Technology and Policy Pathways to Decarbonize Emissions-Intensive and Trade-Exposed Industries

by

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Table of Contents

List of Tables

List of Equations

EITE industries are comprised of heavy and manufacturing industries and the oil and gas sector. Heavy and manufacturing industries make the primary products and materials we use in our daily lives. Cement lays the foundation of our buildings and cities, we use steel to make the cars we drive, and chemical products make gloves and masks for our hospitals and fertilizers for our food production. Demand for these industrial commodities has increased significantly over the past two decades and is expected to persist in a low-carbon world (Bataille, 2020; IEA, 2020a). Despite global improvements in material efficiency and recycling, the need for fewer energy-intensive materials, growing economies, and the push towards net-zero may even result in increasing demand for certain industrial products (Senate Canada, 2018). For instance, wind turbines will demand steel, batteries will require an increase in the mining of minerals, and the continued need for strong and light materials for transportation could cause a rise in the use of aluminum.

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Achieving net-zero emissions for EITE industries has only recently begun to permeate the literature. Much of the existing literature on EITE decarbonization has focused on technology and policy review, demonstrating the technological feasibility of net-zero without determining the policy stringency needed to support the transition (Bataille, 2020; CICC, 2021; IEA, 2020a; Rissman et al., 2020). Furthermore, studies have focused on industry-specific decarbonization pathways and have not addressed the potential for regional strategies to identify economic opportunities and challenges like resource availability.

I aim to fill this knowledge gap by asking the question: What are the technology and policy pathways to decarbonize Canada's EITE industries? To address this research question, I have three objectives:

1) Determine policy stringencies needed to achieve different levels of EITE decarbonization depending on the risk of carbon leakage;
2) Identify near-commercial and emerging technologies to decarbonize EITE industries and evaluate their uptake and emissions reductions as the result of GHG reduction policy; and
3) Evaluate major EITE decarbonization pathways based on regional circumstances, such as industrial heterogeneity and resource availability.

For my first objective, I create two Canadian EITE policy scenarios based on different levels of global action on climate change: action and inaction. In the Global Action scenario, a global push on GHG reduction policy eliminates the risk of carbon leakage in Canada. It allows policymakers to use stringent policy to achieve high levels of EITE industry decarbonization by 2050. In the Global Inaction scenario, where Canada is a leader in achieving net-zero by 2050, carbon leakage remains a significant risk. Policymakers must balance this risk with decarbonization efforts, resulting in less EITE industry decarbonization.

To determine the policy stringency needed to achieve different levels of EITE decarbonization, I use the CIMS energy-economy model. CIMS represents the capital stocks in an economy and simulates their turnover and competition with one another over time because of GHG reduction policy. CIMS is a partial equilibrium model and does not simulate structural and output changes caused by production cost increases in industry. As my first objective looks at two different scenarios on global action on climate change, I account for carbon leakage and thus do not need to model full equilibrium effects.

CIMS is also an ideal model to address my second research objective: it features a high level of technological detail, allowing me to examine how EITE GHG reduction policies might influence the market shares of specific technologies into the future. I conducted a literature review on near-commercial and emerging technologies to decarbonize EITE industries and added them to CIMS to increase the technological resolution for net-zero by 2050.

For my third research objective, I analyzed the results from my modelling in terms of regional differences. The CIMS model features seven regions: British Columbia (BC), Alberta, Saskatchewan, Manitoba, Quebec, Ontario, and Atlantic Canada, each with its unique combination of EITE industries and resource availability that reflect Canada's regional resource disparities. I look at regional decarbonization pathways and assess how the costs of specific resources affect the uptake of low emissions technologies.

The following chapter provides background information on Canada's EITE industries and the technology and policy pathways to decarbonize them. Chapter 3 explains the methodology used for this study, including the CIMS model, literature review results for low emissions technologies, and a decomposition analysis which was used to determine where emissions reductions were coming from. Chapter 4 explains the two scenarios I have created and the key model and policy differences they have. Chapter 5 outlines and discusses the results of the study. Chapter 6 summarizes the study's main findings and discusses limitations and further avenues for research.

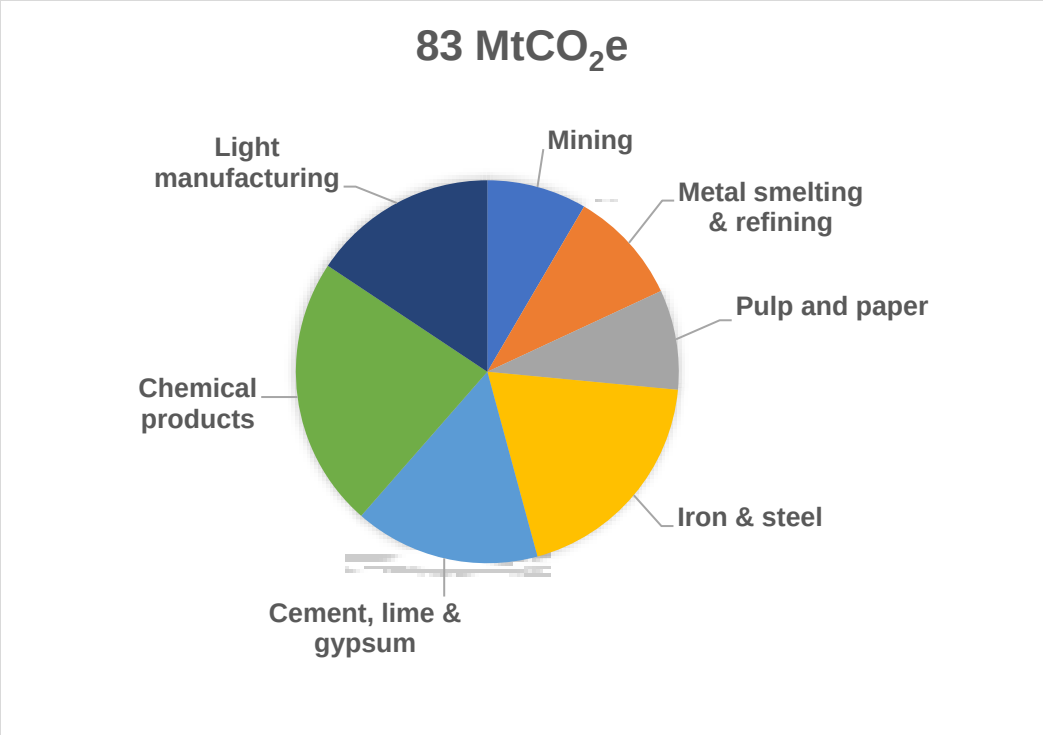

Figure 1. Emissions by EITE industry in 2018

Chemical products, iron and steel, and cement, lime and gypsum make up most of EITE industry emissions, emitting 19, 16, and 13 $MtCO_2e$, respectively. Metal smelting and refining, pulp and paper, and mining make up a smaller portion of emissions, emitting 8, 7, and 7 $MtCO_2e$, respectively. Light manufacturing, although emitting 13 $MtCO_2e$, is an amalgamation of many industries, such as food and beverage products, textiles, transportation equipment, electronics, furniture, and wood products.

Canada produces many chemical products, with ammonia and petrochemicals contributing to half of the industry's emissions due to high energy requirements and the reliance on fossil fuels for production processes (Bataille & Steibert, 2018). Ammonia is a component in nitrogen-based fertilizers, whereas petrochemicals are important plastic precursors. Ammonia production mainly occurs in Alberta and Saskatchewan due to cheap and plentiful natural gas. Petrochemical production mainly occurs in Alberta and Ontario. Ethylene and propylene, the most highly produced chemicals, are made via the steam cracking of crude oil or natural gas feedstocks.

