can be partially explained by two factors. First, Alberta and Saskatchewan were the only two provinces where the adoption of negative emissions BECCS units was permitted because of the highly favourable conditions for this option in those two provinces. If BECCS is capturing a significant amount of market share in the electricity sector, these negative emissions could offset a sizable amount of emissions from other sectors. Second, Alberta has a carbon-intensive economy and may have have more options available for low cost decarbonization compared to regions like British Columbia or Quebec with low carbon intensity economies. Figure 6 shows the 2050 emissions from each of the 6 simulated cases in this study for each of the regions studied.

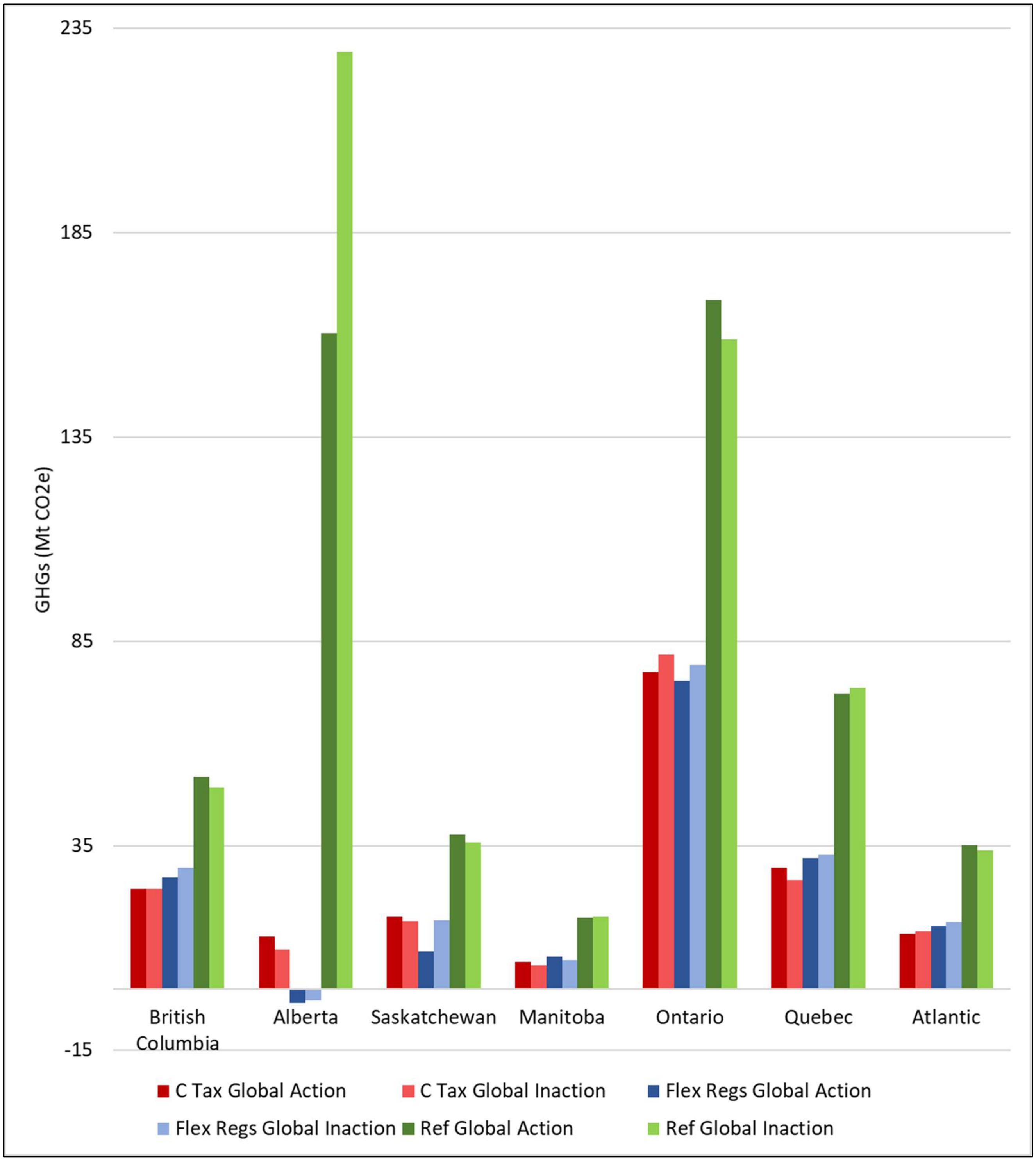


Figure 6: Emissions from each region in CIMS by 2050

3.3. Sectoral Results

The following section describes changes in emissions from the economic sectors in CIMS. A summary of these simulated changes is shown in Figure 7, where 2050 emissions are separated by case and sector.

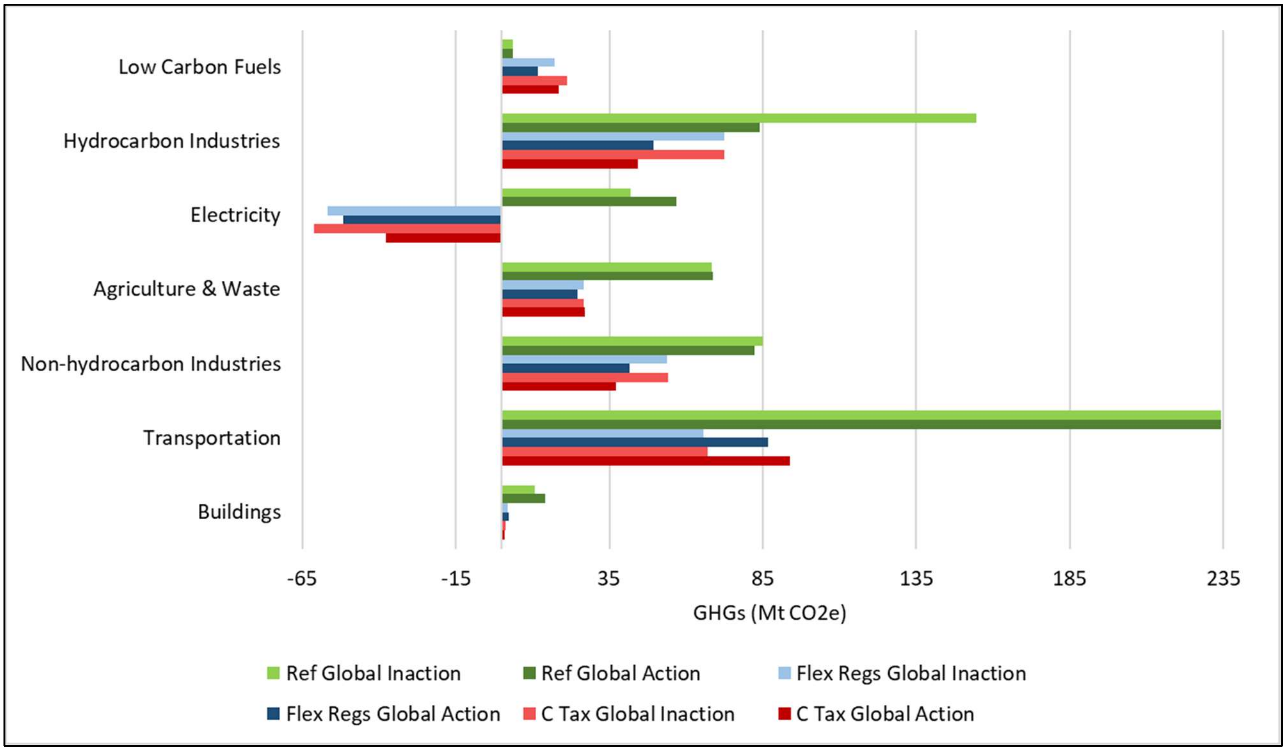


Figure 7: Canadian GHG emissions by case and sector in 2050

3.3.1. Industrial Emissions

In 2005, industrial emissions made up about one-third of the emissions produced by Canada (Environment and Climate Change Canada, 2020a). Since then, this share has been growing as emissions from non-industrial sectors have been falling while those from industry have been rising. My modeled net-zero cases indicate this may trend may continue. In the Global Inaction cases, it is possible industrial emissions could make up over 70% of Canada’s total 2050 emissions, while they may only make up around 45% in the Global Action cases. The difference can be attributed to two main factors: the protection of price sensitive EITE industries in the Global Inaction scenario, and the lower output from oil related sectors in the Global Action scenario.

