# Technology and Policy Pathways to Decarbonize Canada's Emissions-Intensive and Trade-Exposed Industries

by

**Gabrielle Diner**

B.Sc., University of British Columbia, 2016

Project Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Resource Management

in the
School of Resource and Environmental Management
Faculty of Environment


SIMON FRASER UNIVERSITY
Summer 2021

## Declaration of Committee

| | |
|---|---|
| **Name:** | **Gabrielle Diner** |
| **Degree:** | **Master of Resource Management** |
| **Thesis title:** | **Technology and Policy Pathways to Decarbonize Canada's Emissions-Intensive and Trade-Exposed Industries** |
| **Project Number:** | |
| **Committee:** | **Chair:** Jonathan Moore<br>Professor, Biological Sciences |
| | **Mark Jaccard**<br>Supervisor<br>Professor, Resource and Environmental Management |
| | **Bradford Griffin**<br>Committee Member<br>Adjunct Professor, Resource and Environmental Management |
| | **Chris Bataille**<br>Examiner<br>Associate Researcher, Institute for Sustainable Development and International Relations |

## Abstract

The Canadian government has made commitments to transition Canada to net-zero emissions by 2050 but has not addressed the transformative changes needed to decarbonize emissions-intensive and trade-exposed industries. This study uses the CIMS energy-economy model to assess policies and technologies that could help Canada become a leader in the production of low carbon primary products and material goods. Two scenarios were created to represent different levels of global climate action and resulted in different domestic policy stringencies to ensure Canadian industries remained competitive globally. Each scenario was assessed in terms of emissions reductions, technological change, and regional decarbonization strategies dependent on resource availability.

**Keywords**: green house gas reduction policy; emission-intensive and trade-exposed industries; energy-economy modeling; energy; economics

## Acknowledgements

Thank you to my supervisor Mark Jaccard for always being an enthusiastic supporter of my research and for challenging me to be creative in my work. The art of modelling, indeed! A huge thanks goes out to all my peers in the Energy and Materials Research Group: Emily, for always being a calming presence in the lab, Brad Griffin, for answering all my industry and coding related needs, Thomas and Aaron, for offering sage “we’ve been here longer than you” wisdom, and my cohort, Ryan, Brad, and Mariah, for always being there to panic over weird modelling results with me. Thank you to Navius Research, who supported my research through a Mitacs Accelerate partnership. And of course, thank you to my partner Sam for listening to all my late-night ponderings, asking me challenging questions, and supporting me through this process.

# Table of Contents

## List of Tables

## List of Figures

## List of Equations

## List of Acronyms

GHG – Greenhouse gas

IEA – International Energy Agency

EITE – Emissions-intensive and trade-exposed

OBPS – Output based pricing system

CICC – Canadian Institute for Climate Choices

ECCC – Environment and Climate Change Canada

BF-BOF – Blast furnace-basic oxygen furnace

EAF – Electric arc furnace

DRI – Direct reduced iron

CCS – Carbon capture and storage

MEA – Monoethanolamine

EOR – Enhanced oil recovery

IPCC – Intergovernmental Panel on Climate Change

BC – British Columbia

NRC – Natural Resources Canada

CER – Canada Energy Regulator

BECCS – Bioenergy carbon capture and storage

DAC – Direct air capture

LCC – Life cycle cost

NIR – National Inventory Report

RPP – Refined petroleum product

# Chapter 1. Introduction

Over 120 countries around the world have committed to reaching carbon neutrality by 2050 in an effort to limit global warming to 1.5ºC and avert dangerous levels of climate change. Carbon neutrality, or net-zero, requires offsetting any residual greenhouse gas (GHG) emissions by processes that extract emissions from the atmosphere. Clear pathways to achieve deep GHG reductions in large emitting sectors like transportation, electricity, and buildings have emerged through technological breakthroughs and significant levels of cost reduction (de Pee et al., 2018; Khatib, 2012). The industry sector, at 23% of global emissions (International Energy Agency [IEA], 2021), has only recently received political attention due to the difficulty of decarbonizing industrial production.

A subset of global industry, emissions-intensive and trade-exposed (EITE) industries, are challenging to decarbonize for four reasons. First, they have high capital cost technologies that are long-lived and carbon reliant (de Pee et al., 2018; Fischedick et al., 2014). Second, some have high-temperature heat and steam requirements, which can be difficult to supply through sources other than fossil fuels due to their high energy quality and low cost. Third, some have fixed-process emissions, where GHGs result as a by-product of chemical processes instead of fossil fuel combustion. Finally, they compete with international industrial production, meaning that the increased production costs due to domestic GHG reduction policy must be minimal, or all competing countries must have similar GHG reduction policies. Otherwise, industries might shut down or relocate to jurisdictions with lax or non-existent GHG reduction policies, a phenomenon known as carbon leakage (Fischer & Fox, 2012).

In 2019, the Liberal Party of Canada pledged to achieve net-zero GHG emissions by 2050. Prior to that, the government introduced a federal backstop carbon tax and an output-based pricing system (OBPS) for EITE industries to protect them from the full brunt of the carbon tax and thus reduce the risk of carbon leakage. In the continued absence of a globally coordinated effort to combat climate change, carbon leakage will remain at the forefront of policy design for EITE industries in individual countries (Åhman et al., 2017). Moreover, given the long investment cycles that characterize EITE industries, Canada must act now if it wishes to reach deep GHG reductions in the EITE sector over the next one to three decades (Bataille, Sawyer, & Melton, 2015).

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.

The oil and gas sector, which produces the fossil fuels that dominate the current global energy system, is not expected to persist in a net-zero future as other sectors of the economy like buildings and transportation opt for low carbon fuels to decarbonize their energy use (Canadian Institute for Climate Choices [CICC], 2021; IEA, 2021). Thus, I focus in this study on the decarbonization of EITE industries whose expected demand will remain in a low carbon world such that they continue to contribute to a significant portion of Canada’s emissions.

EITE industries in Canada focused on in this study – iron and steel, chemical production, metal smelting, industrial minerals, pulp and paper, mineral mining, and light manufacturing – are heterogenous in that they have many different energy and input needs. They are also distributed across the country, where changes in regional resource availability cause different costs for emissions abatement. Leading scholars studying EITE industries have identified many near-commercial and emerging technologies that can successfully transform industrial processes to achieve deep GHG reductions (Bataille et al., 2018; IEA 2020a; WSP Parson Brinkerhoff & DNV GL, 2015). Near-commercial technologies are well-developed technologies but have prohibitive energy prices or regulatory constraints that limit their widespread adoption. Emerging technologies have a wide range of technological readiness, but many require additional research, development and scale-up to become viable options.

Both near-commercial and emerging technologies rely on the following resources: decarbonized electricity, biomass, and access to geological storage for carbon sequestration (Bataille & Steibert, 2018). Canada has access to all three resources.

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.

# Chapter 2. Background

In this chapter, I provide context for EITE industries in Canada and the technology and policy pathways to decarbonize them. I begin by describing major processes and products by EITE industry, as well as their contribution to overall sector emissions. Next, I summarize the technological options for achieving net-zero in EITE industries. Lastly, I discuss GHG reduction policy options, and how they can induce emissions reductions while reducing the risk for carbon leakage.

## 2.1 EITE industries in Canada

Canada's EITE industries, with the exclusion of oil and gas, employ over 1.5 million Canadians (Government of Canada, 2021a) and contribute to the local, regional, and national economy by transforming natural resources into manufactured goods to be sold domestically and in international markets. EITE industries emitted 83 $MtCO_2e$, 11% of Canada's total emissions in 2018 (Environment and Climate Change Canada [ECCC], 2020a).[1] Figure 1 shows the emissions breakdown by EITE industry in 2018.

[1] These emissions exclude non-energy products from fuels and solvent use.

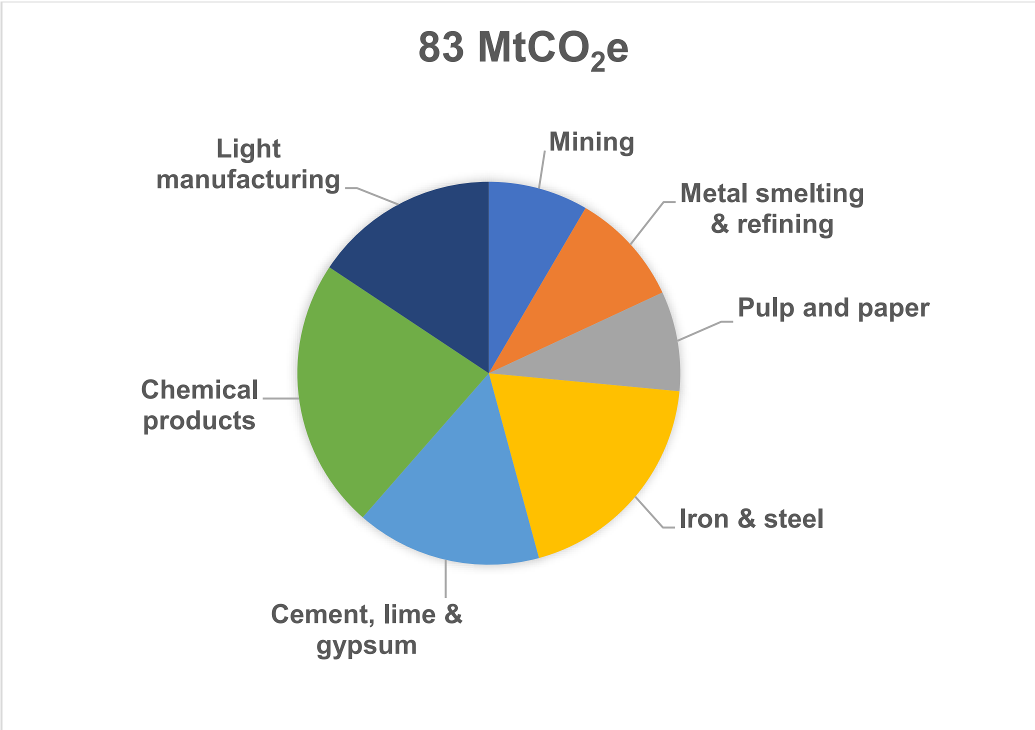


**Figure 1. Emissions by EITE industry in 2018**

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 $^0$C 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 emerging technology options for near-zero emissions. These technologies predominantly rely on the availability of three resources: low carbon electricity, biomass, and geological capacity for carbon sequestration (Bataille & Steibert, 2018).

Although EITE industries are difficult to decarbonize, Canada has access to all three resources. It has a large existing hydropower base and significant capacity for wind and solar generation, it has significant quantities of low-cost biomass from forest and agricultural residues, and it is home to one of the largest geological storage sites for $CO_2$ globally. If Canada's policymakers opt for higher levels of protection against carbon leakage, negative emissions solutions can also be a viable strategy to offset industrial emissions. These solutions are explained further in section 2.2.2 of this chapter.

### 2.2.1 Low-carbon resources

CCS

CCS is a technically viable option for most EITE facilities to keep their current production processes while still achieving deep GHG reductions. The costs of carbon capture vary depending on the concentration of $CO_2$ present in industrial flue stacks: the higher the concentration, the lower the cost of capture. Of the EITE industries, iron and steel, industrial minerals, chemical production, and oil and gas have high flue gas concentrations of $CO_2$. Outside of the EITE industry sector, electricity generation, hydrogen production, and biofuel production can also use CCS to achieve deep emissions reductions.

A promising form of CCS in industry is post-combustion capture with chemical absorption. The industrial facility's flue gas reacts with a chemical solvent such as monoethanolamine (MEA) that binds to $CO_2$. The solvent is heated to release the pure $CO_2$ stream and then recycled to repeat the absorption process. Once captured, the $CO_2$ can then either be used or transported and stored.

Costs of transport and storage vary regionally across Canada. Transportation of $CO_2$ is most economical by pipeline under 1,000 km (Intergovernmental Panel on Climate Change [IPCC], 2005), and costs decrease as distance decreases. Storage opportunities come in different geological media: deep saline aquifers, depleted oil and gas reservoirs, enhanced oil recovery (EOR) reservoirs, coal bed methane recovery processes, and salt caverns. Costs of storage vary by the quality of the storage site, including storage capacity, ease of subsurface injection, 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).

<u>Hydrogen</u>

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 presence of heat. This process is emissions-intensive and accounts for approximately half of hydrogen production today (IPCC, 2018).

---

[2] Biomass, given sufficient processing, can have equivalent energy quality to fossil fuels. For instance, processing woody biomass into biochar can result in a form of bioenergy with the energy quality of coal.

2) Blue hydrogen: like grey hydrogen, but with CCS to capture the $CO_2$ emissions. As hydrogen production from fossil fuels produces a very pure stream of $CO_2$, it has a relatively low cost of carbon capture compared to $CO_2$ in the flue gas of a coal or natural gas electricity plant.
3) Green hydrogen: hydrogen production occurs via renewable resources, such as electrolysis of water using zero-emissions electricity and gasification of biomass with conversion to hydrogen.

Canada's low carbon electricity, biomass, and $CO_2$ storage capacity are viable options for producing low carbon hydrogen. Hydrogen can serve as an energy source and a feedstock to decarbonize many industrial production processes as it produces high-grade heat and has no emissions associated with its combustion. Hydrogen is already used in EITE industries like petroleum refining to reduce the sulphur content of refined products like gasoline. Hydrogen can also be blended into existing natural gas infrastructure up to 20% concentration with little consequence on infrastructure or end-use equipment. Above 20%, hydrogen's corrosive nature can cause metal embrittlement, and pipelines for transportation and end-use technologies like natural gas boilers would need to be retrofitted or redesigned.

Major hurdles to increased use of hydrogen in Canada include the current high production costs for low-carbon hydrogen, infrastructure needs such as pipelines and delivery networks, and policy support to make it a competitive option for decarbonization (NRC, 2020).