Iron and steel is the second highest EITE industry emitter, with the majority of production concentrated in Ontario and Quebec. The most emissions-intensive part of the industry is the production of crude steel. Canada produces crude steel in three ways:

1) Blast Furnace-Basic Oxygen Furnace (BF-BOF), where virgin steel is produced in two steps: 1) coke reduces iron ore to pig iron in the blast furnace, and 2) this liquid iron is then purified via the injection of high purity oxygen in the BOF. This process is highly emissions and energy-intensive, and most facilities that use this type of production are in Ontario.
2) Electric Arc Furnace (EAF), where steel is made from 100% scrap using electricity. Although energy-intensive, this process can be emissions free depending on the emissions intensity of electricity generation. The location of most facilities EAF is in Quebec due to its hydropower resources for low-cost electricity generation.
3) Direct Reduced Iron (DRI-EAF), where virgin steel is made by reducing iron ore using natural gas and syngas, and then melted and alloyed in the EAF. This process is relatively new and eliminates coke use; thus, it is less emissions-intensive than BF-BOF steel. Canada has only one facility, which is also in Quebec.

Cement and lime production is found predominantly in Ontario and Quebec. Cement is responsible for 10 $MtCO_2e$ out of the total 13 $MtCO_2e$ in this sector. The most common type of cement produced globally and in Canada is Portland cement. To make Portland cement, raw materials – lime, iron, and silica-alumina – are pulverized and mixed before being fed into rotary kilns. The kilns are then fired at high temperatures of 1400 ^0C and become clinker. The clinker is then cooled and pulverized with a small addition of gypsum to create the finished product.

The metal smelting and refining industry turns mined ores into various metal products. The production of aluminum, nickel, copper, zinc, lead, magnesium, and titanium are the most energy and emissions-intensive metals in this sector. Aluminum refining industries, which demand significant electricity supply for the Hall-Heroult refining process, are in regions with access to historically low-cost hydroelectricity like Quebec and British Columbia.

Pulp and paper facilities are found across the country but concentrated in areas with active forestry industries. The pulping process breaks wood down into pulp, which occurs via chemical and/or mechanical processes. In mechanical pulping, machinery tears up cellulose in wood fibre to make paper and is electricity intensive. Chemical pulping dissolves the lignin that holds the

cellulose together. In chemical pulping, the dissolved lignin can be used as a biofuel to heat and power the facility using Tomlinson recovery boilers – a net surplus of electricity to the grid is also common. Canada's pulp and paper industry has already achieved significant decarbonization levels using the heat and power from Tomlinson recovery boilers (Bataille & Steibert, 2018). Recycled pulp consumes less energy than mechanical or chemical pathways, but the supply of recycled materials is a significant limitation. The pulp produced then serves as the stock for paper products, such as newsprint, tissue paper, coated and uncoated paper, and linerboard.

Mining in Canada involves extracting, refining, and processing essential minerals like gold, silver, nickel, copper, zinc, and iron. It can also include quarrying, where mines extract sand and gravel for construction purposes. However, I exclude quarrying from this study due to its comparatively small energy use and emissions. The mining industry is spread out across the country, as mining facilities are located near or directly on top of extraction sites for the raw materials. Mines in Canada are either open-pit or underground and although the mining processes are similar, there are key technological differences that change energy consumption. For instance, underground mines must address air quality issues from fuel combustion, which requires cooling, heating, and ventilation processes that consume energy.

Light manufacturing has facilities across the country. Most of the light manufacturing production processes have lower temperature heat and steam requirements than other EITE industries, meaning that there are many low carbon fuel options to decarbonize their production processes (Friedmann et al., 2019; Sandalow et al., 2019).

2.2 Technology pathways to net-zero for EITE industries

There are two dominant pathways to decarbonize EITE industries: decarbonizing current production processes or developing entirely new production processes that rely on low-emissions technologies. If current production processes are maintained, energy efficiency, using fossil fuels with carbon capture and storage (CCS), and switching to low carbon fuels can reduce emissions. Although energy efficiency can reduce emissions, many existing industrial production processes are already close to their technological limits of efficiency (ABB Ltd., 2013). In contrast, CCS and fuel switching can achieve emissions reductions of up to 100%. If investment in new production processes can occur, there are many near-commercial and

and the ability to retain the injected CO_2 (Bachu, 2003). In terms of EOR, where CO_2 is injected to recover an additional 5-15% of the reservoir's oil, storage can become a revenue generating opportunity.

Estimates on storage capacity in Canada vary widely, from 318-2236 Gt CO_2, including all onshore and practically accessible offshore sites (Kearns et al., 2017). Saline aquifers have the highest storage capacity for CO_2 in Canada because of the favourable conditions of the Western Canadian Sedimentary Basin – one of the largest potential geological storage sites for CO_2 in the world. Most Alberta and Saskatchewan industrial facilities are located on top of the basin. British Columbia (BC) has storage capacity in depleted gas reservoirs in the North-East of the province. Eastern Canada has fewer storage opportunities, with only limited storage under Lake Eerie and under the ocean floor off the coast of Atlantic Canada.

Low carbon electricity

Over 80% of Canada's electricity comes from non-emitting sources of primary energy (Natural Resources Canada [NRC], 2019). Quebec, BC, and Manitoba have large hydropower, allowing low-cost emissions-free electricity to dominate their grids. As wind and solar generation costs continue to fall, Canada can also harness its considerable intermittent renewable electricity generation capacity. Lastly, there are low-cost opportunities for fossil fuel generated electricity with CCS in Western Canada.

Although viable from a resource and technology standpoint, industrial electrification would have to pair with an accelerated build-out of low-carbon electricity infrastructure and transmission lines (de Pee et al., 2018; Lechtenböhmer et al., 2016). Furthermore, as national GHG reduction policy strengthens, other sectors in the economy may also rely on electricity to decarbonize, like the transportation and residential sectors. Many studies on deep decarbonization have found that electricity use is likely to double in a net-zero future (Bataille et al., 2015; CICC, 2021; IEA, 2021). This dramatic growth in electricity demand and the subsequent build-out could result in significant economic and political constraints.

Biomass

Biomass can serve as a fuel or a feedstock for many EITE industrial processes and is carbon-neutral, meaning that it produces no net emissions on a lifecycle basis. EITE industries can use biomass in solid, gaseous, and liquid forms to decarbonize their production. Gaseous forms,

such as biomethane, can replace natural gas in heat and steam production. Solid biomass can serve as a low carbon fuel as well as a feedstock. Biofuels, a converted form of biomass, can be used as a fuel source for the transportation of industrial materials and primary products. Lastly, biomass can produce zero emissions fuels like electricity and hydrogen, and when coupled with CCS, it can even result in negative emissions.

Biomass has three advantages compared to other decarbonization pathways: existing fossil fuel infrastructure can use it, it can create similar heat levels to fossil fuels (Stephen & Wood-bohm, 2016),[2] and it is relatively cheap and easy to transport. Despite these advantages, biomass to produce energy, especially when scaled up, is controversial. The availability of land limits biomass use, and if combusted openly, biomass use can result in air quality issues (Industrial Gas Users Association, 2018; IPCC, 2018). It can also directly compete with food sources, such as biomass from corn or palm oil. However, certain forms of biomass, like wood waste from forestry operations, agricultural waste from farming, and biomethane from landfills, are sustainable and relatively low cost compared to dedicated biomass crops. Canada is estimated to be able to produce 1.5-2.2 exajoules of energy per year using these residues or waste biomass streams (Stephen & Wood-bohm, 2016), which is equivalent to ~15% of Canada's total energy demand in 2017 (Canada Energy Regulator [CER], 2021).

Hydrogen

Hydrogen is an abundant element but often exists in nature as a compound like methane (CH_4) or water (H_2O). The process to separate hydrogen from chemical compounds is energy intensive. Recently, it has become a norm to refer to three types of hydrogen produced, each with different emissions associated with them:

1) Grey hydrogen: where hydrogen separates from fossil fuels like natural gas in the p-3(su)A019.72[( )] TJETQq0.00000912 0 612 792 reW*nBT/F3 10.98 TfCy.b0 63(li)-3(0.[(e9i 792 reWp

Nature-based solutions are land limited and must compete with other land uses to play a role in negative emissions in Canada. They can also be impermanent – for example, a forest fire or beetle outbreak can decimate a tree plantation. Engineered solutions, depending on how the carbon is either used or stored, can be more permanent. However, substantial uncertainties are associated with their scalability and cost-effectiveness (CICC, 2021). In this study, I chose a limited representation of these technologies for BECCS in both Alberta and Saskatchewan due to their proximity to high-quality CO_2 storage sites. BECCS will be discussed further in Chapter 3. I treat DAC as a backstop technology, meaning that the government offsets any emissions left over from EITE industries in my scenarios if it upholds the promise of carbon neutrality by mid-century. I do not model DAC explicitly.

