navius research

Achieving net zero emissions by 2050 in Canada

An evaluation of pathways to net zero prepared for the Canadian Institute for Climate Choices

SUBMITTED TO

Canadian Institute for Climate Choices
January 20, 2021

SUBMITTED BY

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About Us

Navius Research Inc. (“Navius”) is a private consulting firm in Vancouver. Our consultants specialize in analysing government and corporate policies designed to meet environmental goals, with a focus on energy and greenhouse gas emission policy. We have been active in the energy and climate change field since 2004 and are recognized as some of Canada’s leading experts in modeling the environmental and economic impacts of energy and climate policy initiatives. Navius is uniquely qualified to provide insightful and relevant analysis in this field because:

- We have a broad understanding of energy and environmental issues both within and outside of Canada.
- We use unique in-house models of the energy-economy system as principal analysis tools.
- We have a strong network of experts in related fields with whom we work to produce detailed and integrated climate and energy analyses.
- We have gained national and international credibility for producing sound, unbiased analyses for clients from every sector, including all levels of government, industry, labour, the non-profit sector, and academia.

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Executive Summary

In November 2020, Canada's federal government introduced Bill C-12 with the objective of achieving net zero greenhouse gas (GHG) emissions by 2050. At the request of The Canadian Institute for Climate Choices, Navius Research undertook an assessment of pathways under which Canada could achieve this mid-century target. This study aims to explore potential net zero pathways for Canada, illustrate trade-offs and quantify uncertainty across pathways, and provide insight into the potential policy priorities needed for Canada to achieve its goal of net zero emissions.

The model used for this analysis is Navius' gTech model. gTech is unique among energy-economy models as it combines a realistic representation of technology adoption, an exhaustive accounting of the economy at large, and detailed representation of energy supply. It was used to simulate and compare many potential scenarios that represent net zero pathways for Canada.

Development of net zero pathways for Canada

A total of 62 net zero pathways were simulated in this analysis. Net zero is defined here as net zero emissions of all GHGs across all sectors and regions of Canada's economy by 2050. Development of these pathways was intended to be policy agnostic, with the only implemented "policy" being a cap on emissions at net zero in 2050 in all scenarios. As a result, all pathways reach the same level of emissions reductions, but vary in the mitigation actions used to achieve those reductions. A decomposition analysis is used to understand the actions driving emissions reductions. Many different abatement options are available in each sector, which get implemented by the model based on what is behaviourally realistic, technologically available, and most cost effective over time.

To account for uncertainty in technology trends and the different possible states of the world under which Canada may achieve net zero emissions by mid-century, assumptions about key uncertainties were varied across scenarios. These include:

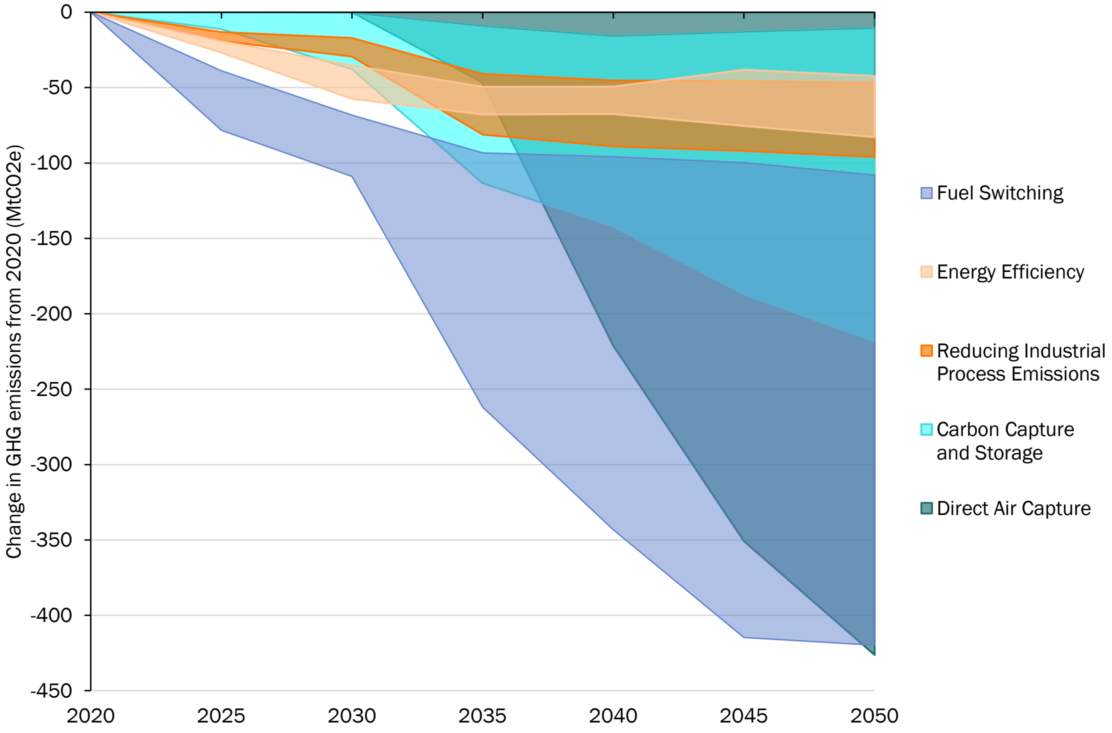
1. **The availability and cost of low carbon technologies** such as the price trajectory of battery electric vehicles, hydrogen fuel cell vehicles, second-generation biofuels, among others.
2. **The availability of negative emission technologies** including direct air capture and carbon capture and storage.

3. **Policy in other jurisdictions and managing competitiveness.** This includes the implementation of climate policy in other major countries, and the implementation of measures to protect competitiveness of Canada's emissions-intensive, trade-exposed sectors.
4. **Commodity prices** including the global oil price forecast.

Drivers of emissions reductions across Canada

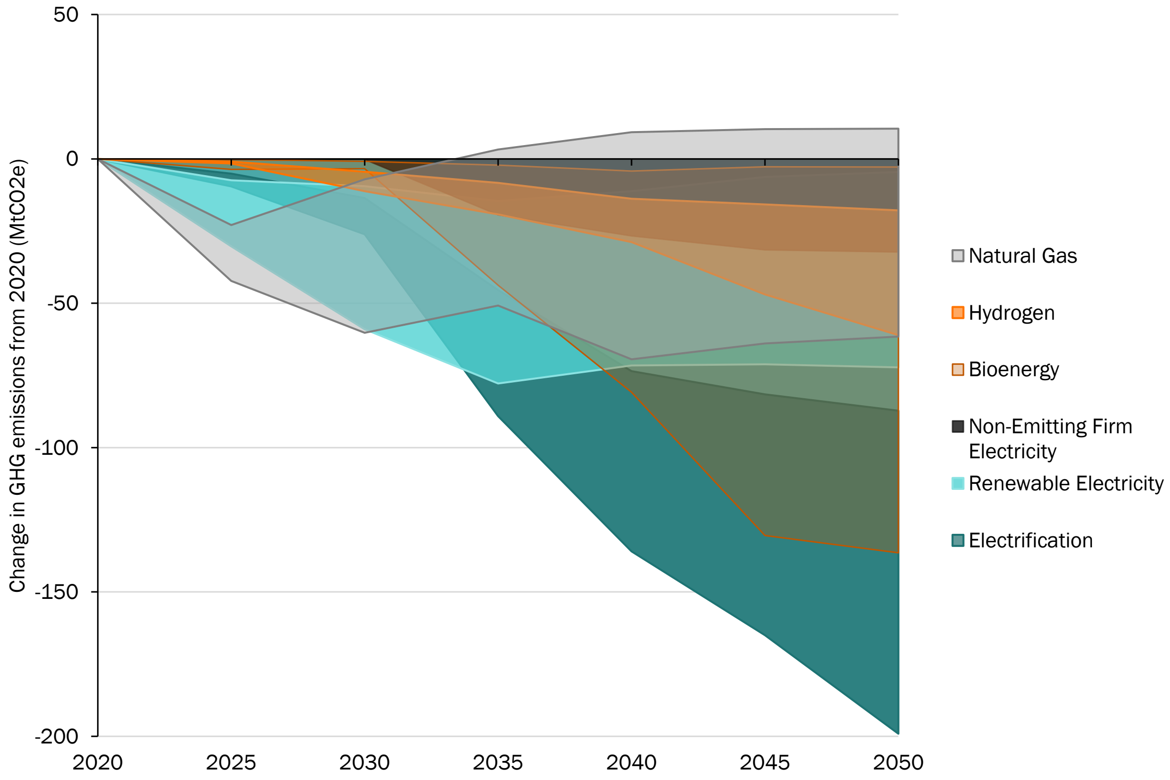
Five key drivers of emissions reductions across Canada's economy were identified in this analysis. They are presented in Figure A, which shows a change in emissions due to each mitigation action compared to 2020 levels. The range presented for each driver represents variation in the role of that mitigation action across net zero pathways. The importance of some drivers, such as DAC, CCS and fuel switching, vary significantly by scenario, while others, including energy efficiency and industrial decarbonization, play a similar role across all net zero pathways.

Figure A: Drivers of emissions reductions in Canada under net zero emissions



An important dynamic indicated here is a trade-off between the use of negative emission technologies, such as DAC and CCS, and the transformation of Canada's energy system to rely on cleaner fuels through fuel switching. In scenarios where DAC and CCS are available, they play an important role, mitigating up to 426 $MtCO_{2e}$ (DAC) and 218 $MtCO_{2e}$ (CCS) of emissions in 2050. When DAC and CCS are not available, fuel switching is the main driver of emissions reductions (up to 420 $MtCO_{2e}$ in 2050). The role of each fuel in reducing emissions from fuel switching is presented in Figure B. Of the emissions reductions occurring from fuel switching, electrification is the largest driver, followed by bioenergy (including renewable natural gas), and hydrogen.