### 2.2.2 Negative emissions

To keep global warming to 1.5ºC, not only is net-zero required by 2050, but many studies show the necessity of negative emissions (Hoegh-Guldberg et al., 2018). Negative emissions technologies can offset difficult to reduce emissions and play an essential role in lowering and then stabilizing the $CO_2$ concentrations in our atmosphere. There are two broad pathways to negative emissions: nature-based solutions and engineered solutions. Nature-based solutions use the natural environment to derive negative emissions, such as tree planting and converting marginal lands to their natural states. Engineered solutions use technologies to remove $CO_2$ from the atmosphere, like generating electricity using biomass and capturing the carbon (BECCS) or direct air capture (DAC), where $CO_2$ is removed from the atmosphere directly by a human-produced technology.

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 is a binding global agreement that produced a global carbon price or a global emissions cap and trade system. Depending on the policy stringency, this mechanism can allow for high levels of emissions reductions while ensuring that all countries contribute to the climate effort, eliminating the risk of carbon leakage. Thus far, global GHG reduction policy pacts like the Kyoto Protocol and the Paris Agreement have been centered on national approaches and offer no penalties for non-compliance. These voluntary agreements have led to large amounts of free ridership, where countries might receive the benefits of a public good (a clean atmosphere) without contributing to the cost of that good (domestic decarbonization).

In the absence of a binding global agreement, free riding will remain an issue and countries with GHG reduction policies run the risk of harming the competitiveness of their EITE industries. The formation of Climate Clubs is one measure to address such risks. Climate Clubs are an agreement amongst participating countries to reduce their emissions while penalizing nonparticipants (Nordhaus, 2015). Penalties are often imposed through trade mechanisms like sanctions on carbon-intensive goods. With enough countries participating in climate clubs, the resulting trade pressures may hopefully cause a nearly global adoption of GHG reduction policy (Nordhaus, 2015).

If the formation of Climate Clubs is not politically feasible, countries must focus on developing national policies to protect EITE industry competitiveness. In a world without global binding agreements or Climate Clubs, the risk of carbon leakage will remain present, thus making it unlikely that individual countries will be able to achieve net-zero emissions in their EITE industries (Denis-Ryan et al., 2016; Fischer & Fox, 2012). Nonetheless, there are domestic policies that can incentivize decarbonization while combating emissions leakage.

One such policy is partial carbon pricing. This can take the form of a reduced carbon price for EITE industries compared to the rest of the economy, a cap-and-trade system with free allocations for a certain portion of EITE emissions, or an output-based pricing system (OBPS) where industries pay a carbon price on emissions above an emissions intensity standard. In all three of these cases, the partial carbon price provides an incentive to decarbonize industrial production while protecting industry competitiveness. The revenue collected from carbon pricing can also subsidize low carbon technology innovation, aiding the development of technologies critical to a low-cost transition of EITE industries to net-zero.

Another policy is border carbon adjustments (BCAs) paired with carbon pricing. BCAs are a tax on imported goods equal to the incurred carbon costs of domestic production and a rebate of the carbon cost of domestic producers exporting their product for sale. Therefore, the increases in production costs incurred by domestic EITE industries due to carbon pricing are offset at the border. Common critiques of BCAs are the administrative difficulty associated with their implementation (McKibbin & Wilcoxen, 2009) and concerns about their validity under World Trade Organization law (Weber, 2015). However, interest in BCAs is growing as regions like the European Union discusses more stringent GHG policies while much of the rest of the world lags.

A growing body of literature suggests that carbon pricing should be paired with complementary policies to encourage technological innovation and remove barriers to technology adoption (Bataille, 2020; Bataille et al., 2018; de Pee et al., 2018; Rissman et al., 2020). Although carbon pricing alone can achieve net-zero in EITE industries, raising the price to where it is stringent enough to achieve substantial decarbonization is politically difficult as pricing even under low levels is unpopular (Rhodes et.al., 2014). Complementary policies, such as R&D, piloting, and commercialization support can encourage industries to adopt low emissions technologies while reducing the cost of decarbonization.

### 2.3.2 Canada's EITE 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 Reduction (TIER) system. TIER is an OBPS but relies on facility level emissions intensity benchmarks instead of sector level emissions intensity benchmarks as seen in the federal OBPS. BC currently has the CleanBC industrial incentive program, where industrial facilities pay the full carbon price on their emissions, but any revenue collected above $30/tCO_2e$ goes into an industry fund. Industries can use this fund to invest in lowering their emissions. Quebec is part of a cap-and-trade system with California and allocates free tradeable emissions credits to a portion of its EITE industry emissions. Out of the three provinces, BC's policy is the most stringent as it has the highest carbon price applied to its EITE industries (CICC, 2020).

In summary, Canada has both federal and provincial policies in place to encourage EITE decarbonization while reducing the risk of carbon leakage. However, in a world without global action on climate change, Canadian GHG policy makers will continue to be constrained by competitiveness concerns in the EITE sector. Their policy stringency will be influenced by what is happening with GHG reduction policies elsewhere in the world, especially in countries having industries that compete with Canadian EITEs. To incorporate this constraint in my study, I simulate two scenarios of global action on GHG emissions – global action and inaction – and assesses how differences in Canadian policy stringencies will affect decarbonization levels of EITE industries, the uptake of near-commercial and emerging technologies, and the regional decarbonization pathways that may result.

# 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 stock turnover and purchase in five-year periods to the desired simulation end date.

At the end of each five-year period, the model first assesses which technologies have reached the end of their life and should be retired, and which technologies should be retrofitted to more efficient technologies. Next, CIMS will assess if there are enough technologies to meet the demand in the current period and will purchase new technologies if needed.

To determine which technologies to purchase, CIMS compares the life cycle costs (LCC) of technologies using the following equation (Jaccard, 2009):

**Equation 1: CIMS market share equation**

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

Equation 1 calculates the technology market shares (MS) for new capital stocks. A specific technology (j) will capture or lose market share depending on how its LCC compares to the sum of the LCCs of all other competing technologies (k). The equation accounts for both financial costs and behavioural parameters that realistically simulate how decision-makers would acquire technology in response to GHG reduction policy. The financial costs are the capital cost (CC), the maintenance cost (MC), and the energy cost (EC) associated with the technology. The behavioural parameters are the discount rate (r), intangible costs (i), and the market heterogeneity (v). The r parameter is the time preference of decision-makers, who value returns in the present over returns in the future. It is used to annualize the CC of the technology, which shows the present value of equal annual payments over the entire lifespan of the technology (n). The i parameter encompasses all the costs a decision-maker faces that are not financial, such as risk perception, lack of information, and individual preferences. For instance, when deciding on purchasing new technologies for cement production, decision-makers will value a technology tested and proven on a commercial scale over a new technology that has just entered the market. The v parameter determines the level of heterogeneity amongst decision-makers – different cement producers may face different financial costs, have different time preferences, and have different perceptions of risk. The three behavioural parameters in CIMS are estimated using a combination of literature reviews and discrete choice surveys. The literature reviews are used to gather revealed preference data, which encompasses historical data on technology use and acquisition. Discrete choice surveys are used to gather stated preference data, where future technology use and acquisition is assessed.

As new technologies capture market share in CIMS, their costs evolve due to firms gaining economies-of-scale in their manufacturing and experience in their use, and the perceptions of their risks diminish as more firms acquire them. This is represented in CIMS through two equations. First, economies-of-scale and economies-of-learning are represented in the declining capital cost function where a technology's future financial costs are linked to its cumulative production. Second, the improved availability of technology information and the decreased perception of risk over time is represented by the declining intangible cost function, where a technology's future intangible costs are linked to its cumulative production.

The declining capital cost function is of particular importance to this study as it was used to help simulate the evolution of low emissions technology costs in different GHG reduction policy scenarios.

**Equation 2: CIMS capital cost equation**

$$CC_t = GCC_t * \left[ \left( \sum_1^p \frac{CumulNS_{2000,p} + \sum_{j=2005}^{j=t-5} NS_{jp}}{CumulNS_{2000,p}} \right)^{log_2(PR)} \right]$$

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 period in each province, $CumulNS_{2000,p}$ is the cumulative new stock of a technology for all years up to and including the year 2000 in each province, $PR$ is the progress ratio which is the amount cost should decrease in response to a doubling of cumulative production. I have adjusted the $GCC_t$ term for specific technologies to simulate technological evolution – this will be discussed further in Chapter 5 of this study.

The technological richness in CIMS represents on a microeconomic level how GHG reduction policies will induce technological change. However, policy can induce more significant macroeconomic shifts, such as a decrease in demand for industrial products whose costs are rising. CIMS has parameters available that interact with a macroeconomic module through demand functions to simulate these equilibrium feedback effects. The demand functions have elasticities that represent long-run demand response to changes in the cost of production. In this way, CIMS achieves a partial equilibrium between supply and demand for energy services. However, unlike full macroeconomic general equilibrium models, the version of CIMS I used is not set up to fully represent how GHG reduction policy may affect the output and structure of the economy.

## 3.2 CIMS model settings and calibration

### 3.2.1 General model settings

CIMS has several model settings that control the model's macroeconomic functionality. First is the energy supply and demand function, which allows the energy production and consumption of different sectors to interact. Within this function, the modeller can specify whether each energy source's price and production levels are a fixed trajectory determine outside the model (exogenous) or determined based on demand within the model (endogenous). I set production levels and prices for oil, natural gas, coal, and refined petroleum products as exogenous. These energy sources are traded internationally, so I assume they are not sensitive to domestic demand, as producers can simply export their commodities. I set electricity, biofuel, and hydrogen production levels and prices as endogenous. These energy carriers are driven by demand within the model as their markets are domestic aside from some trading with the United States.

Another function is the macroeconomic feedback function in CIMS. The feedbacks include 1) Armington elasticities in the non-energy using industrial sectors, where the output of industrial 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-cognition function which reflects that decision making related to technology acquisition can operate with different levels of foresight. The function can be set to ‘current’, where technology costs are calculated only using the current carbon price; ‘average’, where technology costs are calculated using the anticipated average carbon price through the technology’s lifespan; or ‘discounting’, where technology costs are calculated using the discounted total carbon price expected over the technology’s lifespan. For this study, I chose the ‘average’ setting to represent decision-making with some foresight. As Canada’s electoral system runs in four-year periods, and different parties have different GHG reduction policies, I assume that decision-makers operate under some degree of uncertainty on the future cost of policies like a carbon price, even in the case where a current government promises a 10-year trajectory for the carbon price.

Lastly is the CIMS revenue recycling function, which assumes all carbon pricing revenue is returned to the sector from which it was collected. This means that the carbon price revenue is included in the calculation of a sector’s average cost of production. I turned revenue recycling on, as the current federal Canadian pricing policies return revenue to the provinces from which it came.

### 3.2.2 Calibration

The model was calibrated to align historical emissions with Canada’s most recent National Inventory Report (NIR), which contains emissions data up to 2018 by sector (ECCC, 2020a). The total sectoral emissions in CIMS were calibrated within 5% of NIR data in each time-period, whereas individual sectors were calibrated within 16% (Table 1). The NIR does not break down emissions into categories that exactly match the sectors within CIMS, which could explain some of the differences in sectoral emissions. Also, CIMS emissions reflect an average over a five-year period, whereas the NIR data are for one particular year. Given the large amount of time that would be required to further reduce the differences between CIMS and the NIR data, the percentage difference outlined here was considered acceptable for this study.

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

(Values are in greenhouse gas emissions $MtCO_2eq$)

| | 2005 | | | 2010 | | | 2015 | | | 2018-2020 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CIMS | NIR | Difference | CIMS | NIR | Difference | CIMS | NIR | Difference | CIMS | NIR | Difference |
| Petroleum Extraction | 82 | 79 | 4% | 98 | 88 | 11% | 126 | 115 | 9% | 134 | 123 | 9% |
| Petroleum Refining | 21 | 22 | -6% | 20 | 22 | -8% | 19 | 21 | -8% | 21 | 19 | 9% |
| Natural Gas Extraction | 60 | 55 | 10% | 52 | 48 | 9% | 45 | 50 | -10% | 52 | 50 | 4% |
| Chemical Products | 18 | 19 | -5% | 16 | 16 | -1% | 16 | 20 | -16% | 16 | 19 | -14% |
| Cement and Lime | 13 | 15 | -15% | 11 | 12 | -5% | 12 | 12 | 1% | 14 | 13 | 9% |
| Iron and Steel | 17 | 16 | 9% | 15 | 14 | 5% | 14 | 14 | -4% | 14 | 16 | -13% |
| Metal Smelting | 11 | 12 | -12% | 10 | 10 | 1% | 9 | 9 | 2% | 8 | 8 | -4% |
| Mineral Mining | 6 | 5 | 15% | 5 | 5 | 2% | 6 | 6 | 9% | 6 | 7 | -8% |
| Paper Manufacturing | 7 | 9 | -16% | 6 | 6 | 1% | 7 | 6 | 11% | 7 | 7 | 0% |
| Light Manufacturing | 16 | 16 | 2% | 13 | 13 | 0% | 14 | 13 | 12% | 14 | 13 | 8% |
| Total | 251 | 248 | 1% | 247 | 234 | 5% | 269 | 265 | 1% | 286 | 274 | 4% |

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's Energy Future 2020 Report. Note that exogenous sectoral activity levels for electricity, biofuel, and hydrogen production are not shown, as they are driven entirely by demand within the model.

Sector activity level forecasts for Industry were left as previously existing in CIMS. These forecasts were derived by previous researchers based on a combination of industrial production data and forecasts, population data and projections, other statistical data, and projections from the GEEM energy-economy computable general equilibrium model.

**Table 2 National average annual growth in activity, by sector**

| | | 2020-2030 | 2030-2050 |
|---|---|---|---|
| **Oil and Gas** | Petroleum Extraction | 4.2% | 0.7% |
| | Petroleum Refining | -0.1% | -0.1% |
| | Natural Gas Extraction | 1.3% | 0.1% |
| **Industry** | Chemical Products | 2.3% | 0.7% |
| | Cement and Lime | 0.4% | 0.8% |
| | Iron and Steel | 0.1% | 0.3% |
| | Metal Smelting | 1.9% | 1.4% |
| | Mineral Mining | 1.4% | 0.8% |
| | Paper Manufacturing | 0.3% | 0.1% |
| | Light Manufacturing | 2.4% | 1.0% |

## 3.3 CIMS model updates

To illustrate technological pathways to carbon neutrality in industry by 2050, I updated CIMS with new technological detail. I added new low-carbon technologies to the industrial sector, updated CCS and biomass costs, and introduced a hydrogen supply sector to the model.