Since my policy packages try to avoid inducing carbon leakage, I ensured the production costs of EITE industries did not rise more than 15%. These actions were only used in the Global Inaction net-zero cases and are explained in detail in the Methods section. My modeling revealed that most sectors may see their output costs rise by less than 15% under the $450 per tonne carbon price used in the OBPS, with the two exceptions being the other manufacturing and industrial minerals sectors. Of these two sectors, industrial minerals was likely to be more sensitive and received a lower carbon price, rising to $135 per tonne by 2050, while the price for other manufacturing rose to $340 per tonne by 2050. As a result of this less aggressive carbon pricing schedule, my modeling suggests emissions from these industrial sectors may be higher in the Global Inaction scenario cases compared to the Global Action scenario cases. In the industrial minerals sector, modeling indicates annual emission could fall to 4 Mt in the two Global Action cases, and to 12 Mt in the Global Inaction cases.

As was the case for industrial minerals, emissions in my simulation from the other manufacturing sector fell less in the two Global Inaction scenario net-zero cases than they did in the Global Action net-zero cases. Emissions in both C Tax Global Inaction and Flex Regs Global Inaction were simulated to be be 20 Mt in 2050, the same as they were in 2005, while they could fall to 14 Mt in C Tax Action and Flex Regs Action. Even though the other manufacturing sector emissions were the same as in 2005 in the Global Inaction net-zero cases, this does not mean the implemented OBPS was ineffectual, as they rise by 7 Mt in both Ref cases compared to 2005 levels in my simulations.

My modeling indicates the petroleum crude extraction sector could see the largest difference in emissions between the two scenarios, even though both applied the same OBPS price, which rose to $450 per tonne by 2050. This is not surprising, as the 2050 Global Action scenario demand from the sector is assumed to be half of 2020 levels and one-third of the Global Inaction scenario levels. In both of the Global Action policy scenarios, emissions from the sector are simulated to fall to about 12 Mt by 2050, which is about 20 Mt lower than those my simulation produced in the Global Inaction policy scenarios. My modeling also indicated there could be a significant difference in the emission from the sector between the two reference cases, again due to the large differences in oil price and demand between the scenarios. In the Ref Global Action case, emissions may fall to 34 Mt by 2050 compared to Ref Global Inaction where they may increase to 97 Mt from 77 Mt in 2005. It is interesting to note that simulated sectoral emissions from the Ref Global Action case are similar to emissions from both Global Inaction net-zero cases. This emphasises the impact climate action taken by the rest of the world could have on the Canadian oil sector.

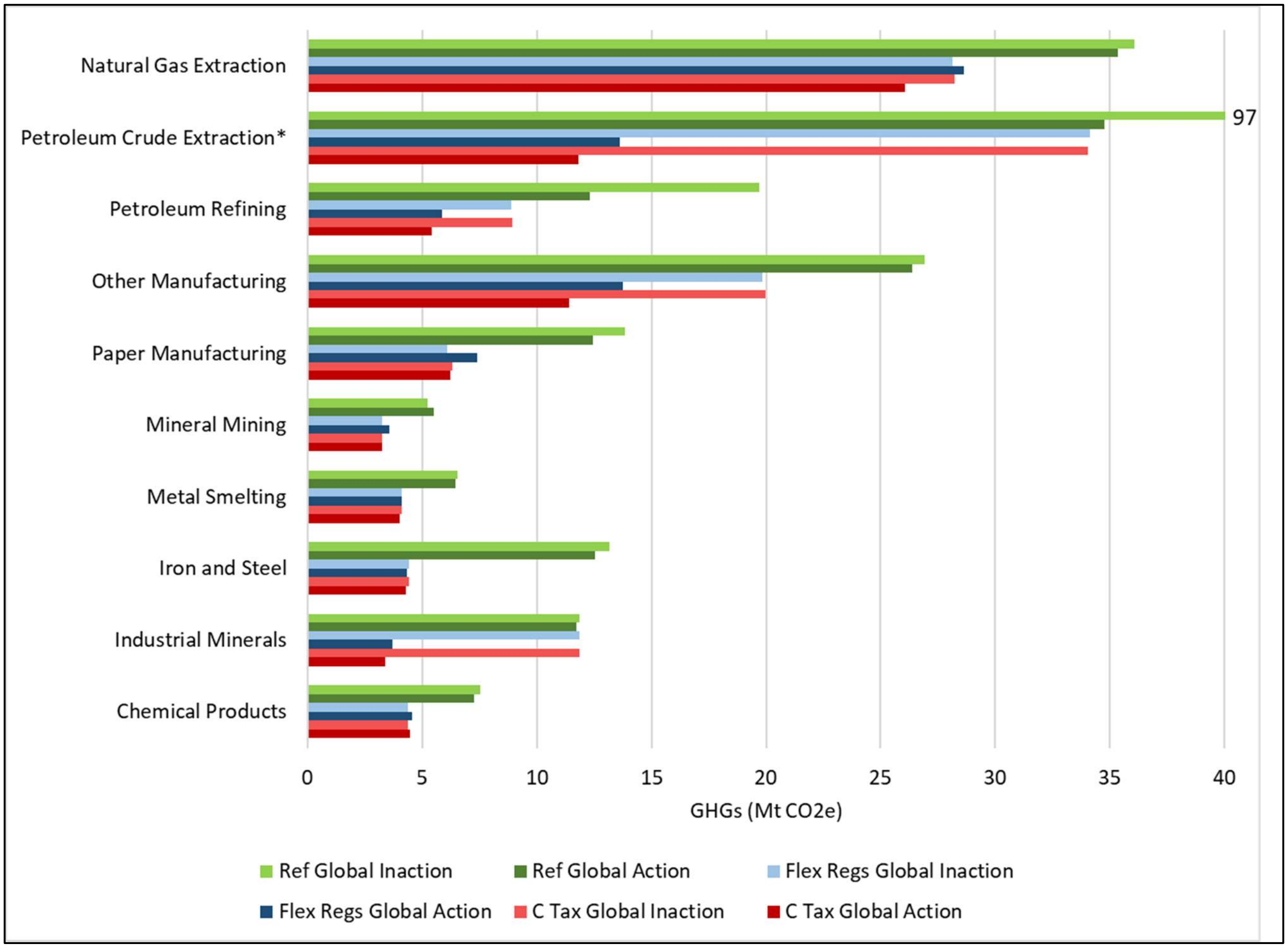


*Figure 8: Emissions EITE sectors in 2050 in all six cases. *Emissions from Petroleum Crude Extraction reach 97 Mt in the Ref Global Inaction case, although this chart has been truncated for clarity.*

The petroleum refining sector is closely related to petroleum crude extraction, and had the same OBPS price schedule implemented. My modeling suggests a notably larger decrease in emissions may occur in the Global Action cases compared to the Global Inaction cases. In the two Global Action net-zero cases, emissions could fall from 20 Mt in 2020 to 6 Mt by 2050. Under the Global Inaction net-zero cases, emissions could fall to 9 Mt, which still represents a large decrease from their peak even though this is 50% larger than in Global Action net-zero cases. The two Ref cases could follow similar trends to those in the petroleum extraction sector, with emissions in the Ref Global Inaction case possibly falling only slightly to 20 Mt and Ref Global Action possible declining more sharply to 12 Mt by 2050.