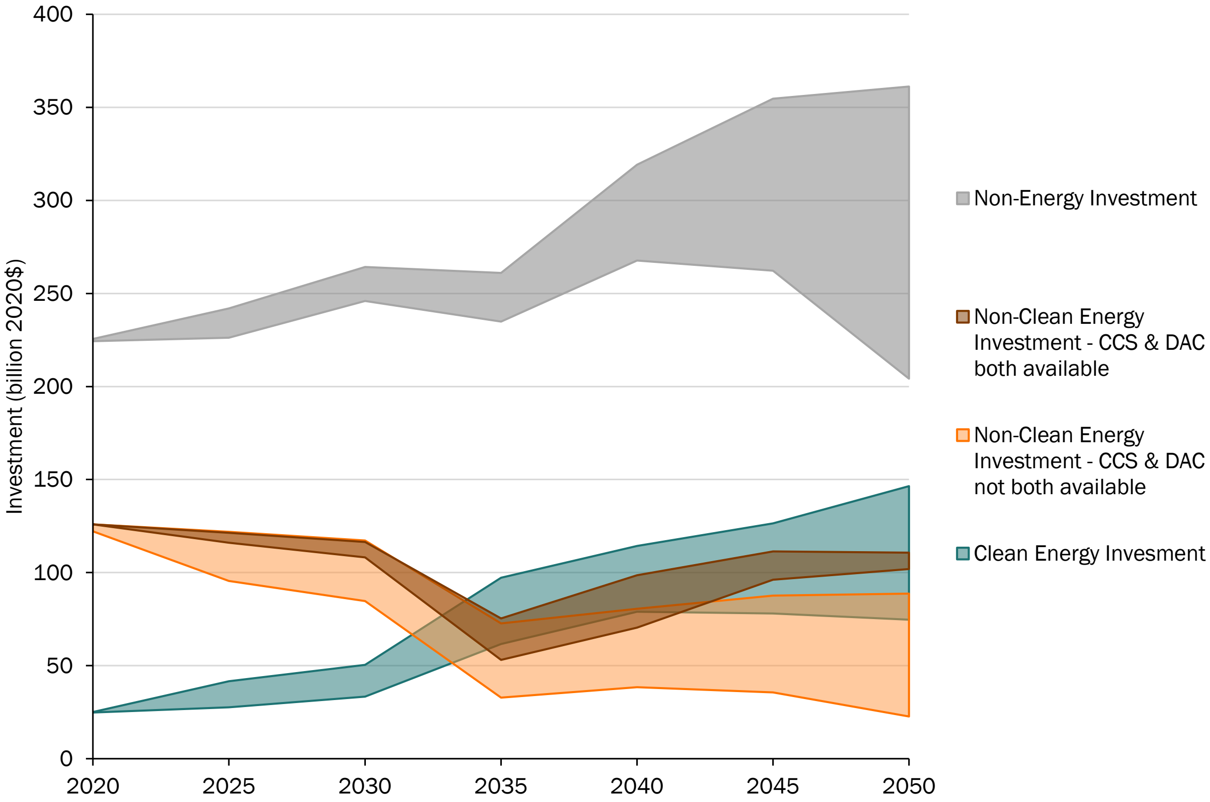
Figure B: Drivers of emissions reductions from fuel switching in Canada under net zero emissions



Investment in the clean economy

The drivers of emissions reductions across Canada are supported by a shift in investment away from non-clean energy, such as fossil fuels, to clean technologies, such as renewable electricity, biofuels manufacturing and electric vehicles (Figure C). Non-clean energy investment decreases from $126 billion in 2020 to $23-111 billion in 2050 depending on the net zero pathway, while clean energy investment increases from $25 billion in 2020 to $75-146.5 billion in 2050. Investment in clean and non-clean energy varies across net zero pathways. In scenarios in which DAC and CCS are available, significant investment is made in these technologies to offset emissions across the economy, and less is made in other means of decarbonization such as electricity generation and biofuels. When DAC and CCS are not available, there is a significant shift away from investment in non-clean energy towards cleaner energy sources. Significant investment is made in electric vehicles across all net zero scenarios.

Figure C: Annual investment in all net zero pathways



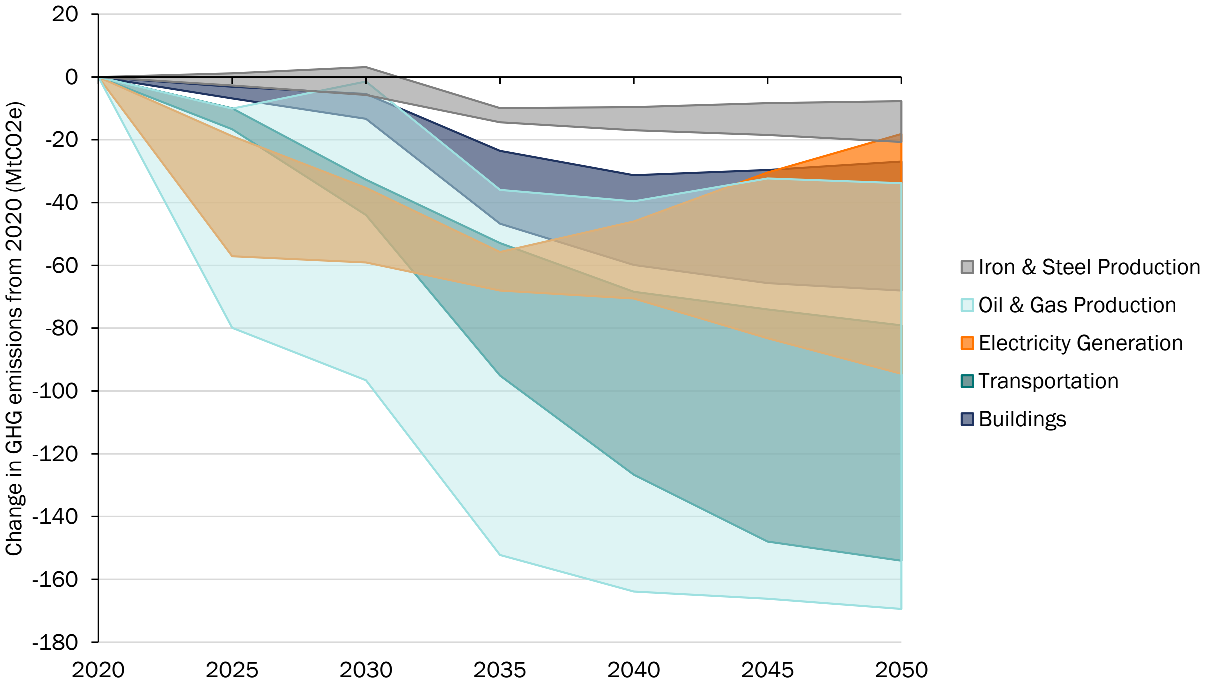
Drivers of emissions reductions by sector

The emissions abatement options available for each sector were also explored in this analysis. Figure D presents the change in total GHG emissions by sector compared to 2020 levels. The range presented for each sector represents variation across different net zero pathways.

A key driver of emissions reductions in commercial and residential buildings is electrification, followed by energy efficiency and biofuels. Electrification is also the largest driver of emission reductions in personal transport, while bioenergy and hydrogen play a larger role in reducing emissions in the medium- and heavy-duty transport sector. Electricity generation increases significantly under all net zero pathways to keep up with increasing demand from clean technologies. All scenarios show a reduction in thermal electricity generation and a significant increase in renewable generation, which is a key driver of emissions reductions in this sector, along with CCS when available.

The industrial sectors explored in this report are oil, natural gas, and iron and steel. Results of this analysis suggest that the future of Canadian oil and gas production is uncertain. When other major countries implement climate policy on pace with Canada and there is less demand for oil and gas, and when DAC is not available, a reduction in activity in these sectors is a key driver of emissions reductions. Another key driver of mitigation in the oil sector is CCS, when available, and in the natural gas sector is electrification. Canada's iron and steel sector completely decarbonizes in all net zero pathways by switching to cleaner production using direct iron reduction or steel recycling.

Figure D: Change in sector GHG emissions under net zero emissions compared to today



Key insights

Results of this analysis provide four key insights:

1. **Canada can achieve net zero emissions by mid-century via more than one pathway.** Canada's net zero goal is achievable with currently known and available technologies and industrial abatement options. What Canada looks like at net zero depends heavily on the cost and availability of negative emission technologies and the international demand for Canadian oil and gas.

2. **An emissions backstop will be needed for Canada to achieve net zero emissions.** Some sectors are unable to achieve zero emissions given a lack of abatement options and some form of negative emission technology, such as DAC and/or CCS and/or land use or forestry sequestration will be needed. The technology that is most widely available, scalable, and cost-effective will play a crucial role in decarbonizing Canada's economy.

3. **The future of Canada's oil and gas sector is uncertain.** Canada's oil and gas sector cannot be sustained without negative emission technologies, either DAC or CCS. If global demand for oil and gas decrease, as a result of climate policy implementation in other major countries, then significant production declines are likely in this sector. In all pathways to net zero emissions, however, carbon dioxide becomes a valuable commodity, and when DAC or CCS are available, the geological storage potential in western Canada becomes an asset and opportunity.

4. **Decisions being made today will determine which net zero pathway Canada takes.** There are some common actions that will be required for any of the net zero pathways simulated in this analysis to become a reality. These include a significant increase in electricity generation capacity, biofuel manufacturing, investment in clean energy technologies and capacity for GHG sequestration, as well as a switch to fully decarbonized steelmaking.

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1. Introduction

In November 2020, Canada's federal government introduced Bill C-12 with the objective of achieving net zero greenhouse gas (GHG) emissions by 2050.[1] This is consistent with Canada's commitments under the Paris Agreement[2] and with the IPCC's finding that limiting warming to 1.5 °C requires net zero carbon dioxide emissions globally around 2050[3]. Net zero is achieved when anthropogenic GHG emissions are balanced by anthropogenic removals and is defined in this study as net zero emissions of all GHGs across all sectors and regions of Canada's economy in 2050.

The Canadian Institute for Climate Choices was established to provide rigorous and independent research, insightful analysis and broad engagement to bring clarity to the climate challenges and transformative policy choices ahead for Canada. To support the Institute in its mission, Navius Research undertook an assessment of pathways under which Canada could achieve net zero emissions by mid-century.

This study aims to explore potential net zero pathways for Canada, illustrate trade-offs and quantify uncertainty across pathways, and provide insight into the potential policy priorities needed for Canada to achieve its goal of net zero emissions.

This report presents the findings of that analysis. It is structured as follows:

- Chapter 2 introduces gTech, the modeling tool used for this analysis, and summarizes the net zero scenario forecasts and key assumptions made.
- Chapter 3 reviews the key drivers of emissions reductions across Canada and in key sectors.
- Chapter 4 provides key insights based on this analysis.