### 3.3.1 Near commercial and emerging low emissions technologies

I compared CIMS' current low emissions technologies with two comprehensive industrial technology databases: The Deep Decarbonization Pathways Project Global Heavy Industry Database (Bataille et al., 2018) and the IEA's Clean Energy Technology Guide (IEA, 2020a). Many of the technologies in these databases already existed in CIMS, and new technologies were added based on a set of rules:

1) The technology has been demonstrated at least on a pilot scale, even if it was in a different sector and can be applied to the sector in question;
2) The technology has the potential to achieve deep GHG emissions reductions compared to current production technologies; and
3) There is sufficient information available on costs and energy inputs to represent the technology in CIMS.

Table 3 shows the near-commercial and emerging low emissions technology options included in the analysis of the decarbonization of the EITE industry production. Cross cutting technologies were 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 |
| | Smelt reduction | Uses iron ore directly and eliminates the use of coke oven gas or coking coal |
| | Smelt reduction with CCS | Smelt reduction with post combustion CCS |
| | DRI-EAF with CCS | DRI-EAF with post combustion CCS |
| | H-DRI | Hydrogen is used for reducing iron ore |
| | Iron ore electrolysis | The production of virgin steel using large amounts of low carbon electricity |
| | Increase EAF route | Increase the production of scrap-based steel |
| Cement and lime | Kiln with CCS | Kiln with chemical looping CCS |
| | Cementitious substitution | Increase use of clinker substitutes |
| Chemical products | Ammonia synthesis with CCS | Synthesis of ammonia from natural gas with post combustion CCS |
| | Ammonia synthesis with low carbon hydrogen | Synthesis of ammonia from hydrogen (emissions depend on how hydrogen is produced) |
| | Olefin production - hydrocarbon cracking with CCS | Hydrocarbon feed cracking with post combustion CCS |
| | Olefin production - biomass cracking | Replacing hydrocarbon feedstocks with biomass feedstocks |
| Light manufacturing | Fuel switching | Replacing fossil fuels in heat and steam production |
| Mining | Fuel switching | Replacing fossil fuels in the extraction, transportation, and manipulation of minerals with electric or bio-fueled processes |
| Pulp and paper | Fuel switching | Replacing fossil fuels in heat and steam production |

| | | |
|---|---|---|
| Metal Smelting | Fuel switching | Replacing fossil fuels in heat and steam production |

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.

[3] These substitutes are often the byproducts of other industrial or energy related processes. Their availability may change in the future as these other industries decarbonize.

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 lower technological resolution compared to iron and steel, chemical production, and cement and lime industries.

The following low emissions technologies were not modelled in this study:

- Alternative cements: there are numerous alternative cements at various stages of development that have lower emissions impacts and energy requirements, but as there was no discernible way to decide which to include, I focus on the decarbonization of Portland cement;
- New catalytic and biological processes for chemical production: many options exist, but do not improve significantly on cost or emissions reductions compared to fuel switching or CCS options; and
- Synthesis of low emissions hydrogen and captured carbon: hydrogen and carbon can be synthesized to create zero emissions fuels that can be used economy wide. Due to the high costs associated with sourcing a steady stream of both hydrogen and captured carbon, this technology option is not considered in this study.

### 3.3.2 CCS cost update

I conducted a literature review of the cost of carbon capture by industry. Post combustion MEA absorption was the dominant form of capture found in the literature and I applied it to all industries other than cement where oxy-combustion with calcium-looping was used instead. In cement plants, the energy penalty and capture cost are nearly halved when compared to the MEA absorption technology. Calcium-looping can use waste calcium oxide produced in kilns to capture $CO_2$, keeping costs and energy use relatively low (Leeson et. al, 2017). Costs in the literature were dominated by new build costs instead of retrofit costs, and thus new build costs were used in the model. Capture efficiency is assumed to be 90% across all industries. Appendix A Table A-1 provides a summary of the average cost of capture, the capture method, and the energy penalty found in the literature review.

The cost of transport and storage of $CO_2$ was also included in the model as a separate service. Availability of storage sites as well as the distance from industrial facilities is highly variable in

Canada, and thus the inclusion of transport and storage costs by province highlights this regional variability. The costs were taken from a previous master's thesis in the Energy and Materials Research group by Kristin Lutes (2012). Her methodology for calculating transport and storage costs was as follows:

1. She obtained locations for suitable storage sites (saline aquifers, enhanced oil recovery reservoirs, and depleted oil and gas reservoirs) from Bachu (2003);
2. She matched industrial capture sites to closest storage sites based on a set of priority rules. As EOR sites provided economic benefits, priority to an EOR storage site was as follows:
    - The storage site must be able to safely store $CO_2$ for at least 10 years;
    - The industrial facilities with the lowest cost of capture and transport get priority;
3. As deep saline aquifers had enough capacity to store all carbon captured in specific regions, priority rules were not applied; and
4. She calculated the distance between storage sites and capture sites to obtain an estimate of transport distance.

Table 4 shows the difference in transportation and storage costs across Canada derived in Lutes' thesis.

**Table 4. Costs of transport and storage of $CO_2$ by province**

| Province | 2005CAD/t$CO_2$ |
|---|---:|
| British Columbia | 8.6 |
| Alberta | 5.2 |
| Saskatchewan | 4.5 |
| Manitoba | 7.6 |
| Ontario | 12.0 |
| Quebec | 24.0 |
| Atlantic Canada | 18.0 |

## 3.3.3 Hydrogen Supply Model

Hydrogen existed in CIMS as an exogenous fuel with a fixed price forecast based on current literature. Since it is considered a key energy carrier in many new EITE technologies, I added a hydrogen supply sector to better simulate changes in price due to demand, technological improvements, and economies-of-scale. I included five production methods:

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, pipelines become cost competitive with trucks. To best simulate changes in transportation costs based on literature estimates (Ramsden et al. 2013; IEA, 2019), a declining capital cost curve was used for the infrastructure cost for centralized hydrogen production pathways.

### 3.3.4 Bioenergy

The price for solid biomass used as either a fuel or feedstock in industry can vary greatly depending on the source of biomass. I used an average price of $2/GJ, which I based on cost estimates from the International Renewable Energy Agency's solid biomass technology brief (2019). I assumed unlimited solid biomass availability in Canada, so the price remained constant out to 2050. I made this assumption for two reasons: 1) Canada has a high availability of forest and agricultural residues and the capacity for dedicated biomass crops on non-arable land and, 2) all solid biomass demand not supplied domestically can be imported. Solid biomass is a globally traded resource – Canada currently ships 80% of its wood chips to Europe for use in their power generation. Unless the global supply for solid biomass becomes limited, the price should not rise substantially.

There are no detailed forecasts available for the price of biomethane, perhaps due to its current limited use or the significant constraints due to limited supply. The price used in this study was derived from Fortis BC (2021). Biomethane pricing was set exogenously, with costs rising proportionally to the price changes of natural gas as forecasted by the Canada Energy Regulator in their Energy Future's 2020 report. Although a supply curve estimated from the literature would be a more accurate approach to forecast the price of biomethane, the price of biomethane is prohibitively expensive compared to other low or zero emissions fuels, and thus uptake in my modelling is not high. I assume that technological improvements in biomethane production can offset the price increases due to small increases in demand.

The use of biofuels to decarbonize EITE industries in the literature is limited, as they are relatively expensive forms of biomass energy when compared to low-cost forms like woody biomass. No technology pathways that use ethanol were assessed, but mining could replace its transportation fuels with biodiesel. Biodiesel in CIMS is an endogenous fuel sector, so its price changes over time due to many factors in the model, including GHG policy, demand changes, and technological evolution.

## 3.4 Decomposition Analysis

I used a decomposition analysis to understand the actions driving emissions reductions in EITE industries in each of my scenarios. I decomposed the difference between my reference and policy cases using the logarithmic mean Divisia index (LMDI) approach (Ang, 2005). The LMDI approach is easy to use, robust, and has no residual term. As industry has both combustion and process emissions, and the pathways to reduce emissions differ between the two, I have 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: Decomposition identity for combustion emissions in EITE Industries**

$$C_r = Q \frac{Q_i}{Q} \frac{E}{Q^i} \frac{C_g}{E} \frac{C_r}{C_g} = QSIFC_c$$

where $C_r$ represents the combustion emissions released to the atmosphere, $Q$ is the sector output, $Q_i$ is the output of a specific industrial product, $S(=\frac{Q_i}{Q})$ is the structure of the sector,[4] $E$ is the energy consumption, $I(=\frac{E}{Q})$ is the energy intensity of output, $C_g$ is the combustion emissions generated and $F(=\frac{C_g}{E})$ is the emissions intensity of energy consumption, and $C_c(=\frac{C_r}{C_g})$ is the ratio of combustion emissions released to combustion emissions generated.

Reductions in combustion emissions associated with changes in the $I$, $F$, and $C_c$ variables were attributed to energy efficiency, fuel switching, and carbon capture and storage, respectively. Since there were no changes in output ($Q$) or industrial structure ($S$) between reference and policy cases, they were assumed to have a value of 1.

The decomposition identity for process emissions accounts for three factors that influence emissions in EITE industries, and is given in Equation 4:

**Equation 4: Decomposition identity for process emissions in EITE industries**

$$P_r = Q \frac{P_g}{Q} \frac{P_r}{P_g} = QAC_p$$

[4] The structure of the sector refers to the share of each product in the overall production of EITE industries.

where $P_r$ is the process emissions released to the atmosphere, $Q$ is the output or activity level, $P_g$ is the process emissions generated, $A(=\frac{P_g}{Q})$ is the process emissions intensity of output, and $C_p(=\frac{P_r}{P_g})$ is the ratio of process emissions released to process emissions generated.

Reductions in process emissions associated with changes in the $C_p$ variable in equation 4 were also attributed to carbon capture and storage, while reductions associated with changes in the $A$ 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 $(I)$ 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 EITE industries, modelling sectors like transportation and buildings are important in determining changes in prices of low carbon fuels such as electricity and hydrogen. For instance, a push in the transportation sector to electrify leads to an increase in demand for electricity. This increase in demand will impact the electricity price and influence EITE industries technology choices as they lower their emissions. I capture some of these inter-sectoral linkages by modelling the entire economy.

### 4.1.2 Global oil market

Depending on the level of global action on climate change, the demand for oil and refined petroleum products (RPPs) can change drastically. Under global inaction, the current fossil fuel dominated energy system would not be required to change, demand levels would remain high, and thus the global price for crude oil would remain high as well. Under global action, the switch to zero-emissions energy sources will substantially decrease the demand for oil, and thus the global price would be lower.

These scenarios impact Canada and my modelling in two ways. First, the oil price dictates the price of RPPs, which then influences consumer behaviour. For instance, a high price for transportation based RPPs like gasoline and diesel will encourage consumers to switch to transportation modes that are either less energy intensive or use alternative energy sources like 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) | Diesel Price ($/L, before carbon price, 2019 CAD) |
|---|---|---|---|---|
| Global Inaction | $70 | 6.0 | $1.27 | $1.36 |
| Global Action | $40 | 2.3 | $0.98 | $1.04 |

In my Global Inaction scenario, the oil price rises to $70 US per barrel from 2030-2050 due to continued high demand for fossil fuels. This allows Canadian production of oil to rise 15% from 2020 levels to 6 million barrels/day by 2050. Most of this production, 5.7 million barrels/day, occurs in the oil sands. The high oil price also results in higher RPP prices, with gasoline and diesel at $1.28 and $1.37 per litre respectively by 2050 (not including the carbon price).

In my Global Action scenario, the oil price stays low at $40 US per barrel from 2030-2050 due to decreases in demand for fossil fuels. By 2025, there is a decline in Canadian oil production, halving current production levels by 2050.

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**

| | % Change in Capital Costs 2020-2050 | | | | | |
|---|---|---|---|---|---|---|
| Scenario | Solar Power | Onshore Wind | EV Batteries | Hydrogen Fuel Cell | Distributed Hydrogen Production via Electrolysis | Centralized Hydrogen Production via Electrolysis |
| Global Inaction | -50% | -10% | -35% | -40% | -45% | -10% |
| Global Action | -75% | -30% | -60% | -60% | -60% | -25% |

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 (2009) technical report on the levelized cost of hydrogen production.

One key low-emissions technology whose capital costs I did not change between my Global Inaction and Global Action scenarios was CCS. The dominant CCS technology used in my study is post-combustion MEA absorption. Although CCS has not reached high adoption levels, 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 fuels are all key components to industrial decarbonization and thus need to be quickly decarbonized themselves, and most of their production is consumed domestically, and thus they are not trade exposed.

### 4.2.2 Stringent policy

In the **StringPol Global Inaction** case, Canada's domestic GHG reduction policy is based on the existing federal policies with an increase in stringency to align with the goal of net-zero by 2050. There is an economy-wide carbon tax starting at $10 in 2019, rising to $170 by 2030, and

$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 $450 by 2050, and applied it to EITE industries. I removed the OBPS, as a partial carbon price policy was unnecessary due to global climate action negating the risk of carbon leakage.

The carbon price ceiling of $350 and $450 for my stringent policy cases in my Global Inaction and Global Action scenarios respectively was chosen as a backstop price for the use of direct air capture (DAC). This means that above a $350 - $450 price on carbon depending on the scenario, industry would choose to pay for DAC to offset its emissions instead of adopting new low emissions technologies and reach net-zero by 2050. Cost estimates for commercial DAC put the price of capturing a tonne of $CO_2$ between $130 and $320 CAD (Keith et al., 2018). I chose a higher price of $350 and $450 due to two reasons: first, the lower cost estimates do not include the cost of transport and storage and, second, the technology is in early stages of development. In my Global Inaction scenario, I chose a lower price ceiling as I assume that to protect EITE industries from carbon leakage, the government will invest more in negative emissions technologies to offset their emissions to achieve net-zero by 2050.