In all non-petroleum EITE sectors (chemical products, iron and steel, metal smelting, mineral mining, and paper manufacturing) my modeling suggests there would be little difference in emissions between the two scenarios, with emissions potentially falling in all net-zero cases by between 50% and 70% compared to 2005 levels. These reductions are driven by the most stringent OBPS tier, which rises to $450/tonne by 2050. Emissions declines from these sectors are likely to be to be smaller in the reference cases where reductions only occur in the metal smelting and chemical products sectors and increase in the other three sectors in both the Global Inaction and Global Action scenarios.

3.3.2. Electricity

From 2005 to 2018 emissions from the Canadian electricity sector fell by close to 50%, driven by decarbonization efforts such as the phase-out of coal electricity generation in Ontario (Environment and Climate Change Canada, 2020a) In all of my cases, this could possibly trend continues. As expected, modeling suggests the two reference cases are likely to see the smallest decrease in emissions, falling to around 40 Mt a year by 2050 in the Global Inaction scenario and 57 Mt in the Global Action scenario, as compared to 119 Mt in 2005. Reductions would be driven by current policies, like the federal phase-out of high emissions intensity generation units and the planned rising carbon price. The higher levels of emissions in Ref Global Action would be due to the higher demand for electricity, which would be likely driven by the accelerated cost decline of EVs. In the net-zero cases, modeling suggests these much greater reductions could be largely due to negative emissions technologies. Simulated emission trends in the electricity sector from 2005 to 2050 are highlighted in Figure 9.

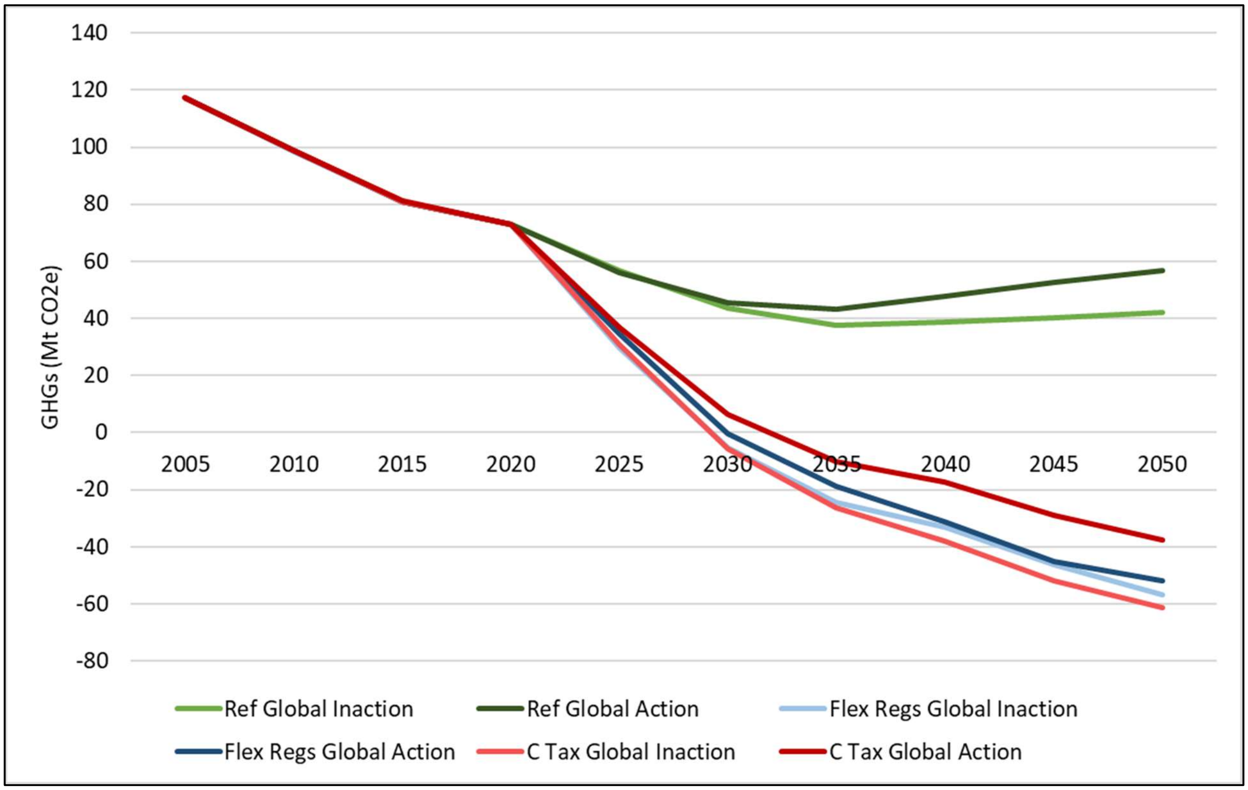


Figure 9: Net annual GHG emissions from the Canadian electricity sector

In all four net-zero cases, modeling suggests electricity sector emissions could fall well below 0 Mt per year with the C Tax Global Action case falling to -36 Mt, the Flex Regs Global Action case to -52 Mt, the C Tax Global Inaction to -61 Mt and, the Flex Regs Global Inaction to -57 Mt. These negative emissions could be created by BECCS units in Alberta and Saskatchewan, with those provinces accounting for all of the negative emissions in the Canadian electricity sector in my simulation. Alberta could play an especially important role with net electricity sector emissions falling as low as -74 Mt in the C Tax Global Inaction case. This is in line with other studies, which have found that the negative emissions produced by BECCS could provide an important role in offsetting emission from other sectors (Hilaire et al., 2019; Selosse & Ricci, 2014). Without strong policy support, these plants are likely to be more expensive than other generation options and thus do not capture any market share in the modeled reference cases. In my net-zero cases, I assume the federal government either pays firms a rate equal to the carbon price for storing carbon or allows other firms to pay negative emitters to offset their emissions. Despite the electricity sector as a whole reaching negative emissions, modeling suggests some emitting technologies could capture market share even with $450/tonne carbon pricing. These are mainly peaking combined-cycle natural gas powerplants in Alberta, Saskatchewan, and Ontario. Other regions could use dispatchable hydropower to cover peak electricity demand rather than natural gas generation.

While the carbon pricing mechanisms in my study may not be not stringent enough to abate these remaining electricity sector emissions, this does not mean there are no options for addressing them. Research by the Canadian Energy Research Institute (2019) has indicated the expansion of interprovincial electricity trade between Alberta and British Columbia, and Manitoba and Saskatchewan could provide a valuable decarbonization pathway. The peaking electricity generation capacity of both British Columbia and Manitoba is largely composed of zero-emission hydro resources making them ideal partners for replacing the natural gas used in Alberta and Saskatchewan to ensure system reliability as the contribution of non-dispatchable wind and solar increases. The expansion of interprovincial transmission was not included in this study as it may be difficult to achieve without strong cooperation between provincial governments.

An interesting dynamic could occur in the electricity sectors of Alberta and Saskatchewan, which may result in noticeably lower sectoral emissions in both of the Global Inaction net-zero cases compared to their Global Action counterparts. The root cause of this is the lower output from the oil sectors of Alberta and Saskatchewan which, by 2050, is two-thirds lower in the Global Action scenario than the Global Inaction scenario. Lower oil output in turn could cause the demand for electricity in Alberta and Saskatchewan to be lower since there would be less industrial activity overall. Since emissions from the electricity sector as a whole would be negative, a smaller electricity sector would produce fewer negative emissions assuming the relative technology market shares remain the same. This may not however be a realistic dynamic and may prompt a rethinking of how BECCS and possibly other carbon negative technologies should be modeled.

My modeling suggests BECCS units could achieve a negative production cost with the $450 per tonne carbon price in place. We should interpret this as indicating that the action of storing CO2 itself would be profitable even if companies storing the CO2 are not selling any electricity or are being paid $0 for what they generate. Therefore, the amount of electricity produced by BECCS should be determined independently of the amount of electricity demanded by the Albertan electricity grid. Instead, it should be mainly determined by the cost of CCS, the price of biomass, and the unit price paid for carbon storage. This same dynamic already occurs in the Albertan oil sands at cogeneration facilities that produce electricity as part of the heavy oil extraction process. The price of electricity is irrelevant to how much electricity is produced by these cogeneration units, which is instead determined by the price of oil. One can think of BECCS facilities in the same way. Instead of power plants that also store CO2, they should be viewed as CO2 storage facilities that can produce electricity as a co-product. This view makes the amount of BECCS adopted by the Albertan electricity grid independent from other provincial economic dynamics, like the amount of oil produced in the province. I expect this would result in electricity sector emissions being similar across the two scenarios even with different levels of industrial electricity demand.