Additional information about the model and scenario assumptions are provided in the Appendices.

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[1] Parliament of Canada, 2020. Bill C-12 An Act respecting transparency and accountability in Canada's efforts to achieve net-zero greenhouse gas emissions by the year 2050. Available from: https://parl.ca/DocumentViewer/en/43-2/bill/C-12/first-reading

[2] Environment and Climate Change Canada, 2016. The Paris Agreement. Available from: https://www.canada.ca/en/environment-climate-change/services/climate-change/paris-agreement.html

[3] Rogelj et al., 2018. Mitigation Pathways Compatible with 1.5 °C in the Context of Sustainable Development. In: *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*. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf

2. Analytical approach

This Chapter provides an overview of the model and approach used to forecast a net zero emission future for Canada. It introduces energy-economy modeling and Navius' gTech model (Section 2.1) and describes the scenarios modeled in this analysis and the key assumptions made (Section 2.2).

2.1. Introduction to the gTech model

Canada's energy-economy is complex. Energy consumption, which is the main driver of anthropogenic GHG emissions, results from the decisions made by millions of Canadians. For example, households must choose what type of vehicles they will buy and how to heat their homes; industry must decide whether to install technologies that might cost more but consume less energy; municipalities must determine whether to expand transit service; and investors need to decide whether to invest their money in Canada or somewhere else.

All levels of government in Canada have implemented policies designed to encourage or require firms and consumers to take actions to reduce their emissions. Achieving Canada's net zero by mid-century target will require strengthening existing policies and/or implementing new policies that result in additional emission reduction activities.

Existing policies and those required to achieve Canada's net zero target will have effects throughout the economy and will interact with each other. For example, the federal vehicle emission standard and federal/provincial carbon pricing efforts seek to reduce greenhouse gas emissions from passenger vehicles, as do a variety of provincial policies (such as BC's low carbon fuel standard, the proposed federal clean fuel standard and zero-emission vehicle mandates in Québec and proposed in BC). The interactive effects among such policies can be complex. The economic effects of all federal and provincial climate initiatives implemented together are even more complex.

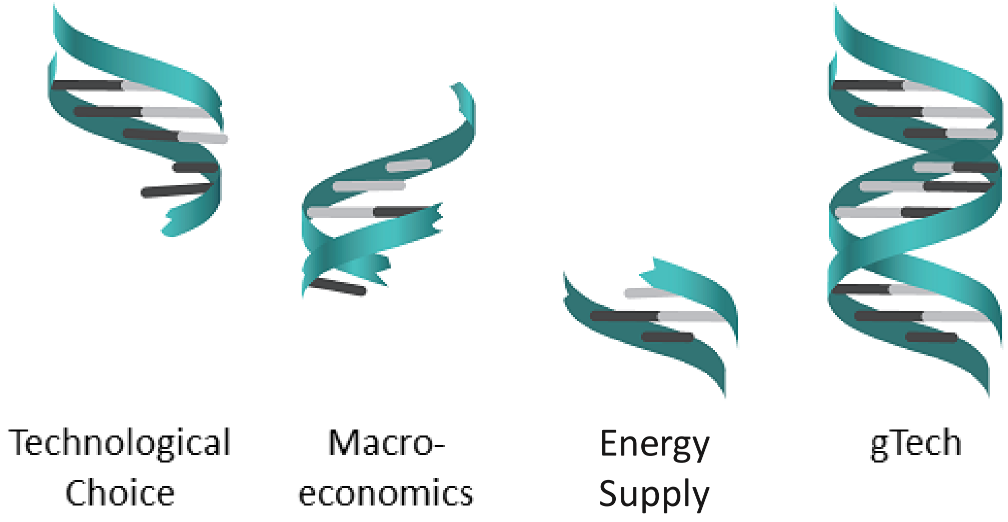
Estimating the regional, sectoral, technological and economic impacts of achieving Canada's net zero emissions target therefore requires a modeling framework that captures the complexity of the energy-economic system.

2.1.1. Summary of gTech

The model used for this analysis is Navius' gTech model. gTech is unique among energy-economy models because it combines features that are typically only found in separate models:

- A realistic representation of how households and firms select technologies and processes that affect their energy consumption and GHG emissions;
- An exhaustive accounting of the economy at large, including how sectors, provinces and territories interact with each other and the rest of the world; and
- A detailed representation of energy supply, including liquid fuel (crude oil and biofuel), gaseous fuel (natural gas and renewable natural gas) and electricity.

Figure 1: The gTech model



gTech builds on three of Navius' previous models (CIMS, GEEM and OILTRANS/IESD), combining their best elements into a comprehensive integrated framework.

gTech simulates technological choice

Technological choice is one of the most critical decisions that influence GHG emissions in Canada. For example, if a household chooses to purchase an electric vehicle over a gasoline car, that decision will reduce their emissions. Similarly, if a mining facility chooses to electrify its operations, that decision reduces its emissions.

gTech provides a detailed accounting of the types of energy-related technologies available to households and businesses. In total, gTech includes over 95 sectors and over 300 technologies across 70 end-uses (e.g., light-duty vehicle travel, residential space heating, industrial process heat, management of agricultural manure). See Appendix A for a list of all covered sectors, technologies and end-uses.

Technological choice is influenced by many factors. Table 1 summarizes key factors that influence technological choice and the extent to which these factors are included in gTech.

Table 1: Technological choice dynamics captured by gTech

Criteria	Description
Purchasing (capital) costs	Purchasing costs are simply the upfront cost of purchasing a technology. Every technology in gTech has a unique capital cost that is based on research conducted by Navius. Everything else being equal (which is rarely the case), households and firms prefer technologies with a lower purchasing cost.
Energy costs	Energy costs are a function of two factors: (1) the price for energy (e.g., cents per litre of gasoline) and (2) the energy requirements of an individual technology (e.g., a vehicle's fuel economy, measured in litres per 100 km). In gTech, the energy requirements for a given technology archetype are fixed (though different archetypes allow energy efficiency improvements), but the price for energy is determined by the model.
Time preference of capital	Most technologies have both a purchasing cost as well as an energy cost. Households and businesses must generally incur a technology's purchasing cost before they incur the energy costs. In other words, a household will buy a vehicle before it needs to be fueled. As such, there is a tradeoff between near-term capital costs and long-term energy costs. gTech represents this tradeoff using a "discount rate". Discount rates are analogous to the interest rate used for a loan. The question then becomes: is a household willing to incur greater upfront costs to enable energy or emissions savings in the future? Many energy modelers use a "financial" discount rate (commonly between 5% and 10%). However, given the objective of forecasting how households and firms are likely to respond to climate policy, gTech employs behaviourally realistic discount rates of between 8% and 25% to simulate technological choice. Research consistently shows that households and firms do not make decisions using a financial discount rate, but rather use these significantly higher rates.[4] The implication is that using a financial discount rate would overvalue future savings relative to revealed (i.e., real) human behaviour and would provide a poor forecast of household and firm decisions.

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[4] For example, see: Rivers, N., & Jaccard, M. (2006). Useful models for simulating policies to induce technological change. *Energy policy*, *34*(15), 2038-2047; Axsen, J., Mountain, D.C., Jaccard, M., 2009. Combining stated and revealed choice research to simulate the neighbor effect: The case of hybrid-electric vehicles. Resource and Energy Economics 31, 221-238.

Criteria	Description
Technology-specific preferences	In addition to preferences around near-term and long-term costs, households (and even firms) exhibit "preferences" towards certain types of technologies. These preferences are often so strong that they can overwhelm most other factors (including financial ones). For example, buyers of passenger vehicles can be concerned about the driving range and available charging infrastructure of vehicles, some may worry about the risk of buying new technology, and some may see the vehicle as a "status symbol" that they value[5]. gTech quantifies these technology-specific preferences as "non-financial" costs, which are added to the technology choice algorithm (with the diversity of preferences addressed in the next point).
The diverse nature of Canadians	Canadians are not a homogenous group. Individuals are unique and will weigh factors differently when choosing what type of technology to purchase. For example, one household may purchase a Toyota Prius while their neighbour purchases an SUV and another takes transit. gTech uses a "market share" equation in which technologies with the lowest net-costs (including all the cost dynamics described above) achieve the greatest market share, but technologies with higher net-costs may still capture some market share[6]. As a technology becomes increasingly costly relative to its alternatives, that technology earns less market share.
Changing costs over time	Costs for technologies are not fixed over time. For example, the cost of electric vehicles has come down significantly over the past few years, and costs are expected to continue declining in the future[7]. Similarly, costs for many other energy efficient devices and emissions-reducing technologies have declined and are expected to continue declining. gTech accounts for whether and how costs for technologies are projected to decline over time and/or in response to cumulative production of that technology.
Policy	One of the most important drivers of technological choice is government policy. Current federal, provincial and territorial initiatives in Canada are already altering the technological choices households and firms make through various policies: (1) incentive programs, which pay for a portion of the purchasing cost of a given technology; (2) regulations, which either require a group of technologies to be purchased or prevent another group of technologies from being purchased; (3) carbon pricing, which increases fuel costs in proportion to their carbon content; (4) variations in other tax policy (e.g., whether or not to charge GST on a given technology); and (5) flexible regulations, like the federal clean fuel standard which will create a market for compliance credits generated from a range of defined activities. gTech simulates the combined effects of all these policies implemented together.

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[5] Kormos, C., Axsen, J., Long, Z., Goldberg, S., 2019. Latent demand for zero-emissions vehicles in Canada (Part 2): Insights from a stated choice experiment. Transportation Research Part D: Transport and Environment 67, 685-702.

[6] Rivers, N., & Jaccard, M. (2006). Useful models for simulating policies to induce technological change. *Energy policy*, *34*(15), 2038-2047.

[7] Nykvist, B., Sprei, F., & Nilsson, M. (2019). Assessing the progress toward lower priced long range battery electric vehicles. *Energy Policy*, 124, 144-155.

gTech simulates the macroeconomic impacts of policy

As a full macroeconomic model (specifically, a "general equilibrium model"), gTech provides insight about how policies affect the economy at large. The key macroeconomic dynamics captured by gTech are summarised in Table 2.