The carbon price increase schedule in all four of my cases is steeper between 2020 and 2030 than the 2030-2050 period. As industries have long-lived capital equipment, the initial steep incline in the carbon price is meant to provide an early signal to adopt low emissions technologies as soon as possible. Figure 2 shows the carbon price schedule in my Ref and StringPol cases.

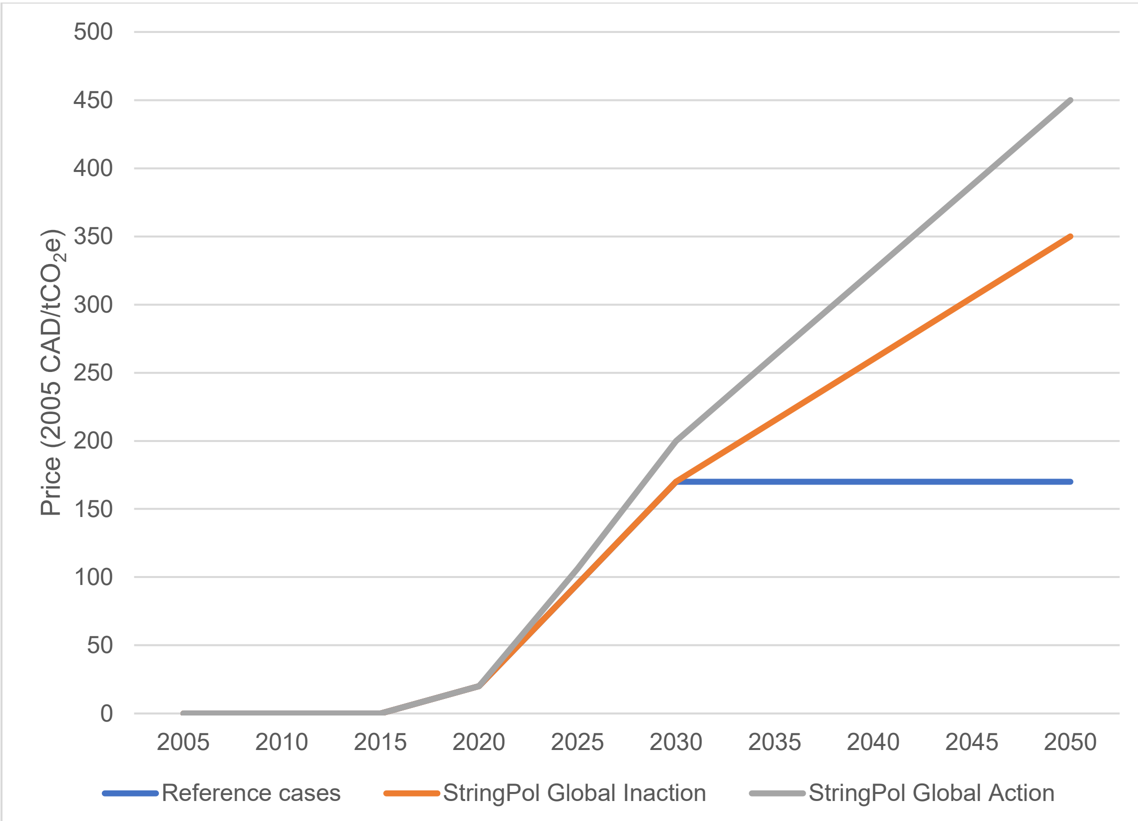


**Figure 2. Carbon price schedule for reference and stringent policy cases**

# 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.

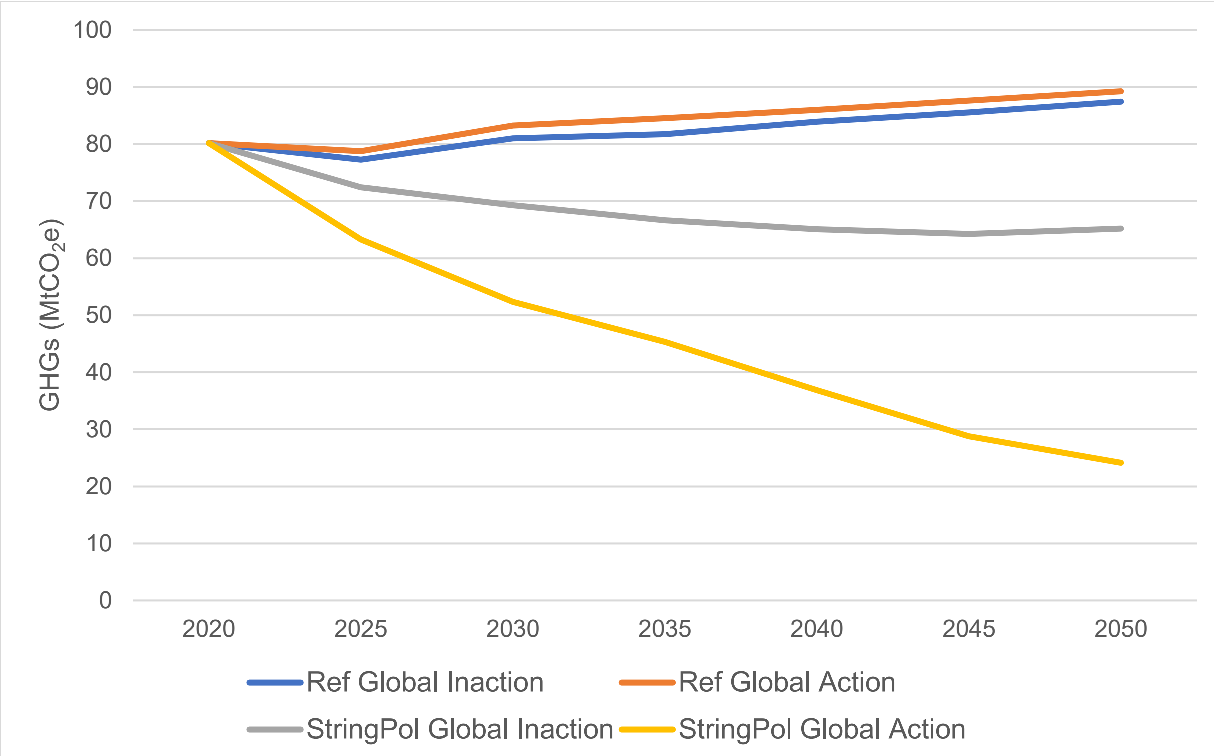


**Figure 3. EITE GHG emissions by case**

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$e, the federal government would use negative emissions technologies to induce further emissions reductions. This carbon price resulted in a 74% reduction in emissions from the **Ref Global Action** case. My simulation suggests that deep decarbonization of EITE industries is technologically feasible given sufficient policy stringency when there is no risk of carbon leakage. However, the remaining 24 Mt$CO_2$e indicate the difficulty of reducing EITE industry emissions 100%.

The remaining emissions could be attributed to a few reasons not explored in my simulation. First, many of the fossil-fuel using technologies in EITE industries are long-lived, meaning that modelling past 2050 might induce further emissions reductions as these technologies retire. Second, is the high cost of deep emissions reductions in EITE industries – although I assumed the adoption of negative emissions technologies above $450/t$CO_2$e to offset EITE emissions, a higher carbon price could result in more decarbonization. Lastly, I assumed that industry decision-makers had average foresight regarding the carbon price. This choice was meant to represent the moderate levels of uncertainty on GHG reduction policy associated with 4-year election cycles in Canada. Allowing decision makers to have perfect foresight could have induced further emissions reductions.

### 5.1.2 Provincial results

EITE industry emissions are not spread evenly across Canada. Figure 4 shows the 2050 emissions by province in all four cases. In the Ref cases, Ontario, Alberta, and Quebec are the highest emitters, while Saskatchewan and Manitoba have the lowest emissions (had I included oil and gas production as an EITE industry, Saskatchewan and Alberta numbers would be substantially higher). Ontario and Quebec have a high diversity of industrial sectors including pulp and paper, iron and steel, chemical production, metal smelting, cement, light manufacturing, and mining, whereas most of Alberta's emissions originate from chemical production.

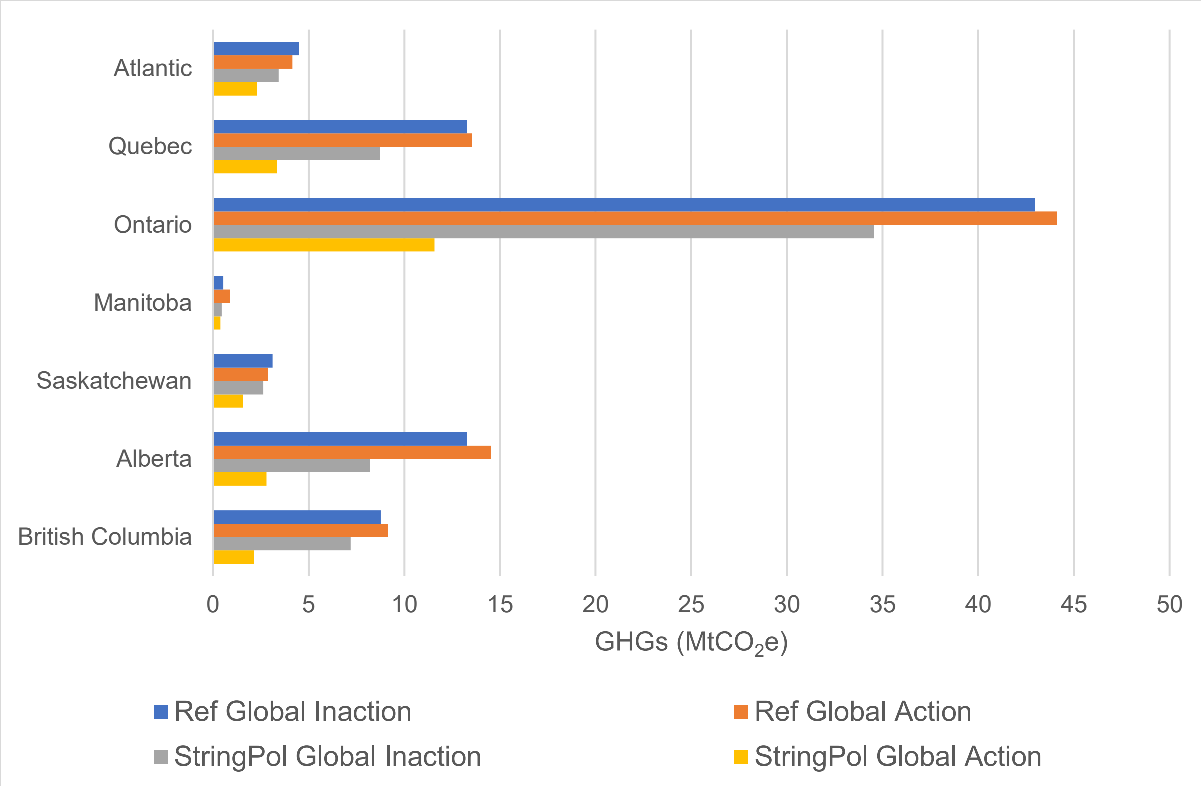


**Figure 4. 2050 GHG emissions by province in all cases**

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. Saskatchewan, Manitoba, and Atlantic Canada reduce their emissions the least from the Ref case, between 45 and 56% reduction.

The ease of which emissions reductions are achieved provincially differs due to two main reasons: resource availability and industrial heterogeneity of the region. Although Ontario makes up most emissions reductions nationally in both the **StringPol Global Inaction** and **StringPol Global Action** cases, it does not achieve the greatest emissions reductions 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.

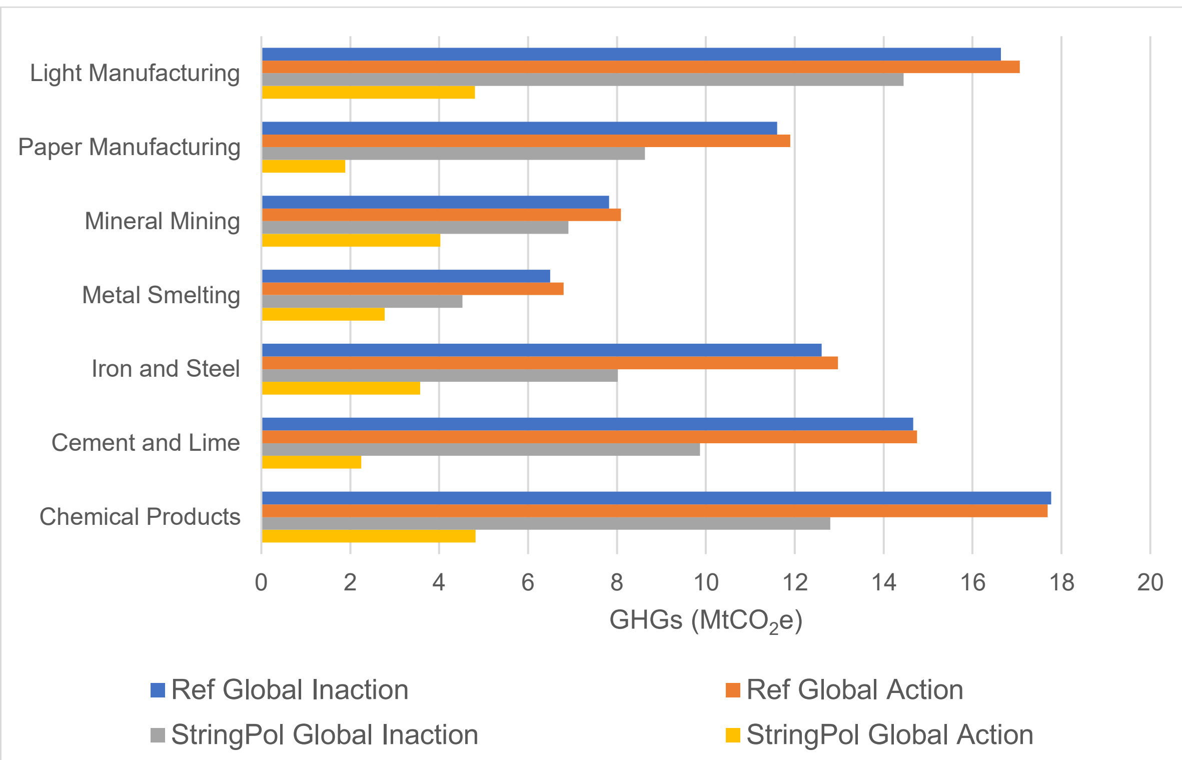


**Figure 5. 2050 GHG emissions by industry in all cases**

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 the highest percentage of emissions reductions from their Ref case. Interestingly, these three industries are also deliberately highly protected from carbon leakage in my modelled OBPS, with emissions intensity benchmarks between 90-95% in 2020 falling to 60-65% in 2050, whereas industries like mineral mining and pulp and paper have emissions intensity benchmarks of 80% in 2020 falling to 45% by 2050. This indicates that despite higher levels of protection from the full carbon price in my simulation, the EITE technologies available to chemical products, cement and lime, and iron and steel in my analysis allow them to reduce their emissions more substantially than other EITE industries.