2.3 EITE GHG reduction policy

Stringent policy is needed to incentivize the technological change needed to decarbonize EITE industries. This section highlights general policies for EITE decarbonization, then explains Canada's current policies.

2.3.1 General EITE GHG reduction policies

The most effective policy mechanism to ensure EITE industry decarbonization while protecting against carbon leakage 7A4-3(E)]] TJsutrality by

commercialization support can encourage industries to adopt low emissions technologies while reducing the cost of decarbonization.

GHG reduction policies

In Canada, the current EITE GHG reduction policy strategy is evolving due to shared jurisdiction on environmental concerns between federal and provincial governments. The Supreme Court of Canada recently ruled that the federal government has the authority to impose a national carbon price to reduce GHG emissions and earlier court rulings had supported its authority to impose nation-wide regulations on GHG emissions. However, provincial governments can also implement GHG reducing policies. Thus, the federal GHG reducing policies might be considered as “backstop” policies which apply to provinces with insufficient or no GHG reducing policies to ensure a consistent, fair, and effective national GHG effort.

An OBPS was introduced as the federal backstop policy for EITE industries in Canada in 2019. The OBPS sets sector-level emissions intensity benchmarks based on average sectoral emissions between 2014-2016 (ECCC, 2018). If a firm exceeds the sectoral benchmark, it must pay the federal carbon price on excess emissions. If the firm outperforms the benchmark, it is allocated tradeable emissions credits for the corresponding additional emissions reductions. The OBPS allows the marginal carbon price to be preserved while the average carbon price paid by all facilities remains low as the policy only operates on the emissions in excess of the benchmark.

The federal OBPS currently applies to Saskatchewan, Manitoba, Ontario, New Brunswick, and Prince Edward Island, as these provinces do not have sufficiently stringent policies to date targeting their EITE industries. However, Ontario and New Brunswick have both put forward their own OBPSs which have been accepted and will be applied after consultation with the federal government (Government of Canada, 2020). Alberta, BC, and Quebec all have carbon pricing systems in place for their EITE industries that align with the federal OBPS stringency.

Alberta’s partial carbon pricing system is called the Technology Innovation and Emissions

an industry fund. Industries can use this fund to invest in lowering their emissions. Quebec is part of a cap-

Chapter 3. Methodology

In this chapter I explain the methodology for my three research objectives. I discuss the reason I choose the CIMS model, its general functionality, and its settings and calibration. I highlight the findings from my literature review on technologies that decarbonize EITE industries and outline the resulting model updates. Lastly, I explain the decomposition analysis I use to determine where emissions reductions occur in each of my scenarios.

3.1 Model overview

3.1.1 Model choice

To determine how Canada's EITE industries will respond to domestic GHG reduction policy, I use the CIMS model developed at the Energy and Materials Research Group at Simon Fraser University. CIMS is a hybrid energy-economy model which simulates how capital stocks of energy producing and consuming technologies change over time in response to GHG reduction policies (Jaccard, 2009).

I use CIMS to model EITE decarbonization for two reasons: it is technology explicit and partial equilibrium. Technological explicitness means that CIMS calculates the costs of competing technologies and processes and can estimate possible low-cost emissions reduction options for EITE industries in response to GHG reduction policy. Partial equilibrium means that while CIMS balances supply and demand within energy producing and consuming sectors of the economy, it can be used without simulating structural and output changes caused by production cost increases. Both these attributes make this model ideal for addressing my research objectives: I aim to assess the uptake of low emissions technologies in EITE industries without explicitly modelling how production cost increases will affect competitiveness with EITE industries in other countries.

To address competitiveness and carbon leakage concerns, I instead create two plausible scenarios to represent how global GHG reduction policy will affect Canadian policy stringency. I assume that either Canada is acting in concert with the rest of the world and can thus implement stringent policy on its industrial sectors, or it is a leading GHG policy implementer

and thus must implement measures to protect EITE sectors from carbon leakage or reduce its policy stringency. I address these scenarios in detail in Chapter 4.

3.1.2 CIMS functionality

In CIMS, capital stocks of technologies are assessed each period and are retired if they have reached the end of their lifespan or retrofitted if economic conditions motivate this response. Next, the model assesses the gap between energy supply and demand and determines which technologies to purchase to match supply and demand in the energy sector. CIMS repeats this

heterogeneity (v). The r parameter is the time preference of decision-makers, who value returns

technology added from 2005 to the previous period in each province, is the cumulative new stock of a technology for all years up to and including the year 2000 in each province, is the progress ratio which is the amount cost should decrease in response to a doubling of cumulative production. I have adjusted the

products changes as costs of manufacturing change and 2) activity elasticities for freight transportation and buildings, where output is based on changes in the output of manufactured products like cement and steel. I turned the macroeconomic feedback function off for this study. I am only assessing industry-specific technological and cost change in this study, not macroeconomic feedbacks like shifts in demand for manufactured goods as prices change.

A third function is the greenhouse gas pre-

Table 1. Comparison of CIMS and NIR emissions, by industrial sector ($MtCO_2e$)

CIMS uses sectoral activity level forecasts as a key driver of emissions projections. The oil and gas and industrial sector activity levels specify the levels of production or other activity in each sector, such as tonnes of iron and steel and billion dollars of GDP in light manufacturing. The activity levels in turn drive energy technology acquisition and energy consumption, and thus emissions. Table 2 shows the exogenous national average annual growth in activity in each sector.

Sector activity level forecasts for the petroleum extraction and natural gas extraction were based on the reference case projections from the CER's Canada ®Я ₴ o[Ï

Table 2 National average annual growth in activity, by sector

		2020-2030	2030-2050
Oil and Gas	Petroleum Extraction	4.2%	

added to all industrial heat and steam production in the form low carbon fuel boilers and burners, or boiler and burners that could apply CCS if industrial flue streams had high concentrations of CO_2. There was a lack of information on technologies available to non-ferrous metal smelting for deep GHG reductions – pathways to net-zero in this sector relied on reducing emissions in heat and steam production.

Table 3. Near-commercial and emerging low emissions technologies

Industry	Low-carbon technology/process	Process Description
Iron and steel	BF-BOF with CCS	BF-BOF with post combustion CCS
		Uses iron ore directly and eliminates the use

The iron and steel industry has many low emissions technology options, mostly replacing the conventional BF-BOF production of crude steel. These new production processes utilize CCS, low carbon electricity, and hydrogen. These are all promising emissions reduction pathways, and their adoption will centre around the availability and cost of resources.

Cement production has limited options for decarbonization other than CCS as 60% of its emissions are process emissions (IEA, 2020c). Another pathway to emissions reductions is through the reduction of clinker content of cement. Clinker requires significant amounts of energy in its production and can be replaced by various cementitious substitutes such as coal fly ash or blast furnace slag.[3] The level at which clinker can be replaced depends less on technology performance and more on the availability of substitutes and the potential for cross-sectoral impacts, like the building sector changing regulations around cement clinker content. Due to these complications, cementitious substitution is often limited to lower levels in cement production (IEA, 2020a; WSP Parson Brinkerhoff & DNV GL, 2015).

Ammonia synthesis can use CCS to capture emission from its production of hydrogen from natural gas, or it can source hydrogen from numerous low carbon production pathways, like biomass gasification and electrolysis of water. The production of ethylene, propylene, and other olefins can continue using its hydrocarbon feedstock while employing CCS or switch to biomass feedstocks to achieve carbon neutral production.