3.3.3. Residential and Commercial

Figure 10 shows the simulated decline in emissions from the residential and commercial sectors in all six cases. In each case, I find the simulated residential and commercial sectors may see significant declines in their emissions, with the residential sector dropping to below 2 Mt in all cases and the commercial sector below 15 Mt. Residential emissions mainly come from home heating devices such as furnaces or water heaters fueled by natural gas or heating oil. In all cases, modeling suggests these devices could be mainly replaced by a mix of biomethane fueled furnaces, electric heat pumps, and electric resistance heaters. This represents a large shift in the current energy mix of the Canadian residential sector, which was comprised of 46% natural gas and 38% electricity in 2018 with most of the rest coming from heating oil, propane, and wood (Natural Resources Canada, 2021). The market shares that each technology could capture vary from province to province, with provinces having higher electricity prices, such as Alberta, possibly adopting more biomethane furnaces and vice versa.

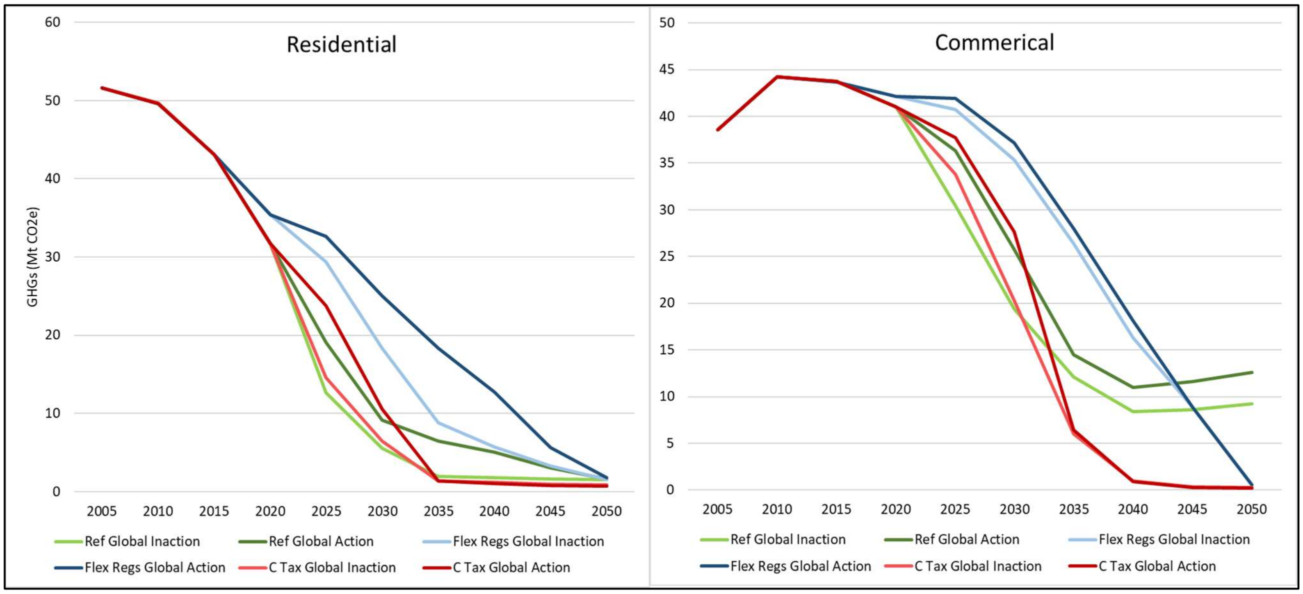


Figure 10: 2050 GHG emissions from the residential and residential sectors by case

Emissions from the commercial sector may also see a steep decline in all cases. The sector does not not fully decarbonize in the simulated reference cases, leaving between 9 and 13 Mt remaining by 2050, but emissions in the four net-zero cases fall to close to 0 Mt in my modeling. Like the residential sector, decarbonization of the commercial sector could be done through the replacement of natural gas, propane, or light fuel oil heating units with those using biomethane or electricity. By 2050, simulations suggest the amount of energy provided by electricity in the commercial sector could increase from 46% in 2018 to between 54% and 61% in all of the net-zero cases, with biomethane possibly capturing the rest. My modeling suggests there may be a slight uptick in emissions from the commercial sector after hitting its low in 2040 in the two Ref cases. This is likely caused by the decreasing real value of the reference case carbon price, which has been adjusted downward for inflation since the government has not specified that the price would be corrected for inflation effects. Table 4 shows the market shares each energy source captures in the six modeled cases in the commercial sector along with 2018 market shares.

Table 4: Fuel Energy shares in the residential and commercial sectors for all of Canada in 2018 and 2050

Residential Fuel (% of Total, 2050)	Electricty	Biomethane	Biomass	Natural Gas	Light Fuel Oil
Ref Global Action	64%	28%	2%	5%	1%
Ref Global Inaction	73%	27%	0%	0%	0%
C Tax Global Action	74%	23%	2%	0%	0%
C Tax Global Inaction	59%	40%	1%	0%	0%
Flex Regs Global Action	61%	38%	0%	0%	0%
Flex Regs Global Inaction	59%	40%	1%	0%	0%
Historical (2018)	38%	0%	11%	46%	4%

Commerical Fuel (% of Total, 2050)	Electricty	Biomethane	Biomass	Natural Gas	Light Fuel Oil
Ref Global Action	59%	24%	0%	12%	4%
Ref Global Inaction	57%	30%	0%	10%	2%
C Tax Global Action	61%	39%	0%	0%	0%
C Tax Global Inaction	54%	46%	0%	0%	0%
Flex Regs Global Action	57%	43%	0%	0%	0%
Flex Regs Global Inaction	54%	46%	1%	0%	0%
Historical (2018)	46%	0%	0%	49%	2%

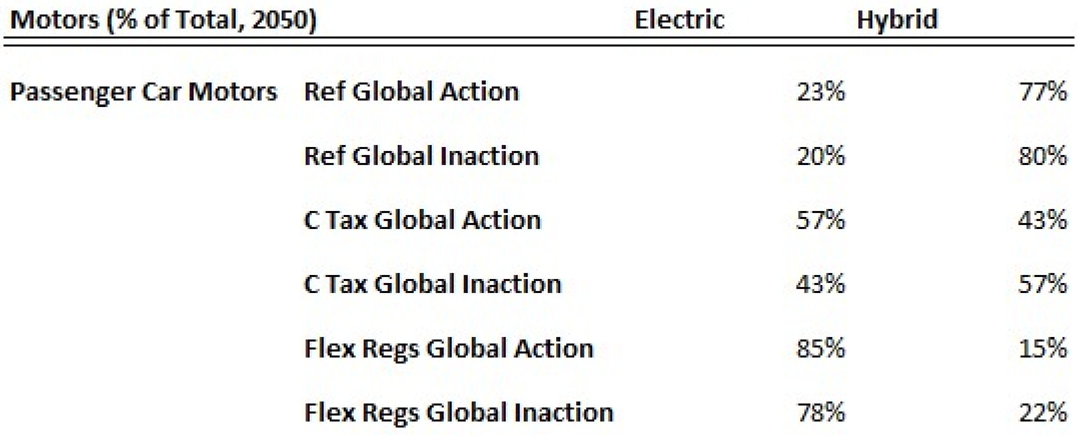
The high level of decarbonization seen in the Ref cases of this study indicates that the residential and, to a lesser extent, the commercial sector could provide low abatement cost options for decarbonization. This information is useful to policymakers looking to achieve carbon neutrality, as it provides them with an idea of what sectors could be quickly decarbonized. In a situation where an economy wide carbon price was being used to drive emissions, these results would be less important. However, if regulations were being used, analysis suggests these two sectors would be a good place to implement policies first. Additionally, the residential and commercial sectors are not trade-exposed, as increasing the price of home and building temperature regulation is unlikely to lead to carbon leakage or hurt the international competitiveness of Canadian industries.