In my **StringPol Global Action** case, the range of emissions reductions is 50-80% from the **Ref Global Action** case. Pulp and paper, chemical products, cement and lime, light manufacturing, and iron and steel all achieve over 72% reduction of their emissions from the reference case. The two EITE industries that achieve the smallest percentage of emissions reductions are mineral mining and metal smelting. The zero-emissions technologies I modelled for both these industries relied solely on fuel switching, compared to other industries like chemical products and iron and steel where I modelled many technology options for decarbonization. The reasoning behind this decision was due to limited information availability – further research into zero-emissions technologies in these EITE sectors could aid in a more thorough assessment of their decarbonization potential.

## 5.2 Technological Change

In this section, I address my second objective: to evaluate the uptake of near-commercial and emerging technologies due to GHG reduction policy. For ease of understanding, I have aggregated low emissions technologies into seven emissions reduction pathways: energy efficiency, electrification, bioenergy, hydrogen, other fuels, CCS, and process emissions reduction. Other fuels refers to waste fuels generated through industrial processes, such as off-gases in iron and steel production and black liquor in pulp and paper. Process emissions reduction refers to any technology change that reduces process emissions other than CCS. I use a decomposition analysis to determine the emissions reductions of each pathway.

### 5.2.1 Emissions reduction pathways

As EITE industries decarbonize, they adopt the lowest cost emissions reduction pathways first, and progressively more costly decarbonization pathways as GHG reduction policy stringency 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).

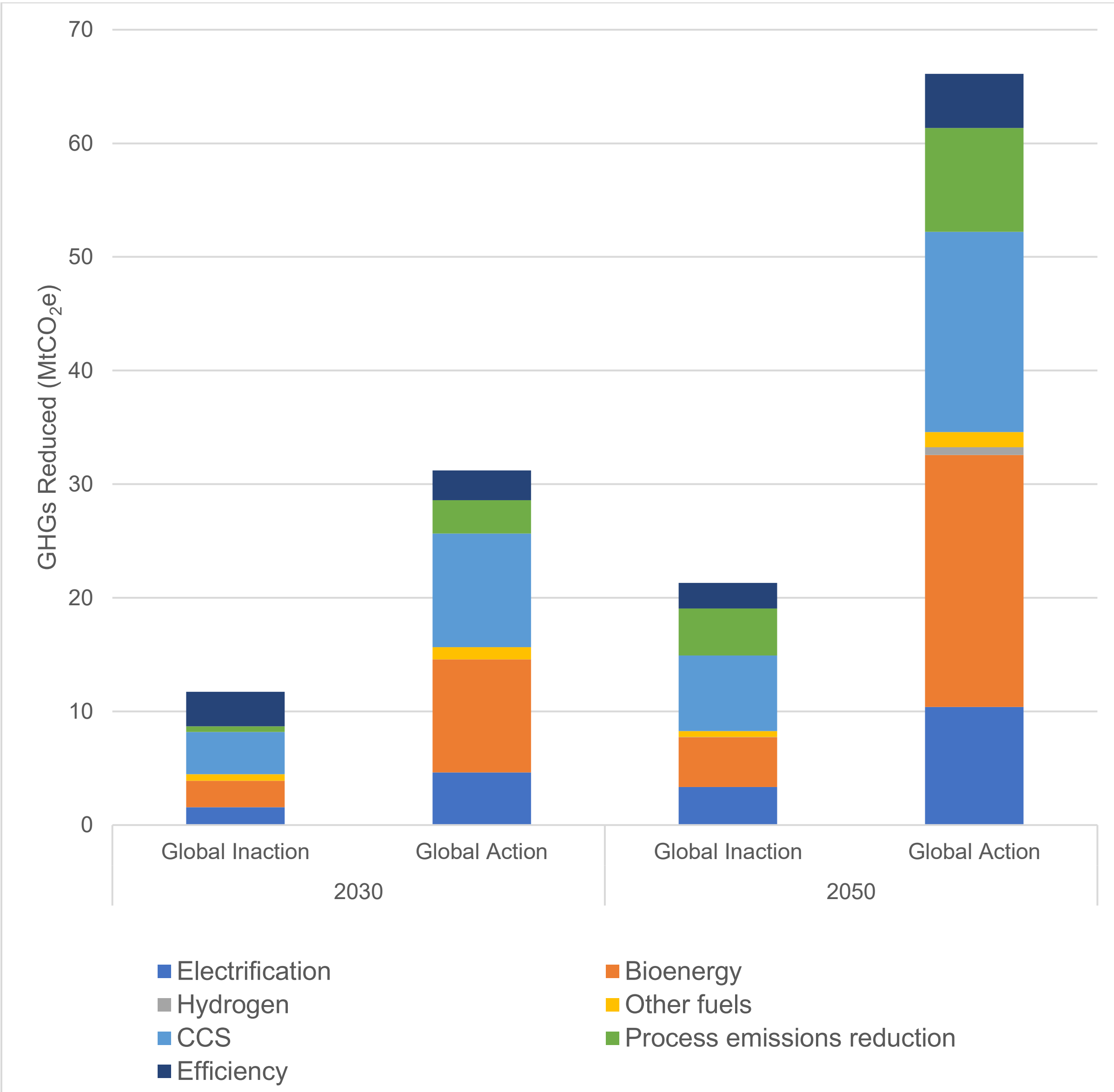


**Figure 6. 2030 and 2050 GHG emissions reductions by pathway in StringPol cases**

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.

Energy efficiency and other fuels belong to the first trend: they make up a more significant share of emissions reductions in 2030 than 2050. These pathways are low-cost decarbonization options as energy efficiency results in reduced fuel use, and waste fuels produced through industrial processes are zero cost for industries to use. However, these pathways contribute less to overall emissions reductions in 2050 due to limits like supply when it comes to waste fuels and technological or economic barriers when it comes to energy efficiency.

Process emissions reductions and hydrogen belong to the second trend: they contribute to a more significant share of emissions reductions in 2050. Both these pathways feature high-cost technologies. Process emissions reductions can require expensive emerging technologies. Hydrogen using technologies are expensive due to the high costs of production and transportation of hydrogen fuel. The hydrogen pathway only sees uptake in the Global Action scenario, as higher levels of policy stringency allow it to become competitive.

Electrification, CCS, and bioenergy make up relatively similar shares of overall emissions reductions in 2030 and 2050, with bioenergy showing a slight increase in use in 2050. The use of solid biomass dominates bioenergy compared to biomethane and biodiesel use. In the Global Inaction scenario, solid biomass makes up 98% of bioenergy used in 2050, and in the Global Action scenario, solid biomass makes up 90% of bioenergy used in 2050.

Electrification, CCS, and bioenergy contribute to most emissions reductions in EITE industries, mirroring findings in other net-zero studies (Bataille, 2020; CCIC, 2020; IEA, 2021). These results suggest that facilitating these pathways could be an area of focus for Canadian policymakers attempting to achieve high levels of decarbonization in EITE industries. Canada's current federal government has already targeted these pathways as investment areas in their 2021 federal budget for a clean industry future. The budget proposes investing billions of dollars into clean fuels over the next five years and introduces a tax incentive and R&D support for the use of CCS in industry (Government of Canada, 2021b).

Electrification, CCS, and bioenergy rely on Canada's natural and physical resources, and their increase in use over time will have significant implications on resource availability. Furthermore, although these emissions reduction pathways are important for EITE decarbonization, they are also important for decarbonizing other sectors of the economy. The transportation and building sectors will rely increasingly on electricity and bioenergy to decarbonize their energy use. CCS can help decarbonize the production of clean fuels like electricity, hydrogen, and biofuels. Table

8 shows the economy-wide use of electricity, $CO_2$ storage capacity, and bioenergy use in 2050 under the two StringPol cases.

**Table 8. Economy-wide resource use of major EITE decarbonization pathways in 2050**

| Scenario | $CO_2$ stored (Mt) | Electricity use (PJ) | Solid biomass use (PJ) |
|---|---|---|---|
| Global Inaction | 197 | 3359 | 915 |
| Global Action | 225 | 4043 | 3209 |

The Global Action scenario features a higher use of all three decarbonization pathways, with a particularly large increase in the use of solid biomass compared to the Global Inaction scenario. Thus, I focus on the Global Action resource use to determine Canada's potential to meet the increases in demand for electricity, $CO_2$ storage, and solid biomass.

Although there are a wide variety of estimates on safe geological storage capacity, Canada's estimated capacity is 318-2236 Gt $CO_2$ (Kearnes et al., 2017). The yearly quantity captured and stored in 2050 in the Global Action scenario is 225 Mt in my simulation. At this rate of capture and storage, even when using the conservative estimated storage capacity, Canada can continue storing $CO_2$ for over 1000 years.

In the Global Action scenario, electricity demand doubles between 2020 and 2050. This substantial increase is in line with other studies on electricity use and deep decarbonization (Bataille, Melton, & Sawyer, 2015; CICC, 2021). Increased demand causes an increase in prices due to new capacity and transmissions needs. The average national electricity price in 2050 increases by 30% from current levels in the Global Action scenario.

Canada's estimated forest and agricultural residues, the cheapest source of solid biomass, can provide ~1600 PJ of bioenergy per year (Stephen & Wood-bohm, 2016). Total solid biomass use in Canada is 3209 PJ with EITE industries and low carbon fuel producers accounting for most of the use. Both electricity generation and hydrogen production have high bioenergy use due to the uptake of BECCS technologies. As this simulated demand for solid biomass is double the estimated quantity of forest and agricultural residues, this indicates the need for additional supply sources. Solid biomass can be generated by increased sustainable harvest from Canada's forests, the conversion of low-grade agricultural land to biomass crops like oilseeds, grasses, and woody crops, and finally import from other countries. But this additional supply may come at a higher cost, a constraint I have not investigated in this study.

### 5.2.2 Major technological and process change

Of the EITE industries assessed in this study, iron and steel, chemical production, and cement were found to have the highest variability of technology options for deep decarbonization in the literature. Combined, these industries are responsible for the majority of EITE industrial emissions globally (IEA, 2020c) and in Canada (ECCC, 2020a). Many of the low-emissions technologies modelled in iron and steel, chemical production, and cement are considered emerging and must go through major development to reach commercialization. Thus, to highlight the technological transformation of the products from these three industries, results are shown solely from the **StringPol Global Action** scenario, where a full carbon price applied to EITE industries results in higher levels of transformative technological change.

Steel

Steel production has numerous near-commercial and emerging technologies that can allow for deep emissions reductions. This industry has high technological representation in CIMS, meaning a large variety of low-emissions technologies were modelled. Figure 7 shows my projected technological evolution of steel production from 2020 to 2050 as Canada pursues a net-zero future in the Global Action scenario.

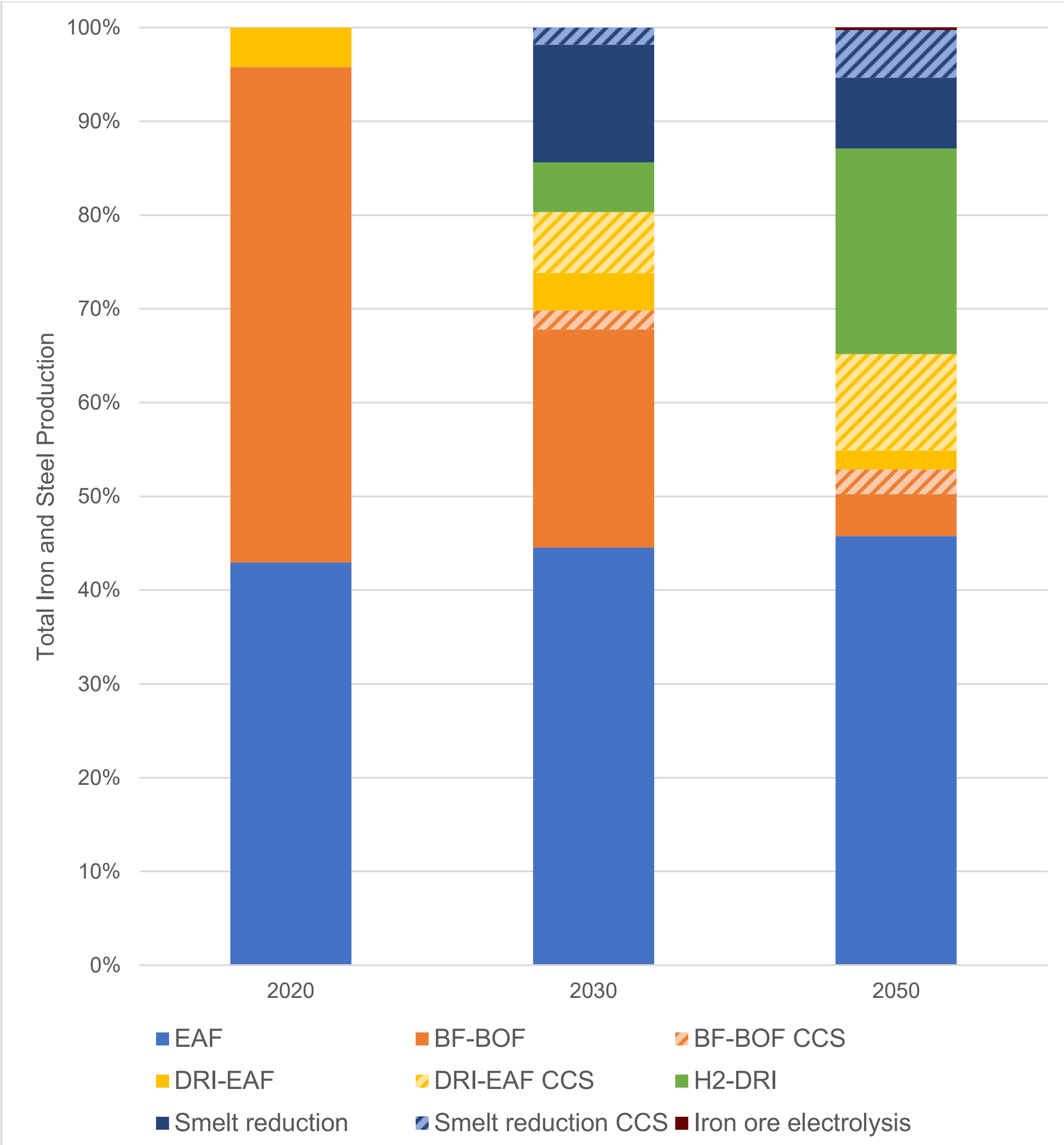


**Figure 7. Technological change in steel production**

The increase in the EAF production to 46% of iron and steel production by 2050 was determined by previous researchers based on industrial production data and forecasts. This route relies on the availability of scrap steel and is in line with forecasted levels of EAF use in the US (IEA, 2020a). The conventional BF-BOF route decreases substantially between 2020 and 2050 as it is the most emissions intensive production route for iron and steel. Both smelt reduction and DRI-EAF technologies play a moderate role in the decarbonization of production, 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.