Mining operations with access to grid electricity can decarbonize the extraction, manipulation, and transportation of metal ores through electrification. Mines that do have grid access are often already partially electrified, as electricity eliminates the need for the ventilation of combustion exhaust from fossil fuel and biofuel, resulting in decreased costs of operation. Remote mines with no access to grid electricity can use biodiesel to extract, transform, and transport ores.

In this study, pulp and paper, mining, light manufacturing, and metal smelting all rely on fuel switching technologies to decarbonize their production processes. There was a lack of technology options for decarbonization found in the literature, and thus these industries have

1. Distributed steam methane reforming (SMR): hydrogen is produced onsite using natural gas and steam;
2. Distributed grid electrolysis: hydrogen is produced onsite using grid electricity to split water;
3. Central SMR (with and without CCS): centralized production using natural gas and steam;
4. Central electrolysis: centralized production using electricity to split water; and
5. Central biomass gasification (with and without CCS): centralized production where biomass is gasified to produce hydrogen. CCS option results in negative emissions as biomass is considered a carbon neutral source of energy.

Although coal gasification is another common method of hydrogen production, I chose to exclude it in this study for two reasons: 1) it has high emissions intensity when compared to SMR, and 2) Canada is phasing out coal generation in the electricity sector. Hydrogen production data was derived from the U.S. Department of Energy's National Renewable Energy Laboratory using their H2A hydrogen production models. Technology details can be found in Appendix A Table A-2.

The price of hydrogen must also account for the compression, storage, dispensing and transportation costs. Compression, storage, and dispensing costs are well established and not likely to decline substantially (Ramsden et al., 2013). They were included in the capital costs of the two distributed production pathways. Centralized production pathways called on a hydrogen infrastructure service which accounted for compression, storage, dispensing and transportation costs.

The cost of transportation varies greatly depending on the quantity of hydrogen transported, the method of transportation, and the distance. Currently, hydrogen transportation is dominated by a relatively expensive compressed gas trucking option (IEA, 2019). Liquifying the hydrogen and transporting it by truck is a cheaper option, and as quantity of hydrogen demanded increases as well as transportation distance,[(o)-6100756 o

separated the decomposition identity into two components. For combustion emissions, the decomposition identity accounts for five factors that influence emissions, which can be seen in Equation 3:

Equation 3:

Reductions in process emissions associated with changes in the variable in equation 4 were also attributed to carbon capture and storage, while reductions associated with changes in the variable were attributed to process emissions abatement that resulted from a change in industrial process or the adoption of a new technology that reduces process emissions.

As carbon capture requires energy, it leads to greater energy intensity ( ) in equation 3. This results in less emissions abatement from the energy efficiency category. To account for this, a portion of the emissions reduction allocated to CCS was removed and added instead to energy efficiency.

Chapter 4. Scenarios

4.1 Scenario overview

I created two scenarios of the Canadian energy system and GHG emission reduction efforts out to 2050 for assessing Canadian EITE decarbonization potential. These scenarios are Global Inaction, where Canada acts alone to tackle climate change, and Global Action, where Canada acts in concert with the rest of the world. These scenarios differ in three distinct ways: domestic GHG reduction policy and its stringency, the global price of oil, and the pace of technological change for low emissions technologies.

Although many Canadian provinces have their own GHG reduction policies, I have chosen to model federal backstop policies nationwide. This helps determine the policy stringency needed nationwide to achieve deep GHG reductions in EITE industries. In each of my scenarios, I model the entire economy. Although the focus of my study is on

electricity, hydrogen, or biofuels. Second, the oil price dictates the production levels of the Canadian oil industry. Canada's oil reserves are predominantly oil sands: an unconventional resource with high costs and emissions intensity associated with its production. If the global oil price is high, it is more economically attractive to expand oil sands production, whereas if it is low, the Canadian oil industry can be outcompeted by countries with conventional oil resources like Saudi Arabia and Russia.

Although I have excluded the oil and gas sector from my assessment of the decarbonization of EITE industries, it is still a major energy consuming sector, and thus can affect the prices of energy received by EITE industries. Therefore, it is still important to model this sector to determine its impact on EITE decarbonization.

I based my two global oil price and Canadian oil sands production scenarios on the CER's Canada's Energy Future 2018 Report. The global oil price trajectory and the resulting impacts on Canadian oil sands production out to 2050 can be seen in Table 5.

Table 5. Oil price, oil production, and RPP price in 2050

Scenarios	Oil Price trajectory (Western Texas Intermediate: $/bbl, 2019 USD)	Canadian Oil Production (million barrels/day)	Gasoline Price ($/L, before carbon price, 2019 CAD)

As the price of oil is highly volatile, these two scenarios for oil price are not meant to represent forecasts, but instead two viable alternate futures. In this way, I can assess the sensitivity of my results to different oil prices.

4.1.3 Pace of technological change

As GHG reduction policy strengthens globally, greater adoption of low or zero-emissions technologies will drive down capital costs due to economies-of-scale and economies-of-learning. Certain technologies, like wind and solar generation, have already seen substantial cost declines (IEA, 2020b).

To reflect capital cost evolution for key low-emissions technologies under my two scenarios, I used the CIMS declining capital cost function to mirror future capital costs found in the research and industry literature. Although none of these technologies are used directly in EITE industries, they influence the price of electricity and hydrogen – two key low carbon fuels for the decarbonization of industrial production. Table 6 shows the capital cost evolution of key technologies from 2020 to 2050.

Table 6. Evolution of the capital cost of key technologies under two scenarios

Solar, wind, and EV battery cost declines are derived from the CER's Energy Future 2020 report. Capital cost declines for hydrogen fuel cells and hydrogen production are taken from the IEA Hydrogen Future (2019) report and the Ramsden, Steward, & Zuboy

it has been used by industry for decades to meet process and demand needs (IPCC, 2005). And, although widespread adoption would foster economies-of-scale, the increasing amount of CO_2 sequestered would have to be either used or stored. As storage capacity decreases, the cost of storing CO_2 would increase. As CIMS currently has no function to replicate this increased storage cost as more CO_2 is captured, I am assuming the cost declines in the capture technology would offset some of this. Thus, I decided there would be little difference in cost for CCS between the Global Inaction and Global Action scenarios.

4.2 Cases

In each scenario of global climate action, I compared a reference (Ref) case to a stringent policy (StringPol) case. This section details the policies modeled in all four cases.

4.2.1 Reference

The Ref cases in both the Global Inaction and Global Action scenario were designed to represent a baseline to compare emissions reductions achieved by stringent policies on EITE industries. Both Ref cases have a carbon price starting at $10 in 2019 and rising to $170 in 2030, where the price remains out to 2050. EITE industries (including oil and gas) are completely exempt from the carbon price in my Ref cases to best demonstrate emissions reductions achieved in EITE industries in my StringPol cases.

Although Canada currently considers electricity, hydrogen, and biofuel sectors as emissions-intensive and trade-exposed, I have chosen to model them as non-EITE sectors, and thus the full carbon tax applies in the Ref cases. I made this choice for two reasons: these f*nB.1 1 0ubre al

$350 by 2050. This price applies to all sectors of the economy except EITE industries. The price schedule is expressed in real dollars, and thus accounts for inflation.

For EITE industries, I replicated the federal government's EITE partial carbon price policy – the OBPS. It sets industry-specific emissions intensity benchmarks based on national industry emissions intensity data from 2014-2016. If a firm exceeds the benchmark, it pays the carbon price on excess emissions. If the firm outperforms the benchmark, it is allocated tradeable emissions credits for the additional emissions reductions.

Emissions intensity benchmarks are adjusted depending on the emissions intensity and trade exposure of each industrial sector to limit the risk of carbon leakage. Table 7 shows the emissions intensity benchmark by industrial sector in CIMS. These are based on the current federal OBPS, but in some instances had to be adjusted as CIMS aggregates industries. For instance, the CIMS metal smelting sector includes the smelting of aluminum and zinc, which have different emissions intensity benchmarks in the federal OBPS. In these instances, I calculated a weighted average benchmark.