Table 2: Macroeconomic dynamics captured by gTech

Dynamic	Description
Comprehensive coverage of economic activity	gTech accounts for all economic activity in Canada as measured by Statistics Canada national accounts[8]. Specifically, it captures all sector activity, all gross domestic product, all trade of goods and services and the transactions that occur between households, firms and government. As such, the model provides a forecast of how government policy affects many different economic indicators, including gross domestic product, investment, household income and jobs.
Full equilibrium dynamics	gTech ensures that all markets in the model return to equilibrium (i.e., that the supply for a good or service is equal to its demand). This means that a decision made in one sector will have ripple effects throughout the entire economy. For example, greater demand for electricity requires greater electricity production. In turn, greater production necessitates greater investment and demand for goods and services from the electricity sector, increasing demand for labour in construction services and ultimately leading to higher wages. The model also accounts for price effects. For example, the electricity sector can pass policy compliance costs on to households, who may alter their demand for electricity and other goods and services (e.g., by switching to technologies that consume other fuels and/or reducing consumption of other goods and services).
Sector detail	gTech provides a detailed accounting of sectors in Canada. In total, gTech simulates how policies affect over 95 sectors of the economy. Each of these sectors produces a unique good or service (e.g., the mining sector produces ore, while the trucking sector produces transport services) and requires specific inputs into production.
Labour and capital markets	Labour and capital markets must also achieve equilibrium in the model. The availability of labour can change with the "real" wage rate (i.e., the wage rate relative to the consumption level). If the real wage increases, the availability of labour increases. The model also accounts for "equilibrium unemployment".
Interactions between regions	Economic activity in Canada is highly influenced by interactions among provinces/territories, with the United States and with countries outside of North America. Each region in the model interacts with other regions via (1) the trade of goods and services, (2) capital movements, (3) government taxation (within Canada only) and (4) various types of "transfers" between regions (e.g., the federal government provides transfers to provincial and territorial governments). gTech accounts for 10 Canadian provinces, the 3 territories in an aggregated region and the United States. The model simulates each of the interactions described above, and how interactions may change in response to policy.

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[8] Statistics Canada. Supply and Use Tables. Available from: www150.statcan.gc.ca/n1/en/catalogue/15-602-X

Dynamic	Description
Households	Households earn income from the economy at large and use this income to consume different goods and services. gTech accounts for each of these dynamics, and how policies change them.

gTech simulates energy supply markets

gTech accounts for all major energy supply markets, such as electricity, refined petroleum products and natural gas. Each market is characterized by resource availability and production costs by province, as well as costs and constraints (e.g., pipeline capacity) of transporting energy between regions.

Low carbon energy sources can be introduced within each fuel stream in response to policy, including renewable electricity and bioenergy. The model accounts for the availability and cost of bioenergy feedstocks, allowing it to provide insight about the economic effects of emission reduction policy, biofuels policy and the approval of pipelines.

The benefits of merging macroeconomics with technological detail

By merging the three features described above (technological detail, macroeconomic dynamics, and energy supply dynamics), gTech can provide extensive insight into the effects of climate and energy policy. As such, this modeling toolkit allows for a comprehensive examination of Canada’s net zero emission pathways and their impacts.

2.1.2. Model calibration

To characterize Canada’s energy-economy, gTech is calibrated to a large variety of data sources. GHG emissions are calibrated in a 2015 base year to align with historical emissions reported by Environment and Climate Change Canada in the National Inventory Report.[9]. Between 2015 and the most recent year for which data is available, modeled emissions are also calibrated to align with historical trends. The ability of gTech to replicate historical trends improves confidence in projections moving forward. Note that the model is intended to capture medium and long-term trends rather than short-term fluctuations due to business cycles and other factors. Therefore, it may not match historical data perfectly over shorter timescales.

Key calibration data sources used in this analysis include:

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[9] Environment and Climate Change Canada. National Inventory Report. Available from: www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory.html

- Natural Resources Canada's Comprehensive Energy Use Database[10] for trends in building and transport energy consumption and efficiency.
- Environment and Climate Change Canada's National Inventory Report[11] for non-combustion emissions as well as the relationship between emissions by IPCC category and NAICS (North American Industry Classification System) economic sector.
- Statistics Canada's Supply-Use Tables[12] for the structure of Canada's economy including sector activity, GDP, trade of goods and services and the financial transactions between households, firms, government and other regions.
- Statistics Canada's Annual Industrial Consumption of Energy Survey[13] for energy consumption by fuel in industry.
- Parliamentary Budget Office's Fiscal Sustainability Report[14] for GDP and labour force trends.

2.1.3. Limits to forecasting

Despite using the best available forecasting methods and assumptions, the evolution of Canada's energy economy is uncertain. Forecasting GHG emissions, in particular, is subject to two main types of uncertainty.

First, all models are simplified representations of reality. The gTech model is, effectively, a series of mathematical equations that are intended to forecast the future. This raises key questions: "are the equations selected a good representation of reality?" and "do the equations selected overlook important factors that may influence the future?"

The use of computable general equilibrium models (like gTech) is well founded in the academic literature. In addition, Navius undertakes significant efforts to calibrate and back-cast the model to ensure that it captures key dynamics in the energy-economic system, as described above.

However, gTech does not account for every dynamic that will influence technological change. For example, household and firm decisions are influenced by many factors,

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[10] Natural Resources Canada. Comprehensive Energy Use Database. Available from: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm

[11] Environment and Climate Change Canada. National Inventory Report. Available from: www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory.html

[12] Statistics Canada. Supply and Use Tables. Available from: www150.statcan.gc.ca/n1/en/catalogue/15-602-X

[13] Statistics Canada. Annual Industrial Consumption of Energy Survey. Available from: www.statcan.gc.ca

[14] Parliamentary Budget Office, 2020 Fiscal Sustainability Report. Available from: https://www.pbo-dpb.gc.ca/en/blog/news/RP-1920-029-S-fiscal-sustainability-report-2020-rapport-viabilite-financiere-2020

which cannot be fully captured by even the most sophisticated model. The inherent limitation of energy-economy forecasting is that virtually all projections of the future will differ, to some extent, from what ultimately transpires.

Second, the assumptions used to parameterize the model are subject to uncertainty. These assumptions include, but are not limited to, oil prices, improvements in labour productivity and a stable climate. If any of the assumptions used prove incorrect, the resulting forecast could be affected. Some of these inherent uncertainties are explored using sensitivity analysis, as described in the following section.

In sum, gTech is the most comprehensive model available for forecasting the techno-economic impacts of climate policy in Canada. Its representation of technological change, macroeconomic dynamics and fuels markets (as described above) mean that it is ideally positioned to forecast how achieving net zero emissions by mid-century in Canada will affect technological change, energy consumption, GHG emissions and the economy. However, no model, including gTech, can predict the future.

2.1.4. Decomposition method

Once the net zero scenarios are simulated using gTech, emissions reductions in each scenario are allocated to key mitigation actions. All net zero pathways in this analysis achieve a similar trajectory of emissions reductions, but what is driving reductions varies by pathway. A decomposition analysis can be used to understand these drivers.

Emissions in each net zero pathway are disaggregated into five factors using the following equation:

$$GHG = O \times \sum_{j} \frac{S_j}{O} \times \sum_{eu} \frac{EU_{j,eu}}{S_j} \times \sum_{t} \frac{T_{j,eu,t}}{EU_{j,eu}} \times \frac{GHG_{j,eu,t}}{T_{j,eu,t}}$$

Where: output (O in the equation above) is the total production of a good or service; sector share of output (S_j/O) accounts for commodities that can be produced with differing emissions intensities by more than one sector; end-use efficiency ($EU_{j,eu}/S_j$) accounts for changes in demand for a GHG-emitting end-use; technology share ($T_{j,eu,t}/EU_{j,eu}$) accounts for the share of a low-emission technology ($T_{j,eu,t}$) used to meet the demand for an end-use ($EU_{j,eu}$); and GHG intensity ($GHG_{j,eu,t}/T_{j,eu,t}$) represents the emissions intensity of a given technology. Results of this decomposition analysis can be used to build a detailed explanation for why emissions change under each net zero pathway. Navius' decomposition methodology is explained in more detail in Appendix B.

2.2. Scenario and forecast assumptions

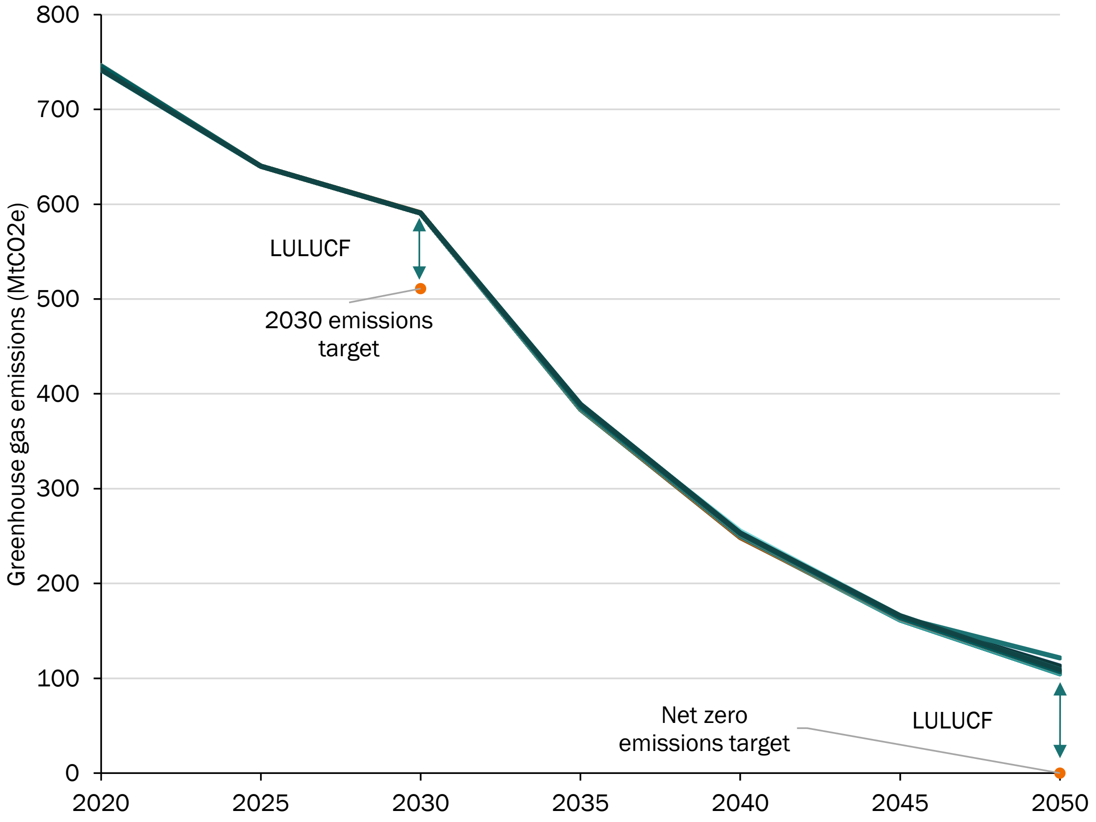
In this analysis, gTech was used to forecast many possible net zero emission futures for Canada. This section describes how those scenarios were designed and how key assumptions were varied to capture uncertainty in Canada's future.