3.3.4. Personal Transportation

My modeling suggests emissions from the personal transportation sector could decrease in all cases, although decreases are likely to be much smaller in the reference cases than in the net-zero cases. 2050 emissions in the Ref Global Action case could be 29% lower than 2005 levels and emissions from the Ref Global Inaction case could be 33% lower. Even though the cost decline for EVs has been accelerated in the Global Action scenario this may not result in significantly higher uptake as EVs capture about 20% of total market share by 2050 in both reference cases of my simulation. The negligible difference in EV market share between these two cases is likely due to the lower price of gasoline in the Global Action scenario which offsets the lower EV price in the scenario. The other approximately 80% of passenger vehicles in my simulation consists of hybrids using gasoline blended with low levels of ethanol, which may not rise above the blending levels required by policy.

My simulation indicates 2050 emissions in the C Tax Global Inaction case could be 59% below 2005 levels while those in C Tax Global Action could be 64% lower. Unlike in the reference cases, this seems to indicate the accelerated cost declines for EVs is enough to offset the lower gasoline price of the Global Action scenario, leading to lower emissions. The market shares for EVs reflect this as modeling indicates they could be 14% higher in the C Tax Global Action case than C Tax Global Inaction. Regulations I use in the Flex Regs cases require the ethanol blending rate with gasoline to reach 100% by 2050. With this regulation in place, EV adoption could reach 85% in the Global Action scenario and 78% in the Global Inaction scenario. Table 5 contains a full list of modeled passenger vehicle motor market shares in 2050.

Table 5: 2050 passenger vehicle motor shares grouped into electric and hybrid.

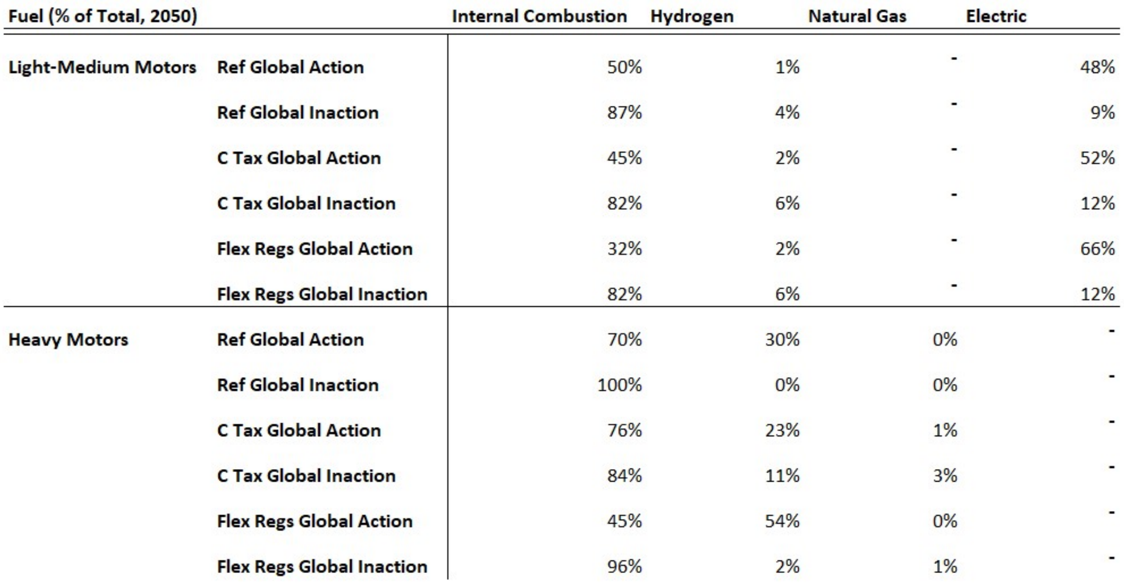


Motors (% of Total, 2050)		Electric	Hybrid
Passenger Car Motors	Ref Global Action	23%	77%
	Ref Global Inaction	20%	80%
	C Tax Global Action	57%	43%
	C Tax Global Inaction	43%	57%
	Flex Regs Global Action	85%	15%
	Flex Regs Global Inaction	78%	22%

3.3.5. Freight Transportation

My modeling indicates emissions from the transportation freight sector may vary greatly between the four policy and two reference cases, with emissions from the reference cases possibly being significantly higher. In the Ref Global Inaction case, emissions could almost double from 94 Mt in 2005 to 173 Mt in 2050, driven by significant increases in the shipment of goods and insufficiently stringent policies. The outlook in the Ref Global Action case could be similar with emissions rising to 167 Mt by 2050. Emissions in both of the Global Inaction net-zero cases could fall below 30 Mt by 2050, with the C Tax Global Inaction possibly reaching 24 Mt and Flex Regs Global Inaction at 14 Mt. Both may be significantly lower than the emission from the Action scenarios, which could fall to 84 in the Flex Regs Action case and 78 in C Tax Action. Within the land freight sector in CIMS, trucks are broken down into two categories, light-medium motors and heavy motors. Table 6 provides a breakdown of how much market share is captured by each engine type in the heavy motors and light-medium motors of the freight sector in my simulation.

Table 6: Light-medium and heavy motor market shares of all six cases in 2050



Fuel (% of Total, 2050)		Internal Combustion	Hydrogen	Natural Gas	Electric
Light-Medium Motors	**Ref Global Action**	50%	1%	-	48%
	Ref Global Inaction	87%	4%	-	9%
	C Tax Global Action	45%	2%	-	52%
	C Tax Global Inaction	82%	6%	-	12%
	Flex Regs Global Action	32%	2%	-	66%
	Flex Regs Global Inaction	82%	6%	-	12%
Heavy Motors	**Ref Global Action**	70%	30%	0%	-
	Ref Global Inaction	100%	0%	0%	-
	C Tax Global Action	76%	23%	1%	-
	C Tax Global Inaction	84%	11%	3%	-
	Flex Regs Global Action	45%	54%	0%	-
	Flex Regs Global Inaction	96%	2%	1%	-

The accelerated cost declines for electric light-medium motors could make a large difference in possible adoption of the technology in all cases, with market shares potentially being between 39% and 54% higher in the Global Action scenario compared to Global Inaction. The faster cost decline for hydrogen fuel cell vehicles could also make a noticeable difference, although it is likely smaller than the impact of the electric light-medium motors. My simulations suggest hydrogen fuel cells in heavy freight trucks could capture between 23% and 54% in the Global Action scenario, while they may only capture between 0% and 11% in the Global Inaction scenario. This wide gap in adoption between the two scenarios is not an unexpected result as I noted there was significant disagreement in previous net-zero studies on the role hydrogen trucks may play. On the high end of this range the Canadian Institute for Climate Choices (2021) estimates hydrogen trucks could capture up to 64% of market share. At the low end the Government of Canada (2016) estimates they might only make up 5% in one of its cases.

Emissions from the freight transportation sector could be very different between the two scenarios, with Global Action scenario emissions being much higher. My simulation indicates this could occur despite the accelerated cost declines for hydrogen and electric trucks in the Global Action scenario, which may result in them capturing larger market shares in all cases. It appears the lower cost of oil and RPPs in the Global Action case could offset the faster cost declines and allow diesel to maintain a significant market share. The dynamic is illustrated in Figure 11, which shows the % of total liquid fuels that could be made up of diesel and biodiesel/HDRD in the C Tax Global Inaction (left) and C Tax Global Action (right) cases. In my simulation of the C Tax Global Inaction case, the share captured by biodiesel/HDRD may rise slowly until 2035 when it reaches 8% market share. After 2035, it could capture large market shares in each of the following periods before reaching 87% in 2050. The C Tax Global Action case may see a more gradual uptake of biodiesel and only reach 8% by 2040. After 2040, there could be an accelerated uptake that reaches 57% by 2050, as suggested by my modeling. This difference in biodiesel/HDRD uptake between these two cases appears to be enough to significantly change the emissions outcomes between the two simulated policy scenarios.