Table 7. Modelled emissions intensity benchmark by industry

Industry	Emissions Intensity Benchmark
Cement and lime, iron and steel	95%
Chemical products	92%
Petroleum refining	90%
Metal smelting	82%
Mineral mining, pulp and paper, light manufacturing, petroleum crude extraction, natural gas extraction	80%

The current federal OBPS features no tightening rate on the emissions intensity benchmark overtime. I chose to introduce a tightening rate after 2025 of 1.5% per year to induce further emissions reductions in EITE industries. To ensure EITE industries were still protected against carbon leakage, I used an iterative process to determine an appropriate tightening rate that resulted in no more than a 10% increase in techno-economic costs per EITE industry. The techno-economic cost, often referred to as the engineering cost, encompasses changes in capital cost, operation and maintenance costs, and fuel costs due to modelled policies. It is only

a portion of the overall production costs for EITE industries, as it does not include the costs of raw input materials, land, and total labour and management costs associated with production. A 10% increase in techno-economic costs (and thus a lower increase in overall production costs) was deemed acceptable as I assumed all revenue collected from the carbon price was returned to EITE industries and could thus be invested into the adoption of low emissions technologies and processes.

CIMS is not able to apply a carbon tax on a portion of industrial emissions, but instead on the industry as a whole. To model the OBPS, I applied an average carbon price across each industrial sector instead of the marginal carbon price. For example, a $50 marginal carbon price on 20% of industrial emissions will be applied as a $10 average carbon price across all industrial emissions. This $10 will also represent the credit trading price. The carbon price is adjusted each five-year period to reflect the new emissions intensity by each industrial sector as well as the increasing price schedule. Appendix B shows the average carbon price I calculated in each EITE sector over time.

In my **StringPol Global Action** case, I kept the economy wide carbon tax, but increased it to $200 by 2030, and $522WeaTm$84 Tm6 toEhT/F3 10.98 Tf1 0 0 1 72 449.02 Tm0 g0q0.0p792 reW*nBT/F3 10

incline in the carbon price is meant to provide an early signal to adopt low emissions technologies as soon as possible.

Chapter 5. Results and Discussion

5.1 Policy scenario comparison

The results I present in Section 5.1 highlight my first research objective: to determine the policy stringencies needed to achieve different levels of emissions reductions in EITE industries. I compare my StringPol cases to my Ref cases in both my Global Inaction and Global Action scenarios, and look at the resulting emissions reductions on national, provincial, and sectoral scales.

5.1.1 National results

Figure 3 shows national EITE GHG emissions in all four of my cases. The Ref cases both show an emission increase of ~12% from 2020 levels by 2050. This increase is due to the continued use of fossil fuels and increases in production in EITE industries over time. Despite the greater capital cost declines in low emissions technologies in the Global Action scenario, it does not lead to a decrease in emissions in EITE industries in the reference case. This suggests that with an absence of GHG reduction policy in the Ref cases on EITE industries, conventional fossil fuel using technologies outcompete low emissions technologies, and industrial emissions will continue to rise with increased output. The emissions in the **Ref Global Action** case are also slightly higher than the **Ref Global Inaction** case, and this could be the result of lower costs of RPPs due to the global oil price being at $40USD/bbl.

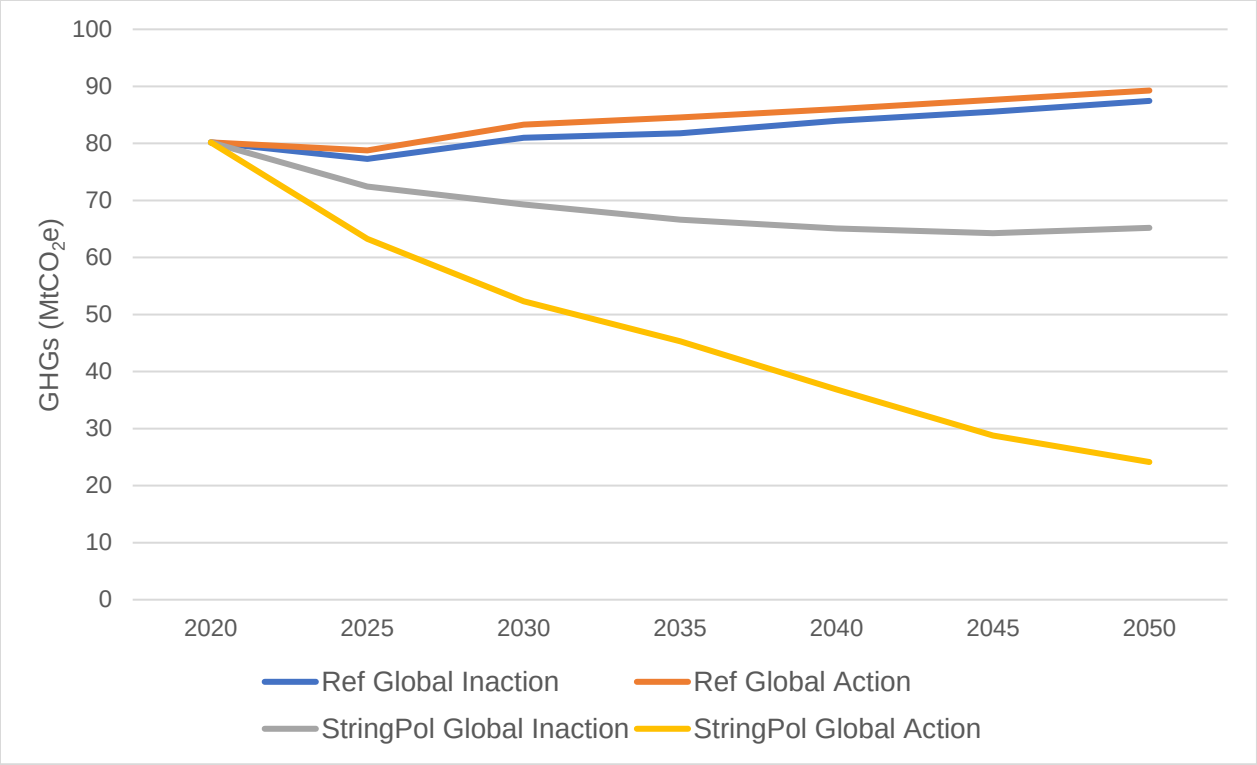

Figure 3. EITE GHG emissions by case

My StringPol cases achieve significant GHG emissions reductions despite having the same increases in output as the Ref cases. In my **StringPol Global Inaction** case, I subject EITE industries to a stringent OBPS designed to achieve emissions reductions while reducing the risk of carbon leakage. To reduce the risk of carbon leakage, I set performance benchmarks that would limit the increase in techno-economic costs to 10% per industry. The resulting emissions reductions were 25% from the **Ref Global Inaction** case. While there is a steady decline in emissions out to 2040 in the **StringPol Global Inaction** case, there is a flattening in emissions reductions between 2040 and 2050 and even a slight increase of ~1 $MtCO_2e$ between 2045 and 2050. This possible outcome suggests that by 2040, the policy stringency of my simulated OBPS is not strong enough to incentivize further emissions reductions in EITE industries as their output continues to increase. This result is not surprising, as many studies have found that the technological transformation needed for high levels of decarbonization in EITE industries will be expensive and thus requires highly stringent GHG policies (Rissman et al., 2020; Bataille 2020; Bataille et al., 2018; CCIC, 2020; IEA, 2020). If carbon leakage risk remains a policy constraint, my results indicate that achieving deep decarbonization of Canada's EITE industries is highly unlikely without enormous direct government subsidies for process shifts and CCS.

In my **StringPol Global Action** case, the risk of carbon leakage was eliminated, and I applied a carbon price that rose to $450 in 2050. I assumed that above $450/t$CO_2$e, the federal government would use negative emissions technologies to induce further emissions reductions. This carbon price resulted in a 74% reduction in emissions from the **Ref Global Action** case. My simulation suggests that deep decarbonization of EITE industries is technologically feasible given sufficient policy stringency when there is no risk of carbon leakage. However, the remaining 24 MtCO_2e indicate the difficulty of reducing EITE industry emissions 100%.