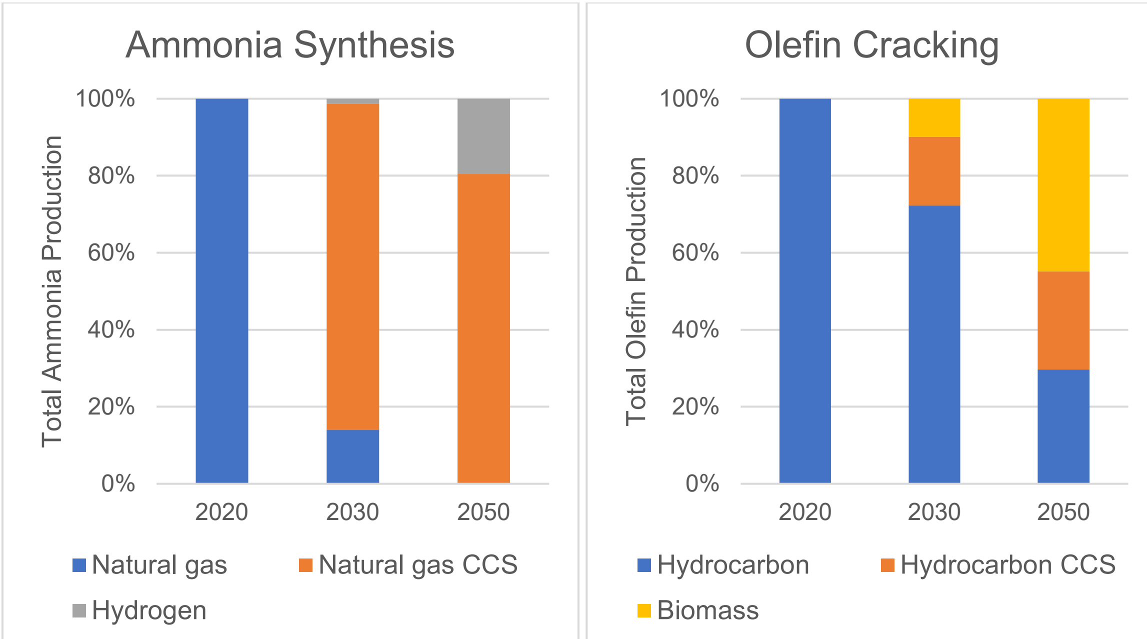


**Figure 8. Technological change in ammonia and olefin production**

Ammonia production is dominated by natural gas synthesis with CCS in 2050. Alberta and Saskatchewan are the largest producers for ammonia in Canada, and with access to the Western Canadian Sedimentary Basin, CCS is a low-cost emissions reduction pathway. Hydrogen based production accounts for 20% of ammonia produced in 2050 as it is a more competitive option in Ontario where $CO_2$ storage is more expensive due to limited site availability.

The production of ethylene, propylene, and other olefins can switch from using fossil fuel feedstocks to biomass or continue to use fossil fuel feedstocks and employ CCS. The production of olefins is split evenly amongst Alberta and Ontario. Much like in the production of ammonia, CCS is a low-cost alternative in Alberta, whereas industry in Ontario switches to biomass feedstocks for their production as it is less costly than CCS.

Cement

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.

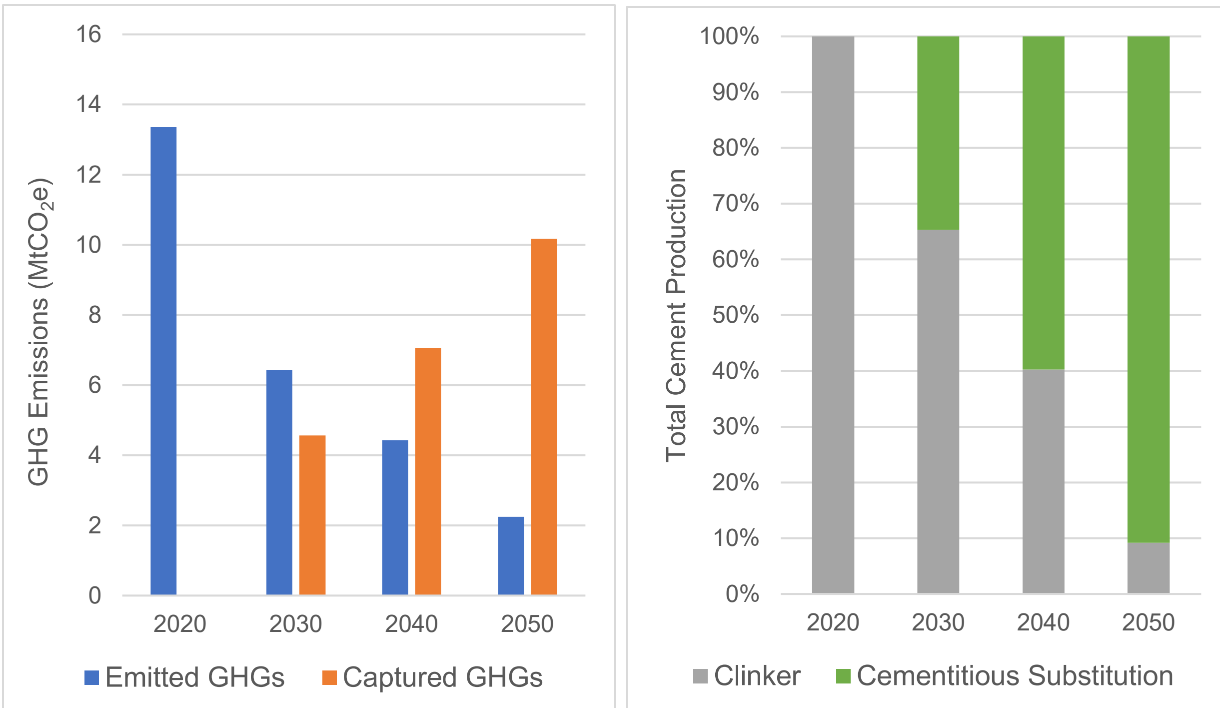


**Figure 9. CCS and cementitious substitution in cement production**

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 EITE industries across Canada. There are three main resources that have high degrees of regional variability – low carbon electricity, low carbon hydrogen, and geological storage capacity for $CO_2$.

Table 9 shows the price variability by province for electricity and hydrogen in 2050 in the StringPol cases in each scenario.

**Table 9. 2050 electricity and hydrogen prices in stringent policy cases**

| | Electricity (2005CAD/GJ) | | Hydrogen (2005CAD/GJ) | |
|---|---|---|---|---|
| Province | Global Inaction | Global Action | Global Inaction | Global Action |
| BC | 21.07 | 17.75 | 29.69 | 12.97 |
| Alberta | 23.29 | 29.94 | 28.68 | 24.29 |
| Saskatchewan | 30.68 | 28.42 | 30.27 | 20.36 |
| Manitoba | 13.66 | 11.28 | 30.55 | 13.73 |
| Ontario | 39.06 | 33.84 | 29.38 | 17.76 |
| Quebec | 13.37 | 13.22 | 29.67 | 13.51 |
| Atlantic Canada | 25.86 | 21.75 | 28.43 | 16.38 |

The 2050 price for electricity in the Global Inaction and Global Action scenarios is lowest in Manitoba and Quebec, followed by BC. Ontario has the highest price of electricity in both cases (over $30/GJ) while Alberta has the second highest prices in the mid to high 20s. Manitoba, BC, and Quebec have access to large hydro resources, which allows their electricity grid to decarbonize at a low cost, whereas Ontario and Alberta must rely on other low carbon 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.

The price of hydrogen in the Global Action scenario does not vary greatly by province and remains at ~30$/GJ by 2050. The provinces with the lowest hydrogen prices are BC, Manitoba, and Quebec, as access to low-cost, low-emission electricity allows electrolysis to be a viable production pathway. Alberta and Saskatchewan have the highest hydrogen price despite having access to low-cost storage opportunities for carbon captured from SMR based hydrogen production. This is due to relatively low hydrogen production in these provinces – 99 Petajoules (PJ) and 26 PJ respectively – compared to Ontario, whose production was 196 PJ in 2050. In my simulation, each province produces their own hydrogen, meaning that lower levels of production leads to fewer declines in capital cost for both production and distribution of hydrogen.

The cost of CCS varies regionally and by industry. There is no difference in the cost between the Global Action and Global Inaction scenarios, as no declining capital costs were used for CCS technologies. The capture cost depends on the purity of the $CO_2$ stream and the type of capture technology used, and the cost of transport and storage depends on distance to and quality of the storage site. The average cost of CCS for EITE industries by province can be seen in Table 10.

**Table 10. Average cost of CCS by province**

| Province | 2005CAD/t$CO_2$ captured and stored |
|---|---|
| BC | 67.32 |
| Alberta | 52.23 |
| Saskatchewan | 54.41 |
| Manitoba | 76.33 |
| Ontario | 62.53 |
| Quebec | 76.20 |
| Atlantic Canada | 76.80 |

Alberta and Saskatchewan have the lowest costs of CCS across the country, which is expected. CCS in this region is a low-cost emissions reduction pathway. Costs are most expensive in Manitoba, Quebec, and Atlantic Canada, due to limited proximity to good storage sites and a mix of industries with more expensive capture costs.

### 5.3.2 Regional emissions reduction pathways

In this section I analyze differences in regional emissions reduction pathways in Canada in both StringPol cases compared to their Ref cases. Figure 10 shows emissions reduction by pathway by province in the Global Inaction scenario. Of the overall emissions reduced, Ontario reduces ~8 Mt$CO_2$e, Alberta and Quebec reduce ~5 each, and the rest of the provinces reduce less than 2 each.

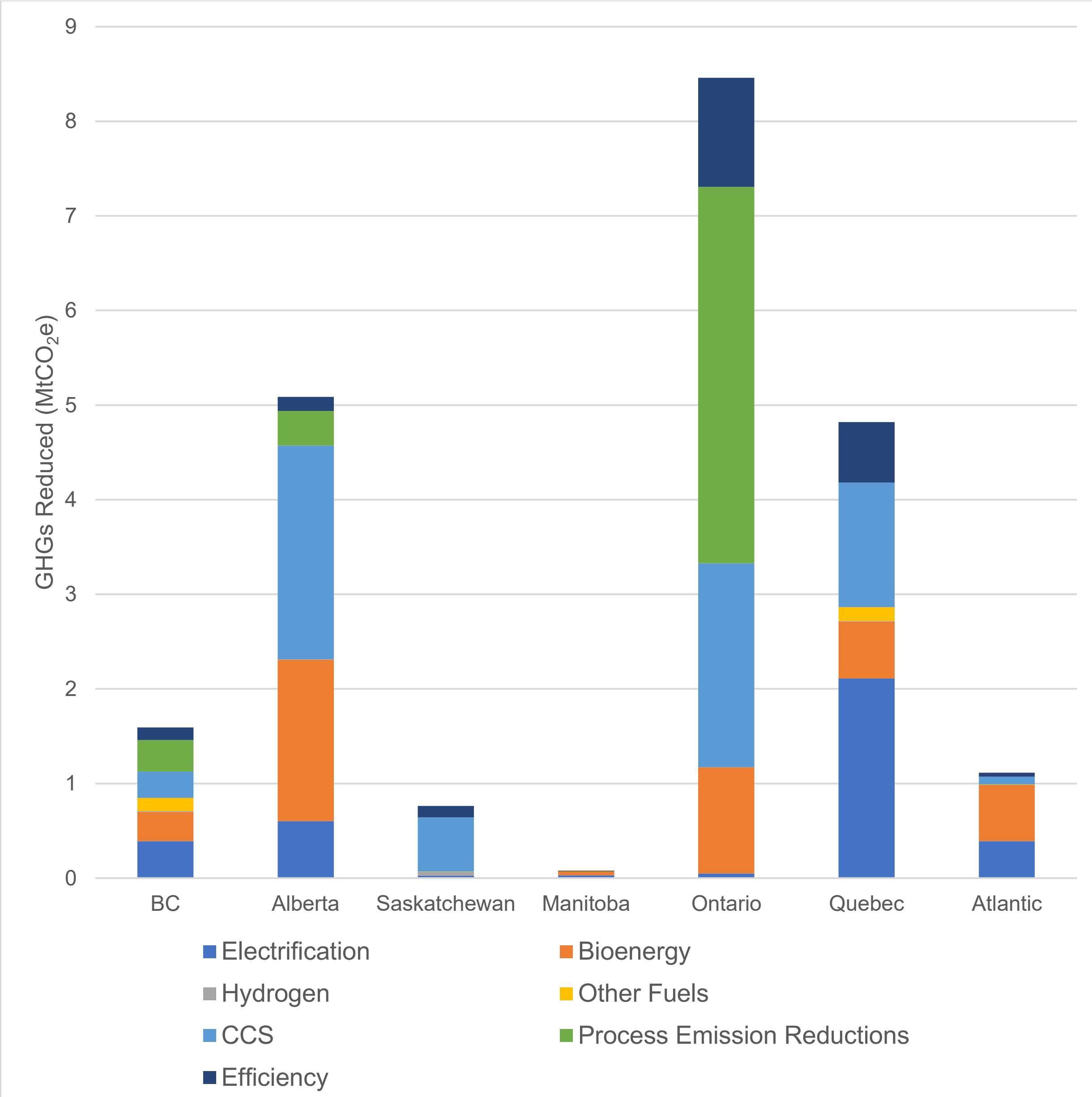


**Figure 10. Regional emission reductions in the Global Inaction scenario in 2050**

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 hurdle for uptake involves the cost of electricity in the region. Electrification plays a much more 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 decarbonize heat and steam in all EITE industries but competes against many low emissions technologies and receives little uptake due to its high price.