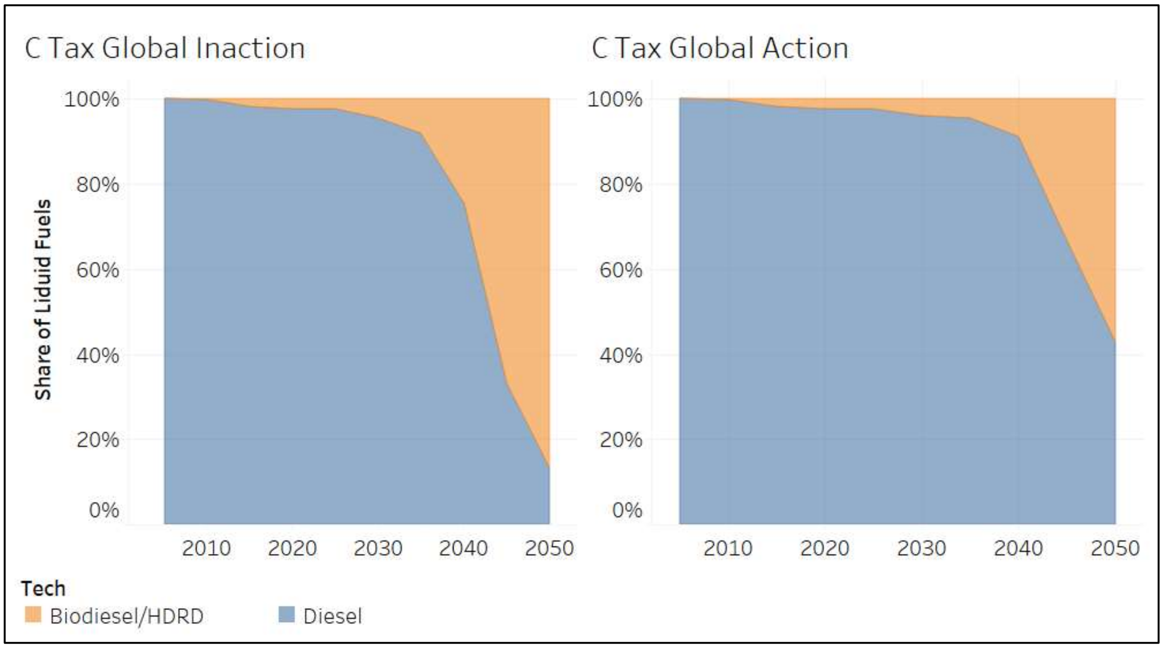


Figure 11: Share of liquid fuels provided by biodiesel/HDRD and diesel in the C Tax Global Inaction and C Tax Global Cases

3.3.6. Low Carbon Fuel Sectors

The low carbon fuels that I represent with discrete production sectors in the version of CIMS I used for this study are biodiesel, ethanol, and hydrogen. Figure 12 lists the simulated 2050 emissions from these three sectors. Unlike most of the other sectors in this study, my simulation suggests emissions from the biodiesel sector could be higher in the net-zero cases than in the reference cases. In both of the reference cases, simulated emissions are 2 Mt per year, and between 13 and 35 Mt in the net-zero cases. This is due to the demand for biodiesel which is much higher in the net-zero cases than in the reference cases. According to my modeling, emissions from the biodiesel sector could also be higher in the Global Inaction scenario net-zero cases compared to their Global Action counterparts. I suspect this difference is due to the lower demand for biodiesel from the freight sector in the Global Action net-zero cases which was explained in the previous section. Emissions in the biodiesel sector come from the use of natural gas and diesel in the production process. While diesel could still used in the net-zero cases, natural gas may be completely phased out and replaced by either biomethane or processes using electricity as an energy source. The diesel in this sector is used in the agricultural production of the feedstock material. In my simulations, some biodiesel endogenously replaces conventional diesel in agricultural input production, but it only captures 10% of the market share in the C Tax Global Action case and 20% in the C Tax Global Inaction case by 2050. The policies used in the Flex Regs cases were designed to approximate these results, which can explain why the production of biodiesel does not fall to zero emission in any modeled case.

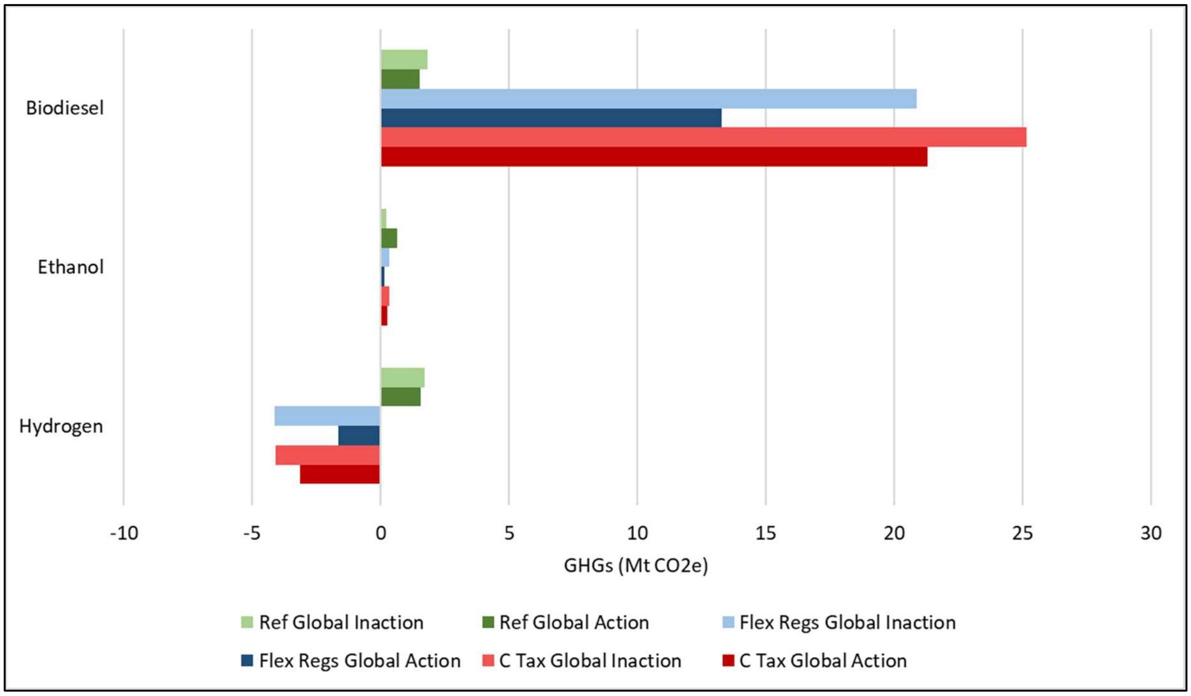


Figure 12: Emissions from the Biodiesel, Ethanol, and Hydrogen sectors in 2050 in all six cases

My modeling suggests emissions from the ethanol sector might not rise above 2 Mt in any of the cases, with emissions peaking between 2020 and 2030 for all cases then falling below 1 Mt by 2050. Even with stringent carbon pricing in place, ethanol may not capture market share above what is mandated in the personal transportation sector.[7] In

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[7] See Appendix A Table A1 for reference case transportation biofuel blending requirements.

the Flex Regs cases, ethanol is mandated to replace 100% of gasoline used in the personal transportation sector, although this might not lead to higher ethanol consumption. Instead, there may be a sizeable shift away from internal combustion engines to EVs, which could keep ethanol consumption at similar levels between the net-zero cases.