2.2.1. Defining net zero

Net zero is defined in this analysis as net zero emissions of all GHGs across all sectors and regions of Canada's economy by 2050. This is simulated by implementing a cap on emissions at net zero in 2050, effectively simulating a nationwide cap-and-trade system. More specifically, emissions are capped at Canada's 2030 emission target of 511 $MtCO_{2e}$ in 2030 and at net zero in 2050, with interim caps every five years set by interpolating between the two, as shown in Figure 2.

Mitigation potential from land-use, land-use change, and forestry (LULUCF) were not explicitly modeled in this analysis. Instead, an assumed fixed number of emissions offsets were available between now and 2050 from land-use and forestry measures. The size of this potential offset was based on a pending analysis from Nature United. A total offset potential per year from land-use and forestry measures was assumed to be 80 $MtCO_{2e}$ in 2030 and 105 $MtCO_{2e}$ in 2050, based on reduction potentials of afforestation, forest management, agriculture and wetlands. These LULUCF offsets account for the difference between the emissions trajectory of net zero scenarios and Canada's 2030 target/2050 net zero target in Figure 2. Variations between scenarios in 2050 is due to small differences in LULUCF offset assumptions.

Figure 2. GHG emissions trajectory of all net zero pathways



To achieve the required reduction in emissions to net zero, many different abatement options are available in each sector, which get implemented by the model based on what is behaviourally realistic, technologically available, and most cost effective over time. These options range from sector and production changes, to mode, fuel and technology shifting, to income, preference and behavioural changes. Options to reduce emissions are sector-specific and are illustrated here by two examples.

Example: personal transportation

Emissions from passenger transport can be mitigated in several ways. First, people can drive less. This can result from a change in income, or from another behavioural change such as car sharing or mode shifting to public transportation. Second, people can choose to purchase a less emissions intensive vehicle. This choice includes vehicle size (e.g., car vs. SUV), motor (e.g., electric vs. fuel cell vs. more efficient combustion engine), and fuel (e.g., electricity vs. hydrogen vs. biofuel blend). Third, the fuel used in vehicles can be produced in a less emissions intensive way. Process improvements can be made in the production of the fuel, such as using clean electricity to power the production process, a higher portion of biofuels can be blended into the fuel stream, or carbon capture and sequestration technology can be used at the manufacturing facility. The fuel can also be produced using a different process entirely, such as hydrogen that can be produced using electricity or biomass instead of natural gas. All of these abatement opportunities are simulated in this analysis to facilitate the light-duty vehicle sector in decarbonizing by 2050.

Example: iron and steel production

Iron and steel production in Canada occurs mainly in Ontario and Québec. Emissions from the production of iron and steel in these provinces can be mitigated in several ways. First, there can be a change in the output of the sector, such as a reduction in production quantity. Second, there can be a change in the way the steel is produced. Facilities can switch from the use of basic-oxygen furnace (BOF) steelmaking to the use of direct reduced iron (DRI) and electric-arc furnace (EAF) steelmaking or increase the use of recycled steel using an EAF. Third, there can be a change in the fuel that is used to power the production process. DRI, for example, can be powered using hydrogen instead of natural gas to lower emissions. All of these abatement opportunities are simulated in this analysis to facilitate the iron and steel sector in decarbonizing by 2050.

A full list of abatement options available for each sector is provided in Appendix C.

Note that some known abatement options have yet to be included in gTech or have been excluded from this analysis due to a high level of uncertainty or high reliance on political intervention. These include high-speed rail transport, thorium-based nuclear power, small modular nuclear reactors, and long-distance transport infrastructure for hydrogen fuel. Other dynamics that have not been simulated include full integration of the hydrogen and electricity generation sector, increased electricity interties between regions, and other recent trends, such as synthetic meat consumption, all of which could lead to further emissions abatement.

2.2.2. Scenario development

A total of 62 net zero pathways for Canada were simulated in this analysis. Development of these pathways was intended to be policy agnostic, with the only implemented “policy” being a cap on emissions at net zero in 2050 in all scenarios.[15]

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[15] Note that there are several different types of policies or policy combinations that can be used to achieve emissions reductions, all of which lead to different impacts (e.g., carbon pricing in the form of a tax, cap-and-trade or tradeable performance standard, or prescriptive or flexible economy-wide or industry-focused regulations). For this reason, policy design assumptions are important to keep in mind when discussing the impacts of a policy scenario. In this case, an emissions cap was used to simulate achievement of climate targets via economically efficient policy, but the economic and other impacts of the net zero pathways simulated here would vary if a different policy or different policy design were used to achieve emissions reductions.

As a result, all pathways reach the same level of emissions reductions, but vary in the mitigation actions used to achieve those reductions.

Due to the inherent uncertainty in Canada's future energy-economy, several assumptions must be made in this type of forecast. To account for uncertainty in technology trends and the different possible states of the world under which Canada may achieve net zero emissions by mid-century, assumptions about key uncertainties were varied across scenarios. These include:

1. **The availability and cost of low carbon technologies**.
    - Price trajectory of battery electric vehicles.
    - Cost of producing hydrogen fuel.
    - Price trajectory of hydrogen fuel cell vehicles.

      There are two supply pathways for hydrogen refueling stations for transport: distributed production (where a small-scale hydrogen plant is located at the refueling station) and centralized production (where trucks transport hydrogen from a large-scale plant to a refueling station). In this analysis, distributed steam methane reformation (SMR) with and without CCS (captured carbon is piped to locations with geological storage), distributed electrolysis, and centralized biomass gasification are available. It is assumed that hydrogen is transported via truck or rail since there is currently no hydrogen pipeline network in Canada. Centralized electrolysis is not yet an option available in gTech, though we expect the fuel would have a higher final cost due to the cost of transport.

    - Limit of hydrogen blending into the natural gas system.

      This limit, without the need for pipeline or end-use retrofits/upgrades, is constrained by technical and safety considerations. SMR without CCS is not available for blending in this analysis since it does not provide GHG emission benefits compared to natural gas.

    - Availability of new, non-emitting firm power generation, such as nuclear and geothermal.
    - Availability of second-generation biofuels such as those made from switchgrass.
    - Future reductions in the emissions intensity of the oil sands sector.

2. The availability of negative emission technologies.

- Availability of direct air capture (DAC).
- Availability of CCS for combustion emissions.

  The end-uses that can adopt CCS in gTech are natural gas formation, cement production, SMR hydrogen production, pulverized coal power plant, combined-cycle natural gas, coal boiler for process heat, natural gas boiler for process heat. Two CO_2 separation technologies are included: combustion CO_2 separation (i.e., from flue gases) for combustion technologies and process CO_2 separation for process emission technologies.

3. Policy in other jurisdictions and managing competitiveness.

- Level of climate policy implementation in other countries.

  gTech explicitly simulates bilateral trade between Canada and the US and can therefore explicitly simulate climate policy in the US. To account for trade and policy interaction between North America and the rest of the world, which gTech does not simulate explicitly, changes in commodity prices were used as a proxy. The global price for commodities is typically modelled using a fixed value, but we know the cost of producing commodities is likely to change if the rest of the world implements climate policy at the level needed to achieve net zero emission.

- Measures to protect competitiveness of Canada's emissions-intensity, trade-exposed sectors.

  When applying a carbon price or cap-and-trade system, assumptions must be made about how carbon pricing revenue is allocated. In this analysis, some scenarios assume all revenue is recycled back to households, while others assume that some is returned to industry via free allocations of emissions. Over time, as emissions are reduced and approach net zero, free allocations available to return to industry disappear. These assumptions have different economic impacts. Recycling of carbon pricing revenue to households means that the economic impacts of the policy are conserved in some areas of the economy (i.e., households) and exacerbated in others (i.e., industry). Inclusion of competitiveness protection measures helps to reduce the impacts of the carbon price on industry.

4. Commodity prices

- Global oil price projection.

The assumptions made for each of these uncertainties and how they vary across scenarios is presented in Table 3. A list of the 62 scenarios included in this analysis is provided in Appendix D.

Table 3: Summary of key assumptions examined via uncertainty analysis[16]

Uncertainty	Assumption			Source
	Reference	Low / Unavailable	High / Available	
Cost of battery electric vehicles	Battery pack costs decline from $502/kWh to $84/kWh. When these assumptions are applied, the estimated price of a battery electric vehicle declines as a function of adoption to a minimum of $23,700 ($25,100 with charger) by 2030 (includes 30% margin and a $12,000 glider[17]).	Battery pack costs decline to $75/kWh. The estimated price of a battery electric vehicle declines to a minimum of $22,120 (23,540 with charger) by 2030 (same margin and glider assumptions as reference case).	--	Bloomberg New Energy Finance (2017, 2019, 2020). Electric vehicle outlook ICCT (2019). Update on electric vehicle costs in the United States through 2030.
Cost of hydrogen production – natural gas steam methane reforming (SMR) pathway	Small SMR plants are assumed to produce hydrogen at the refueling station because it is the most cost-effective hydrogen delivery pathway for this technology. The levelized cost of producing and dispensing the hydrogen is $5.0/kg or $35/GJ$_{HHV}$[18] (10% discount rate, 30-year project life, $4.9/GJ). Station utilization is assumed to be 86%. No capital cost decline is assumed.	Station utilization is assumed to be 95% capacity, resulting in a levelized cost 10% below the reference case.	--	NREL (2019). H2A Hydrogen Production Analysis.