Figure 4. 2050 GHG emissions by province in all cases

In the **StringPol Global Inaction** case, Ontario, Alberta, and Quebec reduce their emissions from the **Ref Global Inaction** case by 8, 5, and 4.5 $MtCO_2e$, respectively. These three provinces make up 85% of emissions reductions nationally. The greatest percentage reduction in emissions from the Ref case are in Alberta and Quebec, who reduce their emissions by 62% and 52% respectively. Saskatchewan and Manitoba have the smallest change in their emissions between the StringPol and Ref cases, reducing their emissions by 18% and 17% respectively.

In the **StringPol Global Action** case, Ontario, Alberta, and Quebec make up most emissions reductions nationally at 33, 12, and 11 $MtCO_2e$, respectively. The provinces with the greatest percentage reduction in emissions from the Ref case are Alberta, BC, and Quebec, reducing their emissions 81, 77, and 77% respectively. Saskat

compared to its reference case. This appears to be the result of Ontario having high costs of low carbon electricity compared to provinces like BC, Manitoba, and Quebec, and because it is not located near low-cost storage sites for carbon sequestration like Alberta and Saskatchewan. This regional resource availability will be further explored in section 5.3 of the results. Ontario also has the highest diversity of EITE industries, having facilities in all seven sectors, who often require different decarbonization pathways to lower their emissions in a cost-effective manner.

5.1.2 Sectoral results

Just as emissions for EITE vary by province, they also vary by industrial sector. Figure 5 demonstrates the 2050 emissions by industry across all seven EITE sectors analyzed in this study. In the Ref cases, chemical production has the highest emissions, followed by light manufacturing, iron and steel, and cement whereas metal smelting and mineral mining have the lowest sectoral emissions.

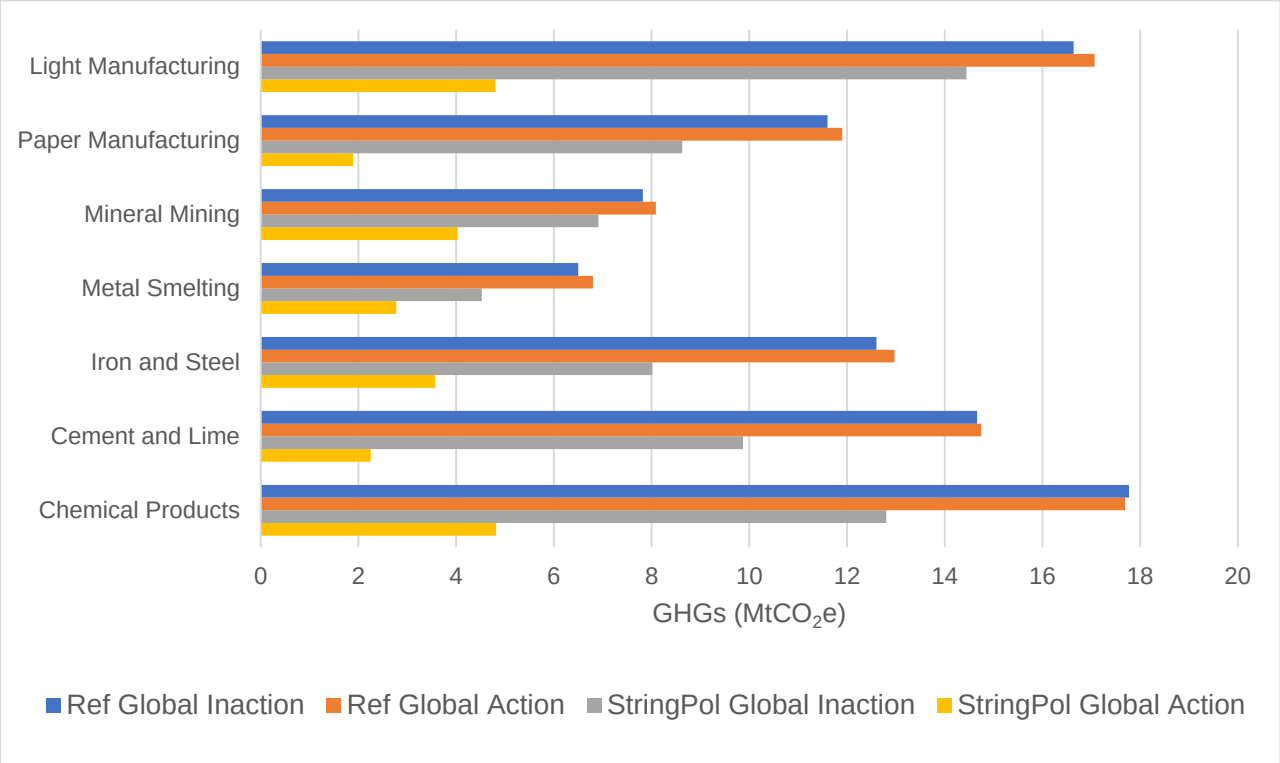

Figure 5. 2050 GHG emissions by industry in all cases

In my **StringPol Global Inaction** case, the range of emissions reductions is 12-36% from the **Ref Global Inaction** case. Chemical products, cement and lime, and iron and steel all achieve

increases. To demonstrate this evolution of technology adoption, I have highlighted the emissions reductions pathways for EITE industries in both the StringPol cases in 2030 and 2050 (Figure 6).