Simulations indicate emissions from the hydrogen sector could vary greatly from case to case due to the differences in the policy stringency and the cost of hydrogen using technologies, namely hydrogen heavy freight trucks. In the reference cases, simulated emissions from the hydrogen sector reach 5 Mt in the Global Action scenario and 2 Mt in the Global Inaction scenario. The hydrogen sector faces the same carbon price in both of these modeled cases, with the difference in emission stemming from the higher demand for hydrogen caused by the lower cost of hydrogen trucks in the Ref Global Action case. As part of the Global Action scenario, I accelerated the cost decline of electrolysers, although simulations indicate they still may not see uptake in any of my cases, with all market share being captured by methane steam reforming with CCS. In all four of the net-zero cases, total emissions could become negative for the hydrogen sector as a whole.

This result can be attributed to the combined use of biomethane and CCS in the manufacture of hydrogen using methane steam reforming, which has net negative emissions in my model. Like with all negative emissions technologies in my study I assumed payments are made to producers of negative emissions in the hydrogen sector at a rate equal to the regular carbon price. With producers receiving this payment, using biomethane in methane steam reforming plus CCS may be able to capture roughly 15% market share in all net-zero cases. The remaining 85% could be taken by methane steam reforming using fossil fuel natural gas and equipped with CCS according to my simulations. As a result, emissions may fall to between -4 and -2 Mt in all net-zero cases, with the lowest values being in the Global Action scenario.

A recent report by Larson et al. (2020) suggests hydrogen produced through negative emissions pathways could be important in American decarbonization, so it stands to reason it could play a role in Canadian decarbonization as well. It should however be noted the price of biomethane is not endogenously calculated in CIMS and instead relies on an exogenously specified price, which does not respond to market dynamics. Future researchers may wish to develop supply curves or production sectors for biomethane to more realistically simulate how its price could respond to changes in demand.

Chapter 4. Conclusions

4.1. Summary of Findings

The goal of my research is to explore potential policy pathways Canada could take to approach carbon neutrality by 2050 and help fill the knowledge gap surrounding this undertaking. Using an energy-economy model, I simulated six cases: a reference case (Reference) and two net-zero cases (Carbon Tax and Flexible Regulations), in two different global scenarios (Global Inaction and Global Action) designed to illustrate different levels of global climate action. The net-zero cases I developed in this study provide two contrasting examples of how carbon neutrality could be achieved in Canada. All of the modeling work in my research was conducted using the CIMS energy-economy model.

Through my work, I have shown net-zero GHG emissions may be approached through a mix of flexibly designed regulations or economy-wide carbon pricing. In all of my net-zero cases, emissions could fall to below 200 Mt CO2e per year, with the remaining emissions possibly offset by negative emissions technologies. The results from my research also indicate the current suite of announced and planned Canadian climate policies may be unable to achieve carbon neutrality, as emissions do not fall below 500 Mt in either Ref case.

In this study, I also assessed which emissions might be more difficult to abate and which may be done more cheaply. Emissions from the commercial and residential sectors appear to offer the cheapest avenues for emissions abatement of the sectors where I applied the full carbon price. In all of my net-zero cases emissions from the residential and commercial sectors may fall to near zero. In the Ref cases annual emissions from the residential sector could fall to 2 Mt in both scenarios and below 15 Mt in the commercial sector.

Emissions from the industrial minerals sector may be hard to abate even with higher carbon prices, as processes like cement production emit GHGs as part of important chemical reactions which have to be abated by expensive alternative production methods or carbon capture and storage. This was illustrated by the sharp rise in production cost when carbon pricing was implemented. To prevent carbon leakage, I chose to use a less stringent OBPS price in the Global Inaction case, which brought down production costs but also resulted in more sectoral emissions. The same situation played out in the other manufacturing sector, but to a lesser extent. While these sectors may be difficult to decarbonize, this does not mean achieving carbon neutrality is impossible, but it does suggest their emissions may need to be offset by negative emissions or enabled by a wider application of carbon capture and storage than I allowed in my modeling assumptions.

The differing emissions outcomes in my two scenarios suggest the level of climate action undertaken by the rest of the world will have impacts on Canadian emissions. If the world acts together on climate change, emissions from the Canadian oil sector will likely fall due to lower demand for Canadian hydrocarbon products and the associated lower oil price, and lower Canadian oil production. In my Global Action scenario, decarbonization is accelerated in some sectors by the faster development of low carbon end-use technologies, such as EVs, which benefit from a larger global market and increased investment. On the other hand, my work suggests lower oil prices will lead to lower prices for fuels such as gasoline and diesel and may keep them cost-competitive longer with low-emission options. Even in the presence of stringent carbon pricing, I found these carbon-intensive fuels were able to capture sizeable market share in the Global Action scenario cases, especially in the freight transportation sector.

If Canada were to act alone or with only a subset of leader countries in tackling climate change, as in the Global Inaction scenario, a key concern would be ensuring our EITE industries remain internationally competitive to not induce carbon leakage while also decarbonizing. My modeling indicates this is possible to achieve if the necessary policies are enacted. This is demonstrated by significant emission reductions in the Global Inaction scenario net-zero cases, which could be 15-20 Mt greater than what is seen in the Global Action scenario net-zero cases despite Global Inaction’s weaker OBPS.

In my study, emissions negative technologies proved to be important for Canadian decarbonization. BECCS could be especially important as it was responsible for transforming the Canadian electricity sector from significant contributor of emissions to a GHG sink. The production of hydrogen may also be an emissions sink, as the hydrogen production sector contributed negative emissions in all of my policy scenarios due to the use of biomethane and CCS in methane steam reforming.

4.2. Limitations and Future Research

The transition to carbon neutrality by 2050 represents a major shift for the Canadian economy over a three-decade horizon. While I attempted to capture the most important dynamics at play in this transition, there are still limitations that should be considered in future research:

1. Much of the emissions reductions achieved in the electricity sector were driven by the uptake of BECCS, yet modeling of the availability of CO2 storage space and biomass production for these facilities lacks detail in the model used for this study. Both the cost of biomass fuel and CO2 storage space are assumed to be fixed in this model, which may not accurately reflect the dynamics at play. To partially offset this the amount of BECCS adopted was limited, although including market feedbacks in the model would help to improve realism.
2. In this study, I did not attempt to model the general equilibrium, macro-economic dynamics of the Canadian economy. As the Canadian economy responds to stringent decarbonization policies, such as those in my Flex Regs and C Tax cases, macroeconomic shifts may occur as investment and employment flow from emissions-intensive sectors to those of lower intensity. The CIMS energy-economy model used for this study is able to incorporate partial equilibrium dynamics but lacks the functionality to simulate full macro-economic dynamics. Work by the Canadian Institute for Climate Choices (2021) has incorporated computable general equilibrium modeling to illustrate possible technology pathways which could be used to achieve carbon neutrality in Canada. However, there is yet to be a study which assesses the policy stringencies needed to achieve net-zero with this type of modeling in Canada. Future researchers have an exciting opportunity to fill this research gap and provide insightful results that could be used to inform the discussion surrounding Canadian decarbonization.