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[16] All prices are reported in 2020 CAD$ unless otherwise specified.

[17] A glider is defined as the vehicle components that are shared across technologies. They include body, wheels, suspension, windows, seats and other interior parts.

[18] A 140 MJ/kg higher heating value is used.

Uncertainty	Assumption			Source
	Reference	Low / Unavailable	High / Available	
Cost of hydrogen production – biomass gasification pathway	A centralized biomass gasification plant is assumed. It delivers hydrogen via trucks within urban center limits (<100 km). The levelized cost of producing, distributing and dispensing hydrogen is \$7.9/kg or \$56/GJ$_{HHV}$ (10% discount rate, 30-year project life, \$88/tonne biomass). Station utilization is assumed to be 86%. No capital cost decline is assumed.	Station utilization is assumed to be 95% capacity, resulting in a levelized cost 10% below the reference case.	--	NREL (2019). H2A Hydrogen Production Analysis. IEA (2019). The Future of Hydrogen.
Cost of hydrogen production – electrolysis pathway	Small polymer electrolyte membrane (PEM) electrolyser plants are assumed to produce hydrogen at the station because it is the most cost-effective grid-powered pathway for this technology. The levelized cost of producing and dispensing hydrogen is \$9.7/kg or \$70/GJ$_{HHV}$ (10% discount rate, 30-year project life, using electricity costing 6.2 cents/kWh). Station utilization is assumed to be 86%. No capital cost decline is assumed.	A future PEM electrolyser minimum capital cost is assumed. Station utilization is assumed to be 95%. Together, this results in a levelized cost 20% below the reference case.	--	NREL (2019). H2A Hydrogen Production Analysis.

Uncertainty	Assumption			Source
	Reference	Low / Unavailable	High / Available	
Cost of hydrogen electric vehicles	Fuel cell stack system costs are assumed to decline from \$306/kW in 2015 to a minimum of \$74/kW. Fuel tanks are assumed to decline from \$31/kWh in 2015 to a minimum of \$11/kWh. When these assumptions are applied, the estimated price of a fuel cell vehicle declines as a function of adoption to a minimum of \$32,810 by 2050 (includes 30% margins and an \$12,000 glider[19]).	Steeper cost declines are assumed. Fuel cell stack system and hydrogen tank costs are assumed to decline to \$39/kW and fuel tanks are assumed to decline to \$9.9/kWh. The estimated price of a fuel cell vehicle declines to a minimum of \$23,825 (same margin and glider assumptions as reference case).	--	SA Consultants (2016). Final report: Hydrogen storage system cost analysis. SA Consultants (2017). Mass production cost estimation of direct H2 PEM fuel cell systems for transportation applications. IEA (2020). Breakdown of cost-reduction potential for electrochemical devices by component category.
Amount of hydrogen blending into natural gas system	Hydrogen can be blended into the natural gas stream to up to 2% by volume (0.5% by energy content).	--	Hydrogen can be blended into the natural gas stream to up to 20% by volume (5% by energy content).	International Energy Agency. (2019). The Future of Hydrogen Atfeld K., Pinchbeck D. (2013). Admissible Hydrogen Concentrations in Natural Gas Systems. National Research Council Canada (2017). Review of hydrogen tolerance of key Power-to-Gas (P2G) components and systems in Canada: final report.

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[19] A glider is defined as the vehicle components that are shared across technologies. They include body, wheels, suspension, windows, seats and other interior parts.

Uncertainty	Assumption			Source
	Reference	Low / Unavailable	High / Available	
Availability of new non-emitting “firm” electricity generation	--	Not available.	Available. Fixed capacity generation costs are in the range of $155/MWh.	US Energy Information Administration (2019). Annual Energy Outlook.
Availability of second-generation biofuels	--	Not available.	Available. Feedstocks are available for an “at-the-plant” cost of $84/ODt for agricultural residue and $97/ODt for forest harvest residue. Residue feedstock costs act as a proxy for the availability and costs of other types of second-generation feedstocks (e.g., switchgrass) that are not directly represented in the model.	Kludze, H., Deen, B., Weersink, A., van Acker, R., Janovicek, K., De Laport, A., McDonald, I. (2013). *Estimating sustainable crop residue removal rates and costs based on soil organic matter dynamics and rotational complexity*. Biomass and Bioenergy, 56, 607-618 Petrolia, R., D. (2008). *The economics of harvesting and transporting corn stover for conversion to fuel ethanol: A case study for Minnesota.* Biomass and Bioenergy, 32, 603-612 Yemshanov D., McKenney, D.W., Fraleigh, S., McConkey, B., Huffman, T., Smith, S., 2014, *Cost estimates of post-harvest forest biomass supply for Canada,* Biomass and Bioenergy, 69, 80-94

Uncertainty	Assumption			Source
	Reference	Low / Unavailable	High / Available	
Emissions intensity of oil sands production	Reference improvement. Forecast of emissions intensity improvements in the oil sands are 0.03 tCO_{2e}/barrel by 2030 for mining and 0.07 tCO_{2e}/barrel by 2030 for in situ production, falling further to 0.02 tCO_{2e}/barrel by 2050 for mining and 0.05 tCO_{2e}/barrel by 2030 for in situ production.	--	Accelerated improvement. Emissions intensity of oil sands production is 20% lower than the reference scenario by 2030 and 30% lower by 2050.	BMO Capital Markets. February 2019. “ESG, Yeah You Know Me. Innovation and the Search for ‘Friendly Oil’”.
Availability of DAC	--	Not available.	Available. The cost of DAC starts at $368/$tCO_{2e}$ and declines as experience with the technology increases to a potential price floor of $125/$tCO_{2e}$ by 2050.	Fasihi et al. (2019). Techno-economic assessment of CO_2 direct air capture plants. Keith et al. (2018). A process for capturing CO_2 from the atmosphere.

Uncertainty	Assumption			Source
	Reference	Low / Unavailable	High / Available	
Availability of CCS	--	Not available for combustion emissions. A limited amount of CCS is available for non-combustion emission sources, such as process emissions in hydrogen, cement, and fertilizer production. The cost of capture for non-combustion emission sources ranges from \$50–\$150/tCO$_{2e}$ depending on the end-use, plus additional costs of transport and storage, which range from \$3.6/tCO$_{2e}$ in Alberta to \$17.9/tCO$_{2e}$ in BC.	Available for combustion and process emissions. A 90% capture rate is assumed. The cost of CCS is dependent on the end-use. The cost of capture ranges from \$50–\$150/tCO$_{2e}$ for non-combustion technologies and from \$20–\$120/tCO$_{2e}$ for combustion technologies. The cost of CCS also varies by region due to costs of CO$_2$ transport and storage, which range from an additional \$3.6/tCO$_{2e}$ in Alberta to \$17.9/tCO$_{2e}$ in BC.	Global CCS Institute. (2017). Global Costs of Carbon Capture and Storage: 2017 Update International Energy Agency. (2011). Cost and Performance of Carbon Dioxide Capture from Power Generation.
Policy implementation in other countries	--	Canada implements policy to achieve net zero emissions by 2050, while the US and the rest of the world proceed with reference case levels of climate policy.	The US implements policy to achieve an 80% reduction in emissions by 2050. Foreign commodity prices are adjusted (based on the change in production costs in North America when net zero climate policy is implemented) as a proxy for climate policy implementation in the rest of the world.	–

Uncertainty	Assumption			Source
	Reference	Low / Unavailable	High / Available	
Competitiveness protection measures (i.e., output based pricing system)	--	No OBPS.	OBPS is in place.	–
Global price of oil[20]	$66 (USD2020) by 2030. $88 (USD2020) by 2050.	$39 (USD2020) by 2030. $37 (USD2020) by 2050.	--	Canadian Energy Regulator (2019). Energy Futures. Canadian Energy Regulator (2018). Energy Futures.

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[20] In the design of these scenarios, it was assumed that in all scenarios where a low global oil price projection is used, DAC and CCS for combustion emissions are not available. Also, in all but two scenarios with a low global oil price projection, it is also assumed that net zero climate policy is implemented in the US and rest of the world. See Annex D for a full breakdown of all scenario assumptions.

2.2.3. Other key assumptions

Economic activity

Canada's reference economic and labour growth is based on the Parliamentary Budget Office's Fiscal Sustainability Report[21]. GDP by sector is largely determined by this rate of growth and the relative capital and labour productivity of that sector (i.e., the value of goods and services produced for a given amount of capital and labour inputs).

It is important to note that the scenarios modeled in this analysis do not account for the economic impacts of COVID-19, which remain uncertain at the time of analysis.

Oil and gas price

Oil and gas prices used in this analysis are calibrated to the Canadian Energy Regulator's 2019 Energy Futures.[22] After the model has been calibrated to the external forecast, the price for natural gas is determined endogenously based on supply and demand for natural gas in North America. The price for oil is an exogenous input to the model (i.e., based on an assumed global price). The oil and natural gas prices used in this analysis are provided in Table 4.

Table 4: Oil and natural gas prices used in gTech

		2020	2025	2030	2035	2040	2045	2050
Oil (2020 USD per barrel)	Reference	58.0	62.8	66.4	71.4	76.8	82.2	87.6
	Low	54.1	39.4	39.3	39.0	38.4	37.9	37.3
Natural gas (2020 USD per mmBTU)	Reference	2.7	3.3	3.5	3.5	3.9	4.4	4.6
	Low	2.7	3.3	3.5	3.5	3.7	3.6	4.0

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[21] Parliamentary Budget Office, 2020 Fiscal Sustainability Report. Available from: https://www.pbo-dpb.gc.ca/en/blog/news/RP-1920-029-S-fiscal-sustainability-report-2020-rapport-viabilite-financiere-2020

[22] Canada Energy Regulator (2019). Canada's Energy Future 2019: Energy Supply and Demand Projections to 2040. Available from: https://www.cer-rec.gc.ca/nrg/ntgrtd/ftr/2019/index-eng.html

Biofuel supply and cost

Second-generation biofuels include liquid and gaseous fuels produced from ligno-cellulosic feedstocks. These are cellulosic ethanol and renewable gasoline, diesel and natural gas produced from wood or grassy organic matter. These contrast with first generation biofuels, which include starch ethanol and biodiesel, as well as renewable gas production from decomposing material (i.e., food waste and cow manure).