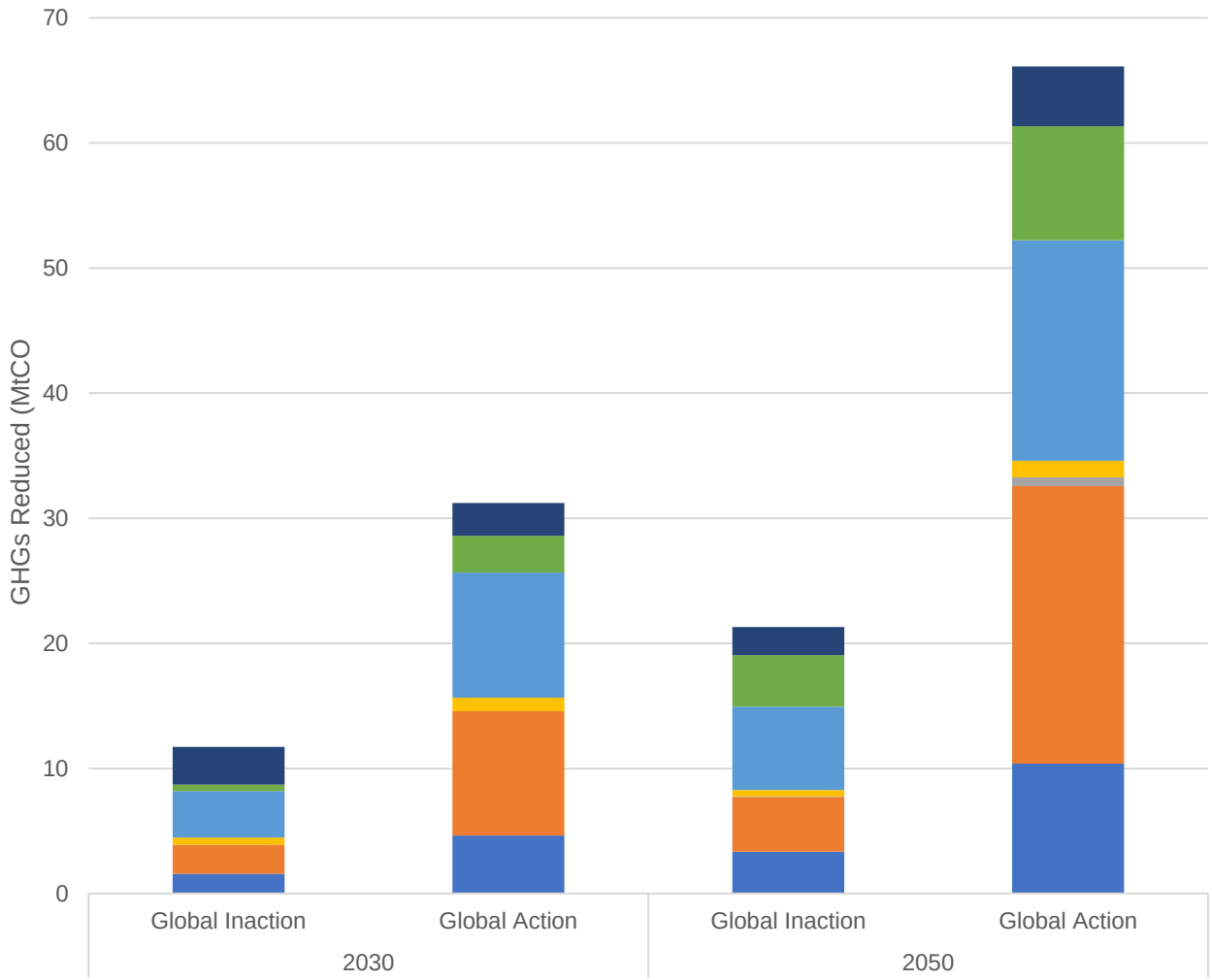

Figure 6. 2030 and 2050 GHG emissions reductions by pathway in StringPol cases

There are three key trends between 2030 and 2050 in both Global Action and Global Inaction scenarios: pathways whose share of total emissions reductions decrease over time, pathways whose shares increase over time, and pathways that maintain a constant share of total emissions reductions out to 2050.

making up between 10-15% of iron and steel production in 2030 and 2050. By 2050, these production routes use more CCS to achieve significant levels of emissions reductions. Hydrogen based direct reduction plays and important role in iron and steel by 2050, making up 22% of total production. This suggests that hydrogen is a competitive decarbonization pathway in the iron and steel industry as hydrogen prices fall. Iron ore electrolysis makes up a negligible portion of production, mainly due to large quantities of electricity needed and most of the production of iron and steel occurring in Ontario where the price of electricity is high.

The technology shares of total steel production in 2050 are in line with results found in the IEA's Sustainable Development Scenario in their Iron and Steel Technology Roadmap (2020a). One notable difference is the higher levels of hydrogen based direct reduction adopted in this study (22%) compared to the Technology Roadmap (11%). This doubling of technology share can be attributed to differences in the costs of hydrogen and assumptions regarding the pace of technological change. One key difference is that hydrogen in my study can be produced through multiple pathways (SMR with CCS, electrolysis, and biomass gasification), whereas the IEA limited their hydrogen production to electrolysis, currently the most expensive production technology (Ramsden et al., 2013).

Chemical Production – Ammonia and Olefins

Chemical production produces many chemicals across Canada, but the major products are ammonia for nitrogen-based fertilizers, and olefins (petrochemicals) for plastics. Figure 8 demonstrates technological change in both ammonia synthesis and olefin cracking from 2020 to 2050.

Figure 8. Technological change in ammonia and olefin production

The main low emissions technologies for cement production modelled in this study were cementitious substitution and CCS via chemical looping. Figure 9 shows the GHG emissions emitted and captured and the uptake of cementitious substitution over time in cement production.

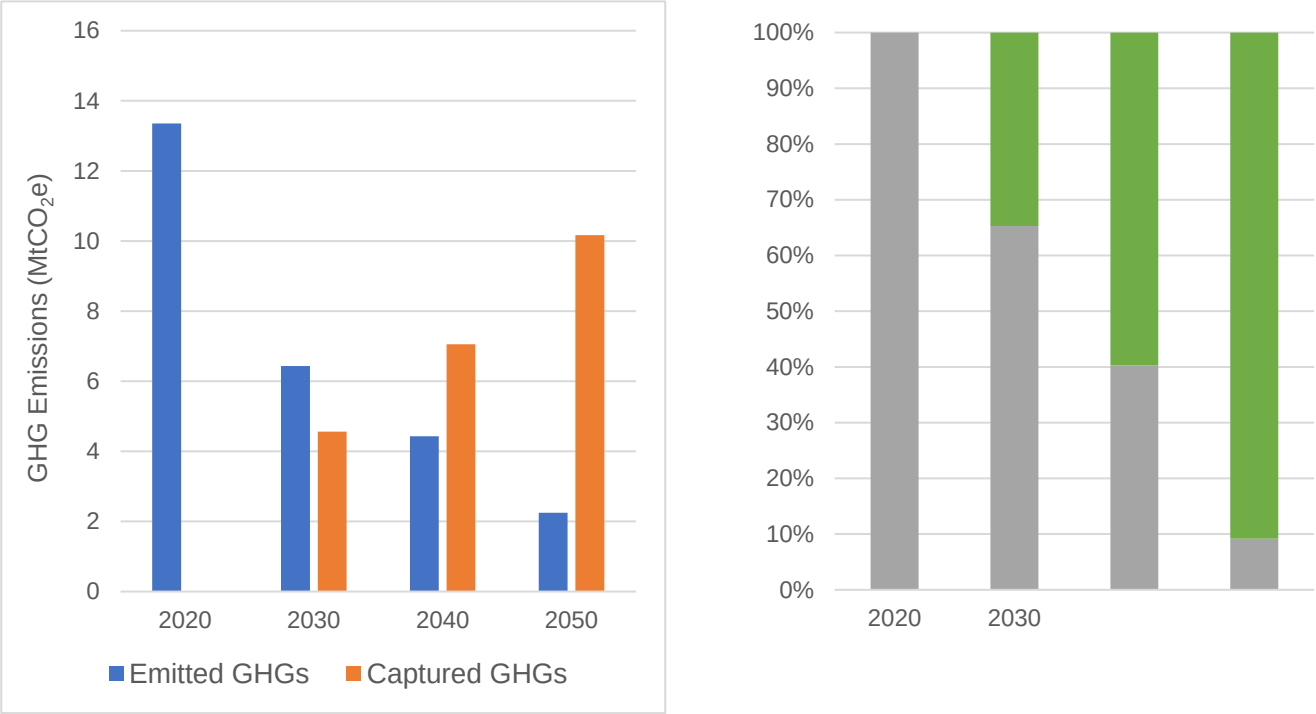

Figure 9. CCS and cementitious substitution in cement production

By 2050, CCS accounts for 70% of emissions reductions in cement production in the **StringPol Global Action** case. In the cement sector, the CCS capture technology I used was oxy-combustion with chemical looping, which halves the costs of capture from post combustion chemical absorption. Although a significant amount of cement production occurs in Ontario and Quebec, where the costs of transport and storage of CO_2 are high, the lower cost of capture allows CCS to still be a better option for low emissions technology for the industry.

By 2050, 90% of cement production uses cementitious substitution. The substitution rate I used in my study was based on a 30% reduction in clinker content, which was an average value found in the literature (IEA, 2020a; Ricardo-EAE, 2013; WSP Parson Brinkerhoff & DNV GL, 2015). The limit on the reduction of clinker content is to reflect the potentially limited availability of clinker substitutes, as well as the potential for cross-sectoral impacts such as revising building codes. Despite the high uptake of cementitious substitution, its 30% limit results in only

1 $MtCO_2e$ reduced by 2050, a substantially lower number of emissions reduced than CCS, which accounts for just over 10 $MtCO_2e$ reduced.

5.3 Regional variability

5.3.1 Regional costs

This results section highlights my third research objective: to focus on regional variability of resources and the resulting impacts on the adoption of low emission technologies in EITE industries. Resource availability by province plays a significant role in determining the cost of low emissions technology options for

alternatives. Alberta, being situated directly over the Western Canadian Sedimentary Basin, can store carbon at a low cost from its fossil fuel-based generation, but Ontario without hydro or nearby low-cost storage sites results in the most expensive electricity nationally by 2050. In the Global Action scenario, Ontario's electricity price is $5/GJ lower than the Global Inaction scenario. This could be the result of greater declining capital costs in wind and solar generation due an increased pace of technological change in the Global Action scenario.