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. Figure 11 shows emissions reduction by pathway by province in the Global Action scenario in 2050.

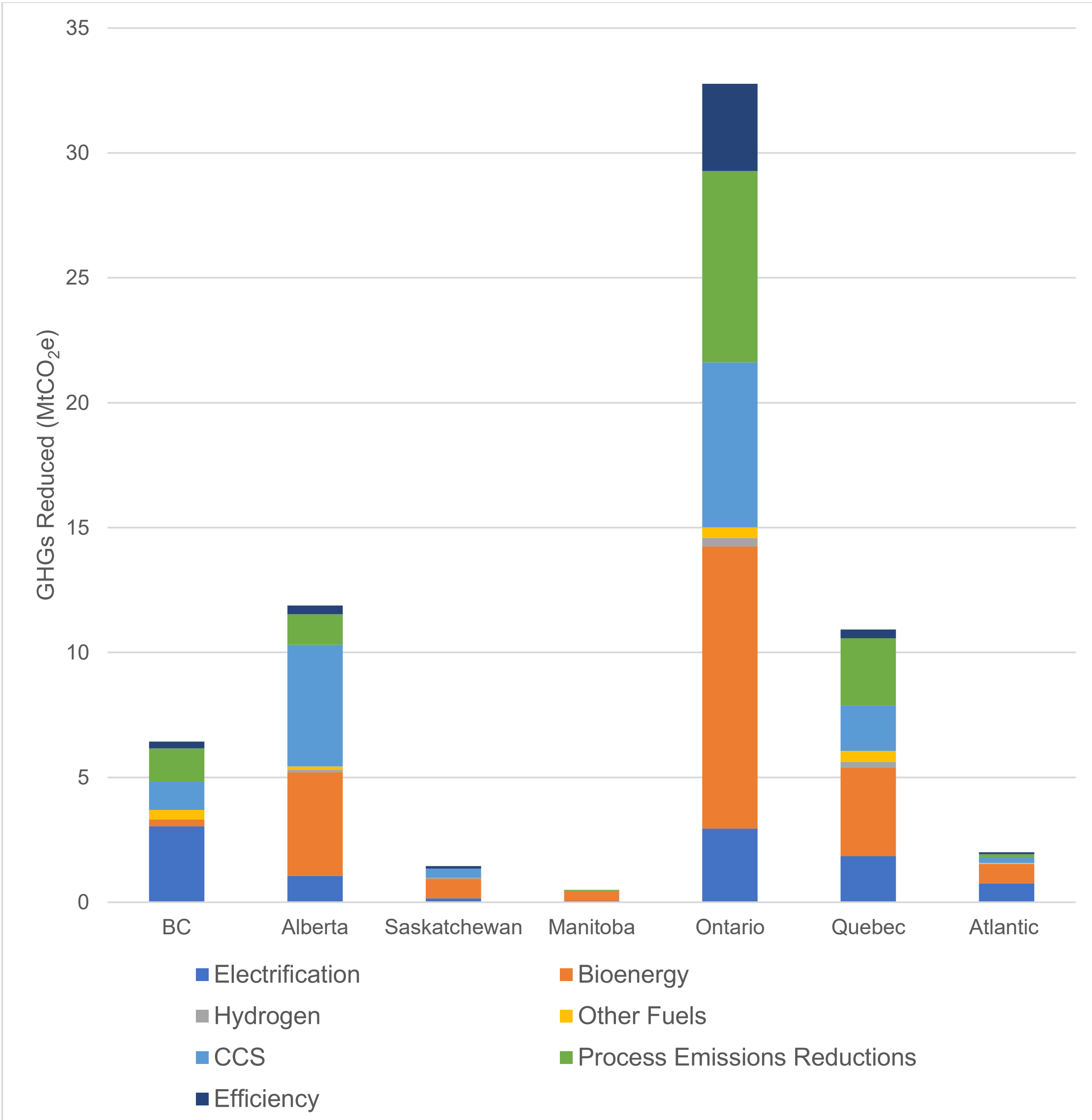


**Figure 11. Regional emission reductions pathways in the Global Action scenario in 2050**

On average, provinces in the Global Action scenario rely more on a mix of decarbonization pathways to achieve their emissions reductions. In the Global Inaction scenario, the OBPS applied to EITE industries only achieved a 25% reduction of emissions compared to the reference case, while the Global Action scenario achieves a 75% reduction using the full carbon price rising to \$450/t$CO_2$e. More expensive low-emissions technologies become competitive at 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 policy stringencies needed to achieve different levels of EITE decarbonization depending on the risk of carbon leakage. I used the CIMS energy-economy model to simulate two scenarios: Global Inaction, where policymakers had to protect EITE industries from carbon leakage, and Global Action, where global GHG reduction policy eliminated the risk of carbon leakage. In the Global Inaction scenario, I applied a modified version of the federal OBPS to EITE industries. Using a cap of 10% on the increases of production costs to mitigate leakage, I increased the OBPS stringency to achieve a 25% reduction in emissions from their reference case by 2050. In my Global Action scenario, I used a full carbon price on EITE industries reaching $450/tCO_2$ in 2050. This price acted as a backstop price above which policymakers would opt to offset EITE industry emissions through negative emissions technologies. In this scenario, EITE industries achieved a 75% reduction in emissions from their reference case by 2050.

My second objective was to identify near-commercial and emerging technologies to decarbonize EITE industries and evaluate their uptake and emissions reductions as the result of GHG reduction policy. From my modelling results, I aggregated technologies into seven emissions reduction pathways: electrification, bioenergy, hydrogen, other fuels, CCS, process emissions reductions, and energy efficiency. Electrification, bioenergy, and CCS technologies contributed to most emissions reductions in both scenarios. Whereas decarbonization options for mining, metal smelting, pulp and paper, and light manufacturing were limited to fuel switching in my study, chemical products, iron and steel, and cement had various emerging technologies modelled for emissions reductions. The uptake of these emerging technologies was significantly higher in the Global Action scenario due to the higher carbon price applied to all EITE emissions.

My third research objective was to evaluate major EITE decarbonization pathways based on regional circumstances, such as industrial heterogeneity and resource availability. I assessed regional variability in terms of decarbonization pathways for EITE industries. Three decarbonization pathways – electrification, hydrogen, and CCS – had cost differences by province. Electrification and hydrogen were the cheapest in Quebec, BC, and Manitoba, 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 policy to be more aggressive, whereas in my global inaction case, I limited it based on a moderate increase in the techno-economic costs associated with production.

Another major limitation to my study was the lack of a comprehensive sensitivity analysis. Sensitivity analyses assess outcomes given a range of variables. For this study, a sensitivity analysis would have involved manipulating the costs of a range of decarbonization pathways and assessing the outcomes on emissions reductions in EITE industries. I completed partial sensitivity analysis in creating my two policy scenarios by using different global oil prices and different paces of technological change. However, two key variables I did not manipulate between scenarios were the cost of CCS and the cost of solid biomass.

The dominant CCS technology I modelled was post-combustion MEA, a relatively mature technology that would not undergo significant economies of scale if use increased. However, many new and emerging CCS technologies, such as oxy-combustion and calcium looping, could significantly lower the costs of CCS. Thus, a sensitivity analysis on CCS costs could have better highlighted its potential to contribute to emissions reductions in EITE industries.

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 substantially if global availability decreases. Using a sensitivity analysis on biomass price may have yielded different results in terms of bioenergy's contribution to EITE industry decarbonization.

There are many opportunities for future research related to EITE industries in Canada, including research into specific policies to help emerging technologies break into the market, assessing the economic impact of GHG reduction policies on EITE industries, and further exploration of transformative solutions such as the production of synthetic fuels and chemicals.

# References


ABB Ltd. – Enerdata. (2013). The State of Global Energy Efficiency: Global and Sectorial Energy Efficiency Trends [WWW Document]. URLhttp://www.oecd-ilibrary.org/environment/aligning-policies-for-a-low-carbon-economy/ strengthening-incentives-for-sustainable-land-use_9789264233294-13-en.

Åhman, M., Nilsson, L. J., & Johansson, B. (2017). Global climate policy and deep decarbonization of energy-intensive industries. Climate Policy, 17(5), 634–649. https://doi.org/10.1080/14693062.2016.1167009

Al Juaied, M., & Whitmore, A. (2009). Realistic costs of carbon capture. Discussion Paper, Cambridge, Mass.: Belfer Center for Science and International Affairs. https://doi.org/10.2172/960194

Arasto, A., Tsupari, E., Kärki, J., Sihvonen, M., & Lilja, J. (2013). Costs and potential of carbon capture and storage at an integrated steel mill. *Energy Procedia, 37*, 7117–7124. https://doi.org/10.1016/j.egypro.2013.06.648

Bachu, S. (2003). Screening and Ranking of Sedimentary basins for sequestration of $CO_2$ in geologic media in response to climate change. *Environmental Geology, 44*, 277-289.

Bataille, C. G. F. (2020). Physical and policy pathways to net-zero emissions industry. Wiley Interdisciplinary Reviews: Climate Change, 11(2), 1–20. https://doi.org/10.1002/wcc.633

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., Fischedick, M., Lechtenböhmer, S., … Rahbar, S. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. Journal of Cleaner Production, 187, 960–973. https://doi.org/10.1016/j.jclepro.2018.03.107

Bataille, C., Sawyer, D., & Melton, N. (2015). Pathways to Deep Decarbonization in Canada Phase 2 Report: Draft Final for Comment. Retrieved from http://cmcghg.com/wp-content/uploads/2015/07/Final-Canada-DDPP-Country-Report-July-14.pdf

Bataille, C., & Stiebert, S. (2018). The transition toward very low carbon heavy industry in the Canadian context: Detailed technical and policy analysis and recommendations for the iron & steel, chemicals, forestry products & packaging, and base metal mining & processing sectors: Phase II of the Canadian Heavy Industry Deep Decarbonization Project. https://doi.org/10.13140/RG.2.2.30872.29447

Budinis, S., Krevor, S., Dowell, N. Mac, Brandon, N., & Hawkes, A. (2018). An assessment of CCS costs, barriers and potential. Energy Strategy Reviews, 22(May), 61–81. https://doi.org/10.1016/j.esr.2018.08.003

Canada Energy Regulator. (2018). *Canada's Energy Future 2018.* Retrieved from https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2018/index.html

Canada Energy Regulator. (2019). *Where does Canada's gasoline come from?* Retrieved from https://www.cer-rec.gc.ca/en/data-analysis/energy-commodities/crude-oil-petroleum-products/report/2019-gasoline/index.html#:~:text=Canada%20has%2017%20refineries%20in,they%20source%20their%20crude%20oil.

Canada Energy Regulator. (2020). *Canada's Energy Future 2020*. Retrieved from https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2020/index.html

Canada Energy Regulator. (2021). Provincial and Territorial Energy Profiles – Canada. Retrieved from https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-canada.html

Canadian Institute for Climate Choices. (2020). *The State of Carbon Pricing in Canada*. Retrieved from https://climatechoices.ca/wp-content/uploads/2021/06/State-of-carbon-pricing-report-English-FINAL.pdf

Canadian Institute for Climate Choices. (2021). *Canada's Net-zero Future: Finding our way in the global transition.* 131. Retrieved from https://climatechoices.ca/wp-content/uploads/2021/02/Canadas-Net-Zero-Future_FINAL-2.pdf

de Pee, A., Pinner, D., Occo, R., Somers, K., Witteveen, M., & Speelman, E. (2018). Decarbonization of industrial sectors: the next frontier. McKinsey & Company. Retrieved from https://www.mckinsey.com/~/media/McKinsey/Business Functions/Sustainability and Resource Productivity/Our Insights/How industry can move toward a low carbon future/Decarbonization-of-industrial-sectors-The-next-frontier.ashx

Denis-Ryan, A., Bataille, C., & Jotzo, F. (2016). Managing carbon-intensive materials in a decarbonizing world without a global price on carbon. *Climate Policy*, 16, 110–S128. https://doi.org/10.1080/14693062.2016.1176008

Department of Energy and Climate Change. (2015). *Industrial Decarbonization and Energy Efficiency Roadmaps to 2050*. Retrieved from https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050

Environment and Climate Change Canada. (2018). *Regulatory Framework for the Output-Based Pricing System.* Ottowa: Government of Canada.

Environment and Climate Change Canada. (2020a). *National Inventory Report 1990-2018: Greenhouse Gas Sources and Sinks in Canada*. Ottowa: Government of Canada.

Environment and Climate Change Canada. (2020b). *A Healthy Environment and a Healthy Economy*. Ottawa: Government of Canada.