The second-generation biofuel feedstocks included in gTech are agricultural and forestry harvest residues that can be sustainably extracted without harming soil fertility. Agricultural residues are the remainders of plants after harvest such as corn stover and wheat straw. Forestry harvest residues are the branches and treetops that are piled and left at the side of forest roads during logging. Residue availability is defined for each source each year as a function of agricultural and forestry activity. The quantity can grow or shrink as the activity of the associated sector changes (i.e., more forestry activity produces more harvest residue, more agricultural production in Canada and the US produces more agricultural residue). However, agricultural production is constrained in gTech assuming a fixed land-base, so the model will not allow runaway residue production, nor does it allow runaway production of first-generation biofuel feedstocks (e.g., corn or wheat).

Table 5: Summary of second-generation biofuel feedstock assumptions in Canada summarizes the feedstocks available in gTech's base year for second-generation biofuels. Feedstock quantities are described in terms of dry mass (e.g., oven dry tonnes or ODt).

Table 5: Summary of second-generation biofuel feedstock assumptions in Canada

	Agricultural residue [23,24]	Forest harvest residue [25,26]	Total
Residue availability in model base year (million ODt/year)	18.2	15.7	**33.9**
Residue availability in model base year (PJ/year)	328	238	**566**
Potential for greater future production	Modest: grows with food production	Modest: forestry activity and residue supply historically has been lower than the annual allowable cut. If there is sufficient demand for wood products, the quantity of forest harvest residue could grow	

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[23] Agriculture and Agri-Food Canada. (2017). *Biomass Agriculture Inventory Median Values*. Available from: www.open.canada.ca

[24] Statistics Canada, CANSIM 001-0017

[25] Yemshanov D., McKenney, D.W., Fraleigh, S., McConkey, B., Huffman, T., Smith, S., 2014, *Cost estimates of post harvest forest biomass supply for Canada,* Biomass and Bioenergy, 69, 80-94

[26] Government of Canada, National Forestry Database, accessed May 28, 2018

The analysis does not include forest product mills waste, urban wood waste and energy crops. Energy crops are excluded from the analysis due to the significant uncertainty in their potential and their GHG impacts. [27] Logging specifically to provide feedstock is also excluded, as it is expensive (in terms of $/ODt) and unlikely to provide a net GHG reduction.

The cost of agricultural and forest residue in gTech is summarized in Table 6. The “at-the-plant” cost of agricultural residue is the sum of the residue’s ‘farmgate’ (which includes harvest and nutrient replacement costs) and transportation costs[28,29]. The “at-the-plant” cost of forest harvest residue is the sum of an assumed harvest cost and transportation cost to the nearest existing biomass cogeneration plant (as a proxy for where the feedstock might be processed)[30].

Table 6: Second-generation biofuel feedstock production cost assumptions (2020 CAD/ODt)

	Agricultural residue	Forest harvest residue
Harvest/Extraction costs	$39	$63
Transportation to fuel plant	$7	$34
Nutrient replacement	$38	-
Total "at-the-plant" Cost	**$84**	**$97**

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[27] US Department of Energy (2016) 2016 Billion-Ton Report

[28] Kludze, H., Deen, B., Weersink, A., van Acker, R., Janovicek, K., De Laport, A., McDonald, I. (2013). *Estimating sustainable crop residue removal rates and costs based on soil organic matter dynamics and rotational complexity*. Biomass and Bioenergy, 56, 607-618

[29] Petrolia, R., D. (2008). *The economics of harvesting and transporting corn stover for conversion to fuel ethanol: A case study for Minnesota.* Biomass and Bioenergy, 32, 603-612

[30] Yemshanov D., McKenney, D.W., Fraleigh, S., McConkey, B., Huffman, T., Smith, S., 2014, *Cost estimates of post harvest forest biomass supply for Canada,* Biomass and Bioenergy, 69, 80-94

Definition of clean economy

To describe how the clean economy changes over time, gTech identifies the share of investment, GDP and jobs that can be classified as “clean” (i.e., related to the supply and use of low carbon technologies). Clean investment is defined here as:

- Any investment into a sector that produces “clean” energy or energy end-uses. These sectors include renewable electricity generation, biofuels manufacturing, transit and renewable natural gas supply. Note that Statistics Canada does not consider transit a clean sector.
- Investment into a technology or process that facilitates GHG reductions. These can occur in any sector of the economy (e.g., electric trucks in the trucking sector). Household consumption of clean technologies is reported as “investment”.

In addition to reporting investment in the clean economy, gTech also reports investment into two additional categories for comparison:

- Rest of energy (i.e., investment in non-clean energy sources such as natural gas and coal mining).
- Non-energy (i.e., all remaining non-energy investment such as insurance services, education, etc.).

3. What does a net zero Canada look like?

This Chapter presents results of Canada's net zero pathways through 2050, focusing on the drivers of mitigation. Section 3.2 provides a description Canada's net zero pathways economy wide, including key drivers of emissions reductions, technology adoption and investment across the country. Section 3.2 provides a description of these pathways by sector, including key drivers of emissions reductions and changes in energy consumption in each sector.

3.1 Drivers of emissions reductions across Canada

This section focuses on the key actions, technologies and investments that are driving emissions reductions to net zero across Canada's economy.

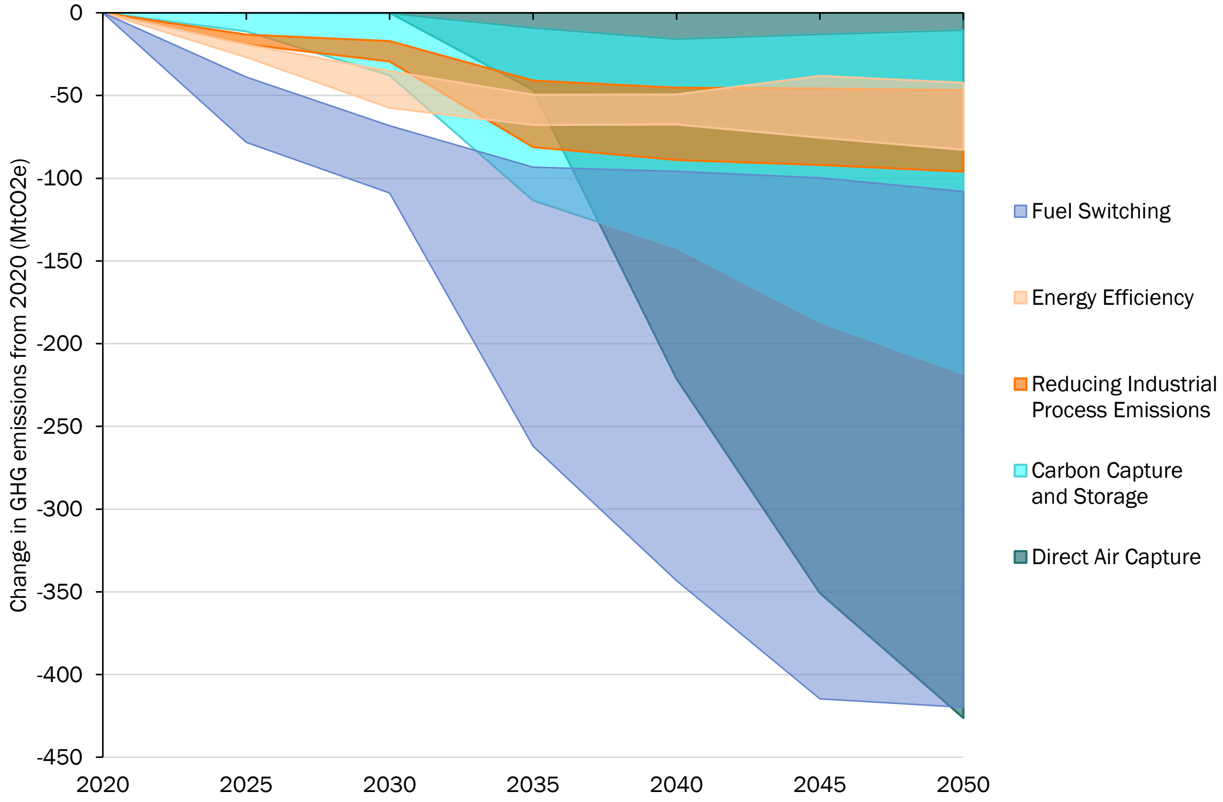
3.1.1 Key actions driving emissions reductions

Five key drivers of emissions reductions across Canada's economy were identified in this analysis and are presented in Figure 3. This figure shows how Canada's emissions change each year compared to 2020 levels and attributes the increase or decrease in emissions to a driver, such as a change in fuel or energy efficiency improvements.

The ranges presented for each driver represent variations in the role of each mitigation action in reducing emissions across net zero scenarios. The importance of some drivers, such as DAC, CCS and fuel switching, vary significantly by scenario, while others, including energy efficiency and industrial decarbonization, play a similar role across all net zero scenarios. An important dynamic indicated here is a trade-off between the use of negative emission technologies, such as DAC and CCS, and the transformation of Canada's energy system to rely on cleaner fuels through fuel switching. In scenarios where DAC and CCS are available, less electrification and other fuel switching occurs, and vice versa.

The role of each driver in achieving net zero emissions is discussed in more detail below.

Figure 3: Drivers of emissions reductions across Canada's economy



Energy efficiency

Energy efficiency plays an important role it all net zero scenarios. This includes efficiency improvements in building shells, heating and cooling, as well industrial efficiency improvements, and the use of public transit. Under net zero emissions, energy efficiency leads to 42-83 $MtCO_{2e}$ of emissions reductions in 2050 compared to 2020. Energy efficiency plays a larger role in scenarios where clean technology costs follow reference case projections and efficiency improvements are an economical mitigation option compared to scenarios where clean technology costs decline faster than expected.

Reducing industrial process emissions

Options to reduce industrial process emissions include managing methane emissions in the oil and gas sector, reducing emissions of hydrofluorocarbons (HFCs), and switching to less emissions intensive forms of steel production in the iron and steel sector. Emissions reductions from industrial process improvements range across scenarios from 30-47 $MtCO_{2e}$ in 2050 compared to 2020. The low end of this range includes scenarios in which CCS is available and industrial process emissions can be captured and stored. When CCS is not available, process emissions must be reduced.