Whereas the prices of electricity between Global Inaction and Global Action scenarios does not vary greatly by 2050, the price of hydrogen shows a large range between scenarios. The highest cost hydrogen production pathway is via electrolysis, and the accelerated cost declines in this technology in the Global Action scenario drive the prices of hydrogen down. Another reason can be attributed to the transport costs, which fall as demand increases. With the Global Action case having a higher carbon tax and EITE industries being subjected to the full price, hydrogen uptake was higher in this scenario and resulted in a greater decrease in transport costs.

Figure 10. Regional emission reductions in the Global Inaction scenario in 2050

The Global Inaction scenario has pronounced regional differences in decarbonization in my simulation. These arise for two reasons: resource availability, which dictates the cost of specific emissions reduction pathways, and the industry mix in the region, which dictates the pathways available for industrial decarbonization.

All EITE industries can use electrification to reduce their emissions; therefore, the primary

significant role in emissions reductions in provinces with access to cheap electricity: Quebec, BC, and Manitoba. Nearly half of Quebec's emissions reductions arise due to electrification in the Global Inaction scenario. Its low-cost electricity allows fuel switching to electricity to be a competitive decarbonization option in its mining, pulp and paper, light manufacturing, and metal smelting industries. Electrification plays a much smaller role in emissions reductions in provinces like Ontario, Saskatchewan, and Alberta. The lack of uptake is due to high costs of electricity in these regions.

CCS is only a viable emissions reduction pathway in cement and lime, iron and steel, and chemical production in my simulations. These industries have high concentrations of CO_2 in their flue gasses, making CCS economically viable. The cost of CCS also varies regionally depending on proximity to storage sites. Alberta and Saskatchewan have access to the cheapest storage in the country due to their proximity to the Western Canadian Sedimentary Basin. Thus, they are also the provinces with the highest share of emissions reductions (44 and 75% respectively) coming from CCS. Ontario has the lowest cost access to storage sites in Eastern Canada due to deep saline aquifers located near Lake Eerie. Thus, CCS also plays an important role in reducing emissions in Ontario as well. Lastly, although Quebec has the highest cost of transportation and storage of CO_2 in the country, it also features a relatively high share of emissions reductions coming from CCS. CCS used in Quebec is due to high levels of cement production in the region - the only major pathway to decarbonization in cement modelled in this study was CCS.

Bioenergy, much like electricity, is an emissions reduction pathway available to all EITE industries. It differs, however, in that there are no regional cost variations. As bioenergy is easy to transport, I held the cost constant across the country. As seen in Figure 9, bioenergy plays a role in emissions reductions in most provinces. I used three types of bioenergy in my modelling: direct combustion of woody biomass from agricultural and forest residues, biodiesel, and biomethane. Of the total amount of bioenergy used in the Global Inaction scenario, 690PJ come from woody biomass, 10PJ come from biodiesel, and 1 PJ come from biomethane. Woody biomass is the cheapest form of bioenergy at $2/GJ, with biodiesel costing $55/GJ and biomethane costing $21/GJ in 2050. Despite its high cost, biodiesel still has uptake in my simulation at it is one of only two pathways to decarbonize mining I modelled. Biomethane can

Process emissions reduction sees regional variation as a decarbonization pathways due to the industrial mix in the region. Chemical products, cement, and iron and steel have the highest process emissions of EITE industries and thus relies strongly on this emissions reduction pathway to decarbonize. Ontario relies the most on this pathway out of any region in the country. 63% of its decarbonization due to process emissions reductions come from its iron and steel industry. In iron and steel, a significant uptake in smelt reduction technologies (both with and without CCS) is responsible for reducing process emissions.

The major difference between the regional decarbonization pathways in the Global Inaction and the Global Action scenario is that regional differences are less pronounced. Fitureire less pronounced. Fituei Act

this high carbon price, and regional differences in resource costs are less of a deterrent to industrial technology uptake.

However, this does not mean that regional resource costs do not play an important role in EITE decarbonization in the Global Action scenario. Instead, my simulation implies that some regions will be spending more to decarbonize than others. Ontario, the most emissions-intensive province, must decarbonize its EITE industries with no resource advantages when it comes to zero-emission alternatives. Its relatively high costs of electricity and CCS make this a daunting task – in my simulation, Ontario relies on a mix of energy efficiency, bioenergy, and process emissions reductions to achieve the brunt of its EITE decarbonization. These results suggest that Ontario is the province with the highest risk of industrial shutdown due to GHG reduction policy, and policymakers should focus on supporting this region to mitigate the economic impacts of EITE decarbonization.

Chapter 6. Conclusion

6.1 Summary of findings

My first research objective was to determine

whereas CCS was the cheapest in Alberta, Saskatchewan, and BC. In the Global Inaction scenario, regional differences in resource costs factored highly into industrial adoption of low-emissions technologies. A carbon price applied to all EITE emissions in the Global Action scenario meant that more expensive low-emissions technologies became competitive, and regional discrepancies were less apparent. Ontario has the most emission-intensive EITE industry as a whole and has no zero-emission or CCS resource advantage, meaning the cost of decarbonization in this province has the potential to be higher than other regions.

6.2 Limitations and future research

One limitation of my study is the absence of a measure of the economic impacts felt by EITE industries as they achieve deep GHG reductions. CIMS is a partial equilibrium model and cannot measure GDP, government investment, or labour changes. Although it has some macroeconomic functionality in the form of Armington elasticities, I chose not to use them for this study. This means that carbon leakage, the most significant concern of policymakers currently developing EITE policies, is not entirely addressed through my research. However, I have approximated it by creating two scenarios on global climate action, assuming that the government will take measures when needed to protect against carbon leakage. In my global action case, I allowed GHG reduction po7hwcy-2( )]6to pbodreage asin

For solid biomass, I assumed no availability constraints, and thus the price remained low at $2/GJ out to 2050. Although Canada has significant agricultural and forest residues, solid biomass was a major decarbonization pathway in EITE industries and low carbon fuel production. Canada can import biomass from other countries, but the price may increase

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Appendix A. Model updates

Table A-1 is the summary of the literature review on the costs of carbon capture by industry, the type of technology used, and the energy penalty for capture. Table A-2 provides the technological information of hydrogen production added to the CIMS model.

Table A-1: Literature review of CO_2 capture costs by industry

Industry	Capture Technology	Cost ($2005/t$CO_2$ captured)	Energy Penalty (GJ/tCO_2 captured)	Sources
Iron and steel	Post combustion MEA on BF-BOF			(Arasto et al., 2013; Budinis et al., 2018; Irlam, 2017; IEA,
Oil sands	Post combustion MEA			
Petroleum Refining	Post combustion MEA on still gas			
	Post Combustion FCC/CHP	157.07	3.2	(IEA, 2013; Juaied & Whitmore, 2009)
Cement	Oxy combustion and calcium looping on kiln	34.39	2.6	(Kuramochi et al., 2012; Leeson et al., 2017; NETL, 2014; Rodriguez, 2012; Romeo, 2011)
Ammonia				

Natural gas processing	Post combustion MEA	17.05	3.2	(IEA, 2013; NETL, 2014)
Aluminum	Post combustion MEA	11.47	3.2	(IEA, 2013)
Coal utilities	Post combustion MEA	59.23	26.5% increase in coal	(Budinis et al., 2018; Irlam, 2017; IEA, 2013; Rubins et al., 2015)
Natural gas utilities	Post combustion MEA	79.87	15.75% increase in natural gas	(Budinis et al., 2018; Irlam, 2017; IEA, 2013; Rubins et al., 2015)
All industries (heat and steam production)	Post combustion MEA	68.71	3.2	(IEA 2013; Friedman et al., 2019)

Table A-2: Hydrogen production technology information

Technology	Capi

Appendix B. Average carbon prices calculated for the OBPS

Table B-1 shows the average carbon prices calculated for the OBPS in the