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Appendix A

Figure A1: Market share heterogeneity based on price and v parameter (Nyboer, 1997)

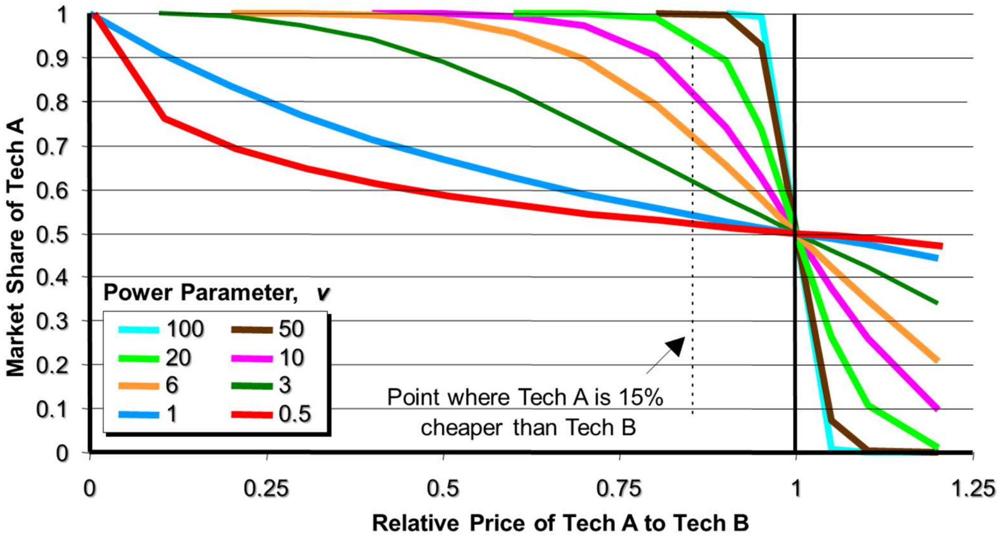
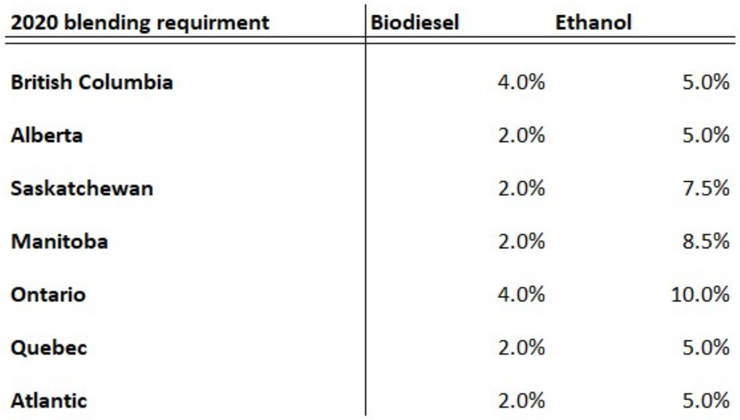


Table A1: 2020 biofuels blending requirement by % volume for each region of Canada



2020 blending requirment	Biodiesel	Ethanol
British Columbia	4.0%	5.0%
Alberta	2.0%	5.0%
Saskatchewan	2.0%	7.5%
Manitoba	2.0%	8.5%
Ontario	4.0%	10.0%
Quebec	2.0%	5.0%
Atlantic	2.0%	5.0%

Table A2: Full list of reference policies included, and techniques used to model them in CIMS

Region	Policy	Description	Implementation
Federal	Carbon Pricing Backstop Fuel Charge	A charge for the release of GHG emissions applied to fossil fuels. It begins at $30/tonne CO2e and rises to $170/tonne by 2030.	I applied an emissions price in CIMS. The price was also adjusted for inflation which resulted in a falling price in real terms. I assume carbon pricing and cap & trade stringencies in all provinces converge to meet this stringency by 2025
	Carbon Pricing Backstop Output Base Pricing System	A performance standard that applies to industrial facilities emitting more than 50kt CO2e per year. Emitters are allocated credits to covering a fraction of their emissions compared to a baseline intensity. It begins at $30/tonne CO2e and rises to $170/tonne by 2030.	Industries in all regions were exposed to the full carbon price and had revenue recycled back into their respective sectors to represent the effect of credit allocation. The price was inflation adjusted
	Coal and natural gas electricity generation CO2 intensity regulations	This policy shuts down coal and natural gas electricity generation facilities emitting more than 420 tonnes CO2e/GWh by 2030	Coal and natural gas facilities emitting more than the specified emissions limit were shut down by 2030
	Renewable Fuel Standard	Requirement for gasoline to be blended with 5% renewable fuels and 2% for diesel	Set minimum market shares for ethanol in gasoline and biodiesel in diesel. This was only applied in Quebec and the Atlantic Provinces
	Heavy-duty vehicle emission standards	Set a minimum emissions standard for freight vehicle efficiency based on CO2/tonne-mile	Made standard efficiency heavy freight vehicles unavailable after 2050
	Light duty vehicles emissions standards	Sets a maximum for how much CO2 can be released per km driven	I made standard efficiency gasoline motors unavailable after 2020
	Building codes	Regulations set minimum efficiency standards for new buildings	Residential: prevented the sale of low and standard efficiency AC units, natural gas furnaces and water heaters, oil furnaces and heaters, and electric heating based on regulation. Commercial: Applied the same method to low and standard efficiency energy devices in the commercial sector

	Energy efficiency regulations	Sets minimum efficiency standards for energy using products	Make non-complaint technologies unavailable by 2020-2015 including; incandescent light bulbs, certain natural gas water heaters, HVAC units
British Columbia	Renewable portfolio standard	Requires 93% of electricity generation come from renewable sources	Disallowed all emitting sources of electricity generation, except some diesel (for northern communities)
	Landfill Regulations	Regulations created to better manage GHGs released from landfills	Required that 50% of landfills in BC use methane reduction technologies
	Renewable Fuel Regulation	Requirement for gasoline to be blended with 5% renewable fuels and 2% for diesel	Set minimum market shares for ethanol in gasoline and biodiesel in diesel.
	Zero-Emission Vehicles Act	Requires 10% of light-duty vehicle sales be zero emission vehicles by 2025, 30% by 2030 and 100% by 2040	Set a shrinking maximum market share for emitting vehicles which them becoming unable by 2040
Alberta	Renewable Fuels Standard	Requirement for gasoline to be blended with 5% renewable fuels and 2% for diesel	Set minimum market shares for ethanol in gasoline and biodiesel in diesel.
	Methane Emissions Reduction Regulation	Requires methane emissions from oil and gas production be 45% lower than 2014 levels by 2025	Disallowed oil and natural gas extraction technologies without leak detection by 2025
Saskatchewan	Boundary Dam Carbon Capture Project	Retrofit of a 115MW coal plant with CCS technology	Forced 115 MW of coal to be converted to coal with CCS in 2015
	Ethanol Fuel Regulations	Requirement for gasoline to be blended with 7.5% renewable fuels and 2% for diesel	Set minimum market shares for ethanol in gasoline and biodiesel in diesel.
	Methane Emissions Reduction Regulation	Requires methane emissions from oil and gas production be 45% lower than 2014 levels by 2025	Disallowed oil and natural gas extraction technologies without leak detection by 2025
Manitoba	The Biofuels Act	Requirement for gasoline to be blended with 10% renewable fuels and 5% for diesel	Set minimum market shares for ethanol in gasoline and biodiesel in diesel.
	Coal phase out	Phased out of coal from Manitoba's electricity sector by 2010	Retires all existing coal generation by 2010
Ontario	Greener Gasoline Regulation	Requirement for gasoline to be blended with 10% renewable fuels and 5% for diesel	Set minimum market shares for ethanol in gasoline and biodiesel in diesel.

	Coal phase out	Phased out coal generation from the electricity sector in 2014	Forced all existing coal generation to retire by 2015
Quebec	ZEV Mandate	Requires zero emission vehicles to capture 9.5% market share in 2020 then 22% in 2025 and after	I set minimum market shares that had to be met by zero emission vehicles
	Renewable Natural Gas Mandate	Biomethane must make up at least 1% of methane distributed by 2020 and 5% in 2025	Set minimum market shares for biomethane in natural gas using sectors to match the regulation
	Renewable Fuel Regulations	Requirement for gasoline to be blended with 10% in 2020 (and 15% in 2025) renewable fuels and 2% in 2020 (and 4% in 2025) for diesel	Set minimum market shares for ethanol in gasoline and biodiesel in diesel.
Atlantic	Electricity GHG emission cap	Nova Scotia's electricity sector regulations which puts an emissions cap on the sector that falls to 2.5 Mt CO2 by 2050	Retired some coal generation and disallowed new coal generation to be built
	Renewable Electricity Regulations	Nova Scotia requirement that requires 40% of electricity generation in the province come from renewable sources	Set minimum market shares for renewable electricity generation sources
	Renewable Portfolio Standard	New Brunswick regulation that requires 40% of electricity sales in the province come from renewable sources by 2020	Set minimum market shares for renewable electricity generation sources