In these scenarios, management of methane emissions in the oil and gas sector plays an important role, reducing emissions by up to 22 $MtCO_{2e}$ in 2050. Changes in the steel production process is also a key driver of emissions reductions, ranging from 9-23 $MtCO_{2e}$ in 2050 across scenarios.

Negative emission technologies

DAC technology becomes commercially available at a large scale in some net zero scenarios, while in others, it does not. This uncertainty in the future role of DAC is demonstrated across net zero pathways, from capturing no emissions in some, to up to 426 $MtCO_{2e}$ in 2050 in others. In all scenarios where DAC is assumed to be available, it plays an important role in achieving net zero emissions (307-426 $MtCO_{2e}$ in 2050). The upper end of this range is scenarios in which the rest of the world also implements climate policy along with Canada, as the cost for clean technologies like DAC come down faster in these scenarios due to increased experience with the technology. DAC also plays a larger role in scenarios where the cost of other clean technologies, such as hydrogen fuel, battery electric vehicles, and hydrogen fuel cell vehicles, follow a reference case price trajectory, in which case DAC technology is a more cost competitive abatement action. The lower end of this range is scenarios in which Canada implements climate policy ahead of other countries, and other clean technologies follow a low price trajectory.

CCS is another driver of GHG reductions that varies significantly across scenarios. Similar to DAC, this is in large part due to scenario design, as some scenarios assume CCS for combustion emissions does not prove viable and cost-effective at a large scale. In these scenarios, CCS is used to reduce emissions from non-combustion sources such as process emissions in hydrogen, cement and fertilizer production, and leads to 10-27 $MtCO_{2e}$ of emissions reductions in 2050 compared to 2020. In scenarios where CCS for combustion emission is available, it leads to up to 218 $MtCO_{2e}$ of emissions reductions in 2050. The upper end of this range is scenarios in which DAC is not available. When both DAC and CCS are available, CCS is used to capture about 100 $MtCO_{2e}$ of emissions in 2050.

These technologies are adopted mostly in Alberta and Saskatchewan, as well as BC, where there is already known access to geological storage for carbon.

Fuel switching

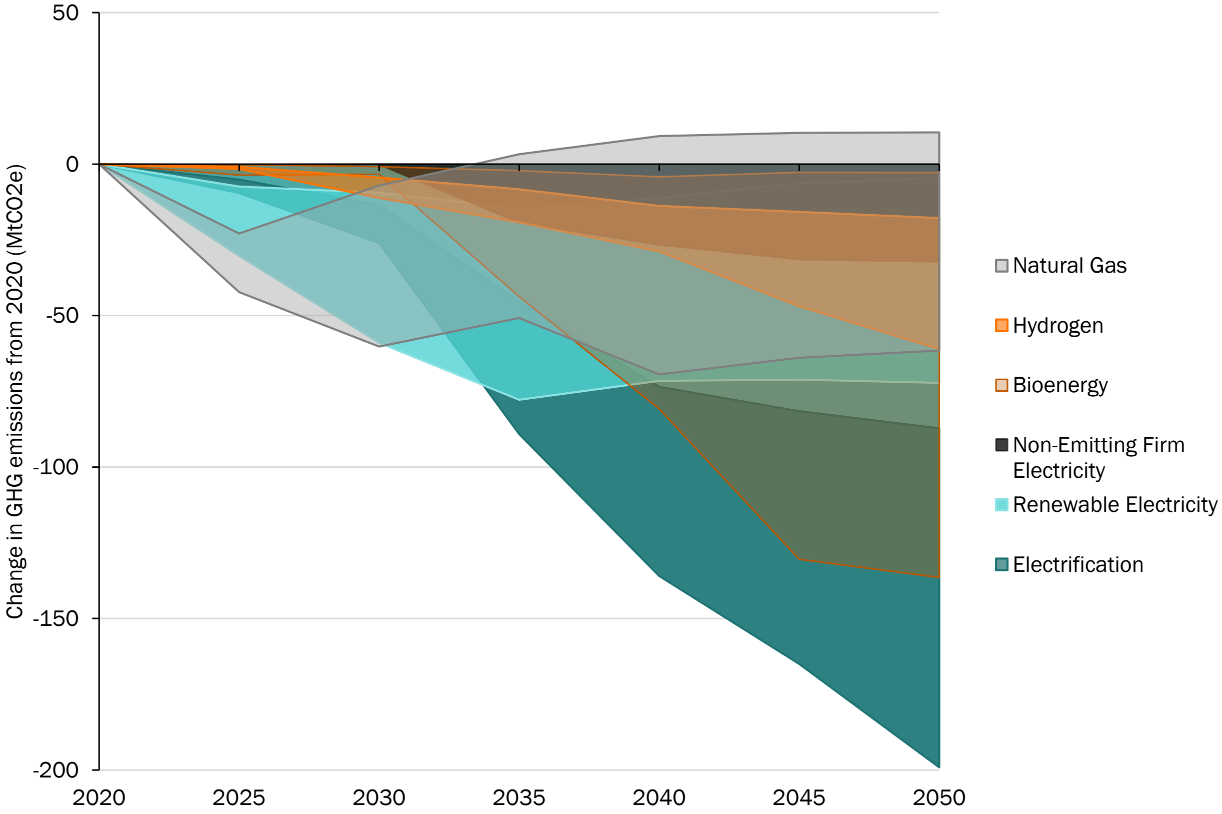
Fuel switching refers to the use of cleaner fuels, such as the use of electricity, hydrogen or biofuels in transport, blending of renewable natural gas (RNG) or hydrogen to reduce the emissions intensity of the natural gas stream, or switching from more emissions-intensive fossil fuels like oil to natural gas. The role of fuel switching in reducing emissions varies significantly across net zero pathways.

In all scenarios, this abatement action is critical to achieving net zero, leading to at least 108 $MtCO_{2e}$ of emissions reductions in 2050 compared to 2020. This lower end of the range is scenarios in which DAC and CCS are both available, so the continued use of more emissions-intensive fuels can be offset by these technologies, as well as when the rest of the world implements climate policy along with Canada, due to an increased demand for biofuels in the US in these scenarios.

In most scenarios, fuel switching drives significantly more emissions reductions by 2050, up to 420 $MtCO_{2e}$. This upper end of the range is scenarios in which both CCS and DAC are unavailable, and fuel switching becomes the most important driver of emissions reductions. In these cases, the most fuel switching occurs in scenarios where the cost for clean technologies such as electric vehicles, hydrogen fuel, and hydrogen fuel cell vehicles follow a low price trajectory, as well as when new non-emitting firm power generation is available at low cost, reducing the price of electricity.

The role of each fuel in reducing emissions from fuel switching is presented in Figure 4. Note that in this figure, renewable electricity refers to using renewable energy (e.g., wind, solar) to generate electricity, while electrification refers to switching from other fuels to electricity. Thus, the magnitudes of these two abatement actions are closely linked, but they do not double count GHG reductions.

Figure 4: Emissions reductions from fuel switching across Canada's economy



Of the emissions reductions occurring from fuel switching, biofuels and RNG contribute 4-127 $MtCO_{2e}$ of emissions reductions in 2050. The use of bioenergy is lowest in scenarios in which DAC and CCS are available and second-generation biofuels are unavailable. It is highest in scenarios in which both DAC and CCS are unavailable, and Canada acts ahead of other countries in implementing climate policy leading to lower demand for biofuels in the US.

Electrification is a key driver of emissions reductions across all scenarios, ranging from 87-199 $MtCO_{2e}$ in 2050 compared to 2020. Similar to bioenergy, the least electrification occurs in scenarios in which DAC and CCS are available, particularly in scenarios where other major countries implement climate policy on pace with Canada and the cost for these technologies therefore comes down more quickly.

Switching to hydrogen fuel contributes to 18-61 $MtCO_{2e}$ of emissions reductions in 2050. The lower end of this range is scenarios in which DAC and CCS are available, and when the cost of electric vehicles comes down more quickly than expected, while the cost of hydrogen vehicles does not. The upper end of this range is scenarios in which DAC and CCS are not available, second-generation biofuels are not available, and a higher hydrogen blending rate into the natural gas stream is assumed.

3.1.2 Clean technology adoption

An important characteristic of all net zero pathways is the increased adoption of clean technologies and fuels. Adoption of clean technologies drives emissions reductions by phasing out fossil fuels and inefficiencies, and in some cases, capturing and storing emissions that do remain. The level of adoption of key technologies is presented in Table 7.

Increased adoption of some key technologies is present across all net zero scenarios. The proportion of electric vehicles on the road increases in all pathways, as does the generation of renewable electricity, as the electricity sector moves away from thermal generation towards renewable generation. Other technologies vary more in their future adoption, particularly negative emission technologies. The availability of DAC and CCS has a significant impact on the way Canada achieves its mid-century target. As such, Canada's path to net zero is highly sensitive to the outcomes of these technologies.

DAC technology pulls carbon dioxide directly out of the atmosphere and delivers the carbon dioxide in a pure, compressed form for storage under the ground, or for reuse. CCS storage technology captures carbon dioxide emissions (produced either from combustion of fuels or from industrial processes) before they enter the atmosphere. CCS can be applied to energy production and at industrial facilities, such as power plants, bitumen upgraders, oil refineries, and steel, cement and fertilizer production plants, to reduce their emissions intensity. Once captured, the carbon dioxide is then stored underground in suitable geological formations. The formations in western Canada are ideally suited for carbon storage, which requires deep porous rocks covered by a solid "cap rock" to prevent leakage. As a result, increased use of this technology under Canada's net zero pathways could provide a valuable economic opportunity for these regions due to their significant storage capacity. Note that suitable geological storage could exist elsewhere in Canada, but it is currently not assessed or characterized.

When available, DAC is adopted at a very large scale in 2050 (up to 426 $MtCO_{2e}$), mainly in Alberta and Saskatchewan due to proximity to carbon storage potential. CCS is also adopted at a large scale when available (up to 218 $MtCO_{2e}$ in 2050). In scenarios where DAC and CCS are not available, the adoption of other clean technologies, including biofuels, renewable electricity, and electric vehicles, is significantly higher. In these scenarios, the level of adoption of battery electric and hydrogen fuel cell vehicles depends on the cost trajectory of these technologies, as well as the availability of second-generation biofuels. Adoption of biofuels and RNG is lowest when electric and hydrogen fuel cell vehicle costs come down faster than expected.