Environment and Climate Change Canada. (2021). *Review of the federal Output-Based Pricing System Regulations*. Ottawa: Government of Canada.

Fischedick, M., Roy, J., Acquaye, A., Allwood, J., Ceron, J.-P., Geng, Y., Kheshgi, H., Lanza, A., Perczyk, D., Price, L., Santalla, E., Sheinbaum, C., & Tanaka, K. (2014). *Industry In Climate Change: Mitigation of Climate Change.* Contribution of Working Group III.

Fischer, C., & Fox, A. K. (2012). Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates. *Journal of Environmental Economics and Management, 64(2),* 199–216. https://doi.org/10.1016/j.jeem.2012.01.005

Fortis BC. (2021). *Renewable Natural Gas Rates*. Retrieved from https://www.fortisbc.com/services/sustainable-energy-options/renewable-natural-gas/renewable-natural-gas-rates

Friedmann, S. J., Fan, Z., & Tang, K. (2019). *Low-Carbon heat solutions for heavy industry: sources, options, and costs today.* Centre on Global Energy Policy. Retrieved from https://www.energypolicy.columbia.edu/research/report/low-carbon-heat-solutions-heavy-industry-sources-options-and-costs-today

Global CCS Institute. (2020). *Global status of CCS*. Retrieved from https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf

Government of Canada. (2020). *Pricing Carbon Pollution*. Retrieved from https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climateplan/annex_pricing_carbon_pollution.pdf

Government of Canada. (2021a). *Labour statistics consistent with the System of National Accounts (SNA), by job category and industry*. Retrieved from https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3610048901

Government of Canada. (2021b). *Federal budget.* Retrieved from https://www.budget.gc.ca/2021/report-rapport/toc-tdm-en.html

Hoegh-Guldberg, O., D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K.L. Ebi, F. Engelbrecht, J. Guiot, Y. Hijioka, S. Mehrotra, A. Payne, S.I. Seneviratne, A. Thomas, R. Warren, and G. Zhou. 2018. Impacts of 1.5°C Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. (V. Masson-Delmotte, P. Zhai, H-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, eds.). Intergovernmental Panel on Climate Change. Geneva. Retrieved from https://www.ipcc.ch/sr15/chapter/chapter-3

Irlam, L. (2017). Global Costs of Carbon Capture and Storage. Global CCS Institute, (June). Retrieved from https://www.globalccsinstitute.com/archive/hub/publications/201688/global-ccs-cost-updatev4.pdf

International Energy Agency. (2013). *Technology Roadmap: Carbon capture and storage*. 1–52. https://doi.org/10.1007/SpringerReference_7300

International Energy Agency. (2019). *The Future of Hydrogen*. https://doi.org/10.1787/1e0514c4-en

International Energy Agency. (2020a). *Energy Technology Perspectives 2020*. https://doi.org/10.1787/ab43a9a5-en

International Energy Agency. (2020b). *Renewables 2020*. Retrieved from https://www.iea.org/reports/renewables-2020

International Energy Agency. (2020c). *The challenge of reaching zero emissions in heavy industry*. Retrieved from https://www.iea.org/articles/the-challenge-of-reaching-zero-emissions-in-heavy-industry

International Energy Agency. (2021). *Net-zero by 2050.* Retrieved from https://www.iea.org/reports/net-zero-by-2050

Industrial Gas Users Association. (2018). Options, Opportunities, and the Efficient Transition. *Senate Canada*, *33*(June), 68. https://doi.org/10.3141/2017-06

IPCC, Intergovernmental Panel on Climate Change (2005). IPCC Special Report on Carbon Capture and Storage. Cambridge University Press. New York, NY.

IRENA. (2019). *Solid biomass supply for heat and power: Technology brief, International Renewable Energy Agency*. Retrieved from https://www.irena.org/publications/2019/Jan/Solid-Biomass-Supply-for-Heat-and-Power

Jaccard, M. (2009). Combining top down and bottom up in energy economy models. In J. Evans & L. Hunt (Eds.), International Handbook on the Economics of Energy. Cheltenham, UK: Edward Elgar Publishing Limited.

Kearns, J., Teletzke, G., Palmer, J., Thomann, H., Kheshgi, H., Chen, Y. H. H., & Herzog, H. (2017). Developing a Consistent Database for Regional Geologic $CO_2$ Storage Capacity

Worldwide. *Energy Procedia*, *114*(617), 4697–4709. https://doi.org/10.1016/j.egypro.2017.03.1603

Keith, D. W., St. Angelo, D., Holmes, G., & Heidel, K. (2018). A Process for Capturing $CO_2$ from the Atmosphere. *Joule 2*, 1573–1594. https://doi.org/10.1016/j.joule.2018.05.006

Khatib, H. (2012). IEA World Energy Outlook 2011 – a Comment. *Energy Policy, 48*, 737-743. https://doi.org/10.1016/j.enpol.2012.06.007

Kuramochi, T., Ramírez, A., Turkenburg, W., & Faaij, A. (2012). Comparative assessment of $CO_2$ capture technologies for carbon-intensive industrial processes. *Progress in Energy and Combustion Science,* 38(1), 87–112. https://doi.org/10.1016/j.pecs.2011.05.001

Lechtenböhmer, S., Nilsson, L. J., Åhman, M., & Schneider, C. (2016). Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. *Energy*, *115*, 1623–1631. https://doi.org/10.1016/j.energy.2016.07.110

Leeson, D., Mac Dowell, N., Shah, N., Petit, C., & Fennell, P. S. (2017). A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *International Journal of Greenhouse Gas Control*, 61, 71–84. https://doi.org/10.1016/j.ijggc.2017.03.020

Lutes, K. (2012). Assessing the Economic Potential of Carbon Capture and Storage in Canada Using an Energy-Economy Model (Master's of Resource and Environmental Management Research Project, Simon Fraser University). Retrieved from https://www.sfu.ca/emrg/Publications.html

Library of Parliament. (2017). Greenhouse Gas Emissions for Large Facilities, Canada, 2015. Retrieved from https://open.canada.ca/data/en/dataset/b8477997-51db-5ee8-91c8-52af2a2d7a96

McKibbin, W.J. & Wilcoxen, P. J. (2009). The Economic and Environmental Effects of Border Tax Adjustments for Climate Policy [with Comments]. Retrieved from https://www.jstor.org/stable/20799647

National Energy Technology Laboratory. (2014). *Cost of Capturing $CO_2$ from Industrial Sources.* Retrieved from https://sequestration.mit.edu/pdf/2013_Summers_Capture_Costs_Industrial_Sources.pdf

Natural Resources Canada. (2019). *Energy Factbook 2019-2020*. Retrieved from https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/energy-facts/20061

Natural Resources Canada. (2020). *Hydrogen Strategy for Canada*. Retrieved from https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf

Nordhaus, B. W. (2015). Climate Clubs: Overcoming Free-riding in International Climate Policy. *American Economic Review*, *105*(4), 1339–1370.

Ordorica-Garcia, G., Wong, S., & Faltinson, J. (2011). Characterisation of $CO_2$ emissions in Canada's oil sands industry: Estimating the future $CO_2$ supply and capture cost curves. *Energy Procedia, 4*, 2637–2644. https://doi.org/10.1016/j.egypro.2011.02.163

Ramsden, T., Steward, D., and Zuboy, J. (2009). Analyzing the Levelized Cost of Centralized and Distributed Hydrogen Production Using the H2A Production Model, Version 2. (September).

Ramsden, T., Ruth, M., Diakov, V., Laffen, M., & Timbario, T. A. (2013). Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios. National Renewable Energy Laboratory, (September), 1–268. Retrieved from www.nrel.gov/publications.

Rhodes, E., Axsen, J., & Jaccard, M. (2014). Does effective climate policy require well-informed citizen support? *Global Environmental Change*, *29*, 92–104. https://doi.org/10.1016/j.gloenvcha.2014.09.001

Rodríguez, N., Murillo, R., & Abanades, J. C. (2012). $CO_2$ capture from cement plants using oxyfired precalcination and/ or calcium looping. *Environmental Science and Technology, 46*(4), 2460–2466. https://doi.org/10.1021/es2030593

Romeo, L. M., Catalina, D., Lisbona, P., Lara, Y., & Martínez, A. (2011). Reduction of greenhouse gas emissions by integration of cement plants, power plants, and CO 2 capture systems. *Greenhouse Gases: Science and Technology, 1(*1), 72–82. https://doi.org/10.1002/ghg3.5

Rubin, E. S., Davison, J. E., & Herzog, H. J. (2015). The cost of $CO_2$ capture and storage. *International Journal of Greenhouse Gas Control, 40,* 378–400. https://doi.org/10.1016/j.ijggc.2015.05.018

Sandalow, D., Friedmann, J., Mccormick, C., & Mccoy, S. (2019). ICEF Industrial Heat Decarboniztaion Roadmap. Retrieved from https://www.icef-forum.org/roadmap/

Senate Canada. (2018). *Decarbonizing Heavy Industry: The Low-Carbon Transition of Canada's Emission-Intensive and Trade-Exposed Industries.* Retrieved from: https://sencanada.ca/content/sen/committee/421/ENEV/reports/2018-0323_EITE_FINAL_WEB_e.pdf

Stephen, J., & Wood-bohm, S. (2016). Biomass innovation: Canada's leading cleantech opportunity for greenhouse gas reduction and economic prosperity.

Tsupari, E., Kärki, J., Arasto, A., & Pisilä, E. (2013). Post-combustion capture of $CO_2$ at an integrated steel mill - Part II: Economic feasibility. *International Journal of Greenhouse Gas Control, 16*, 278–286. https://doi.org/10.1016/j.ijggc.2012.08.017

Weber, R.H. (2015). Border Tax Adjustment — Legal Perspective. *Climatic Change 133* (3): 407-417. doi: 10.1007/s10584-015-1414-2.

Wesseling, J. H., Lechtenböhmer, S., Åhman, M., Nilsson, L. J., Worrell, E., & Coenen, L. (2017). The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renewable and Sustainable Energy Reviews, 79,* 1303–1313. https://doi.org/10.1016/j.rser.2017.05.156

Wiley, D. E., Ho, M. T., & Bustamante, A. (2011). Assessment of opportunities for $CO_2$ capture at iron and steel mills: An Australian perspective. *Energy Procedia, 4*, 2654–2661. https://doi.org/10.1016/j.egypro.2011.02.165

WSP Parson Brinkerhoff, & DNV GL. (2015). *Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050.* Retrieved from https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050

# 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 ($2005/$tCO_2$ captured) | Energy Penalty (GJ/$tCO_2$ captured) | Sources |
|---|---|---|---|---|
| Iron and steel | Post combustion MEA on BF-BOF | 71.54 | 3.2 | (Arasto et al., 2013; Budinis et al., 2018; Irlam, 2017; IEA, 2013; Leeson et al., 2017; Tsupari et al., 2013; Wiley et al., 2011) |
| Oil sands | Post combustion MEA | 163.40 | 3.2 | (Ordorcia-Garcia et al., 2011) |
| Petroleum Refining | Post combustion MEA on still gas | 38.57 | 3.2 | (Leeson et al., 2017) |
| | 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 | Post combustion MEA on synthesis | 18.94 | 3.2 | (Irlam, 2017; NETL, 2014) |
| Hydrogen | Post combustion MEA | 28.20 | 3.2 | (IEA, 2013; Leeson et al., 2017; NETL, 2014) |
| Ethylene | Post combustion MEA | 13.75 | 3.2 | (IEA, 2013; NETL, 2014) |

| | | | | |
|---|---|---|---|---|
| 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 | Capital Cost ($2005/GJ) | Operating Cost ($2005/GJ) | Life (yrs) | Output (GJ/year) | CCS Service Required? | Infrastructure Service Required? |
|---|---|---|---|---|---|---|
| Distributed SMR | 6,760,964 | 363,011 | 20 | 63,346 | No | No |
| Distributed SMR with CCS | 6,760,964 | 363,011 | 20 | 63,346 | Yes | No |
| Distributed electrolysis | 7,503,905 | 407,766 | 20 | 63,346 | No | No |
| Central SMR | 547,533,997 | 62,323,456 | 40 | 16,202,277 | No | Yes |
| Central SMR with CCS | 547,533,997 | 62,323,456 | 40 | 16,202,277 | Yes | Yes |
| Central electrolysis | 149,522,315 | 6,537,818 | 40 | 2,470,000 | No | Yes |
| Central coal gasification | 545,423,504 | 27,967,332 | 40 | 12,090,000 | No | Yes |
| Central coal gasification with CCS | 545,423,504 | 27,967,332 | 40 | 12,090,000 | Yes | Yes |
| Central biomass gasification | 512,056,540 | 34,339,485 | 40 | 7,364,240 | No | Yes |

| | | | | | | |
|---|---|---|---|---|---|---|
| Central biomass gasification with CCS | 512,056,540 | 34,339,485 | 40 | 7,364,240 | Yes | Yes |

# Appendix B. Average carbon prices calculated for the OBPS

Table B-1 shows the average carbon prices calculated for the OBPS in the **StringPol Global Inaction** case. Average carbon prices were calculated each five-year period and are rounded to the nearest dollar.

**Table B-1: Average carbon price applied by EITE industry in the StringPol Global Inaction case**

| Industry | 2020 (2005CAD/ $tCO_2e$) | 2030 (2005CAD/ $tCO_2e$) | 2040 (2005CAD/ $tCO_2e$) | 2050 (2005CAD/ $tCO_2e$) |
|---|---|---|---|---|
| Cement and lime | 1 | 56 | 84 | 167 |
| Chemical production | 2 | 17 | 57 | 130 |
| Iron and steel | 2 | 10 | 63 | 187 |
| Metal smelting | 3 | 30 | 64 | 124 |
| Mineral mining | 2 | 22 | 78 | 145 |
| Pulp and paper | 0 | 11 | 33 | 79 |
| Light manufacturing | 2 | 8 | 45 | 100 |
| Natural gas extraction | 2 | 43 | 88 | 174 |
| Petroleum crude | 2 | 40 | 68 | 104 |
| Petroleum refining | 1 | 26 | 100 | 182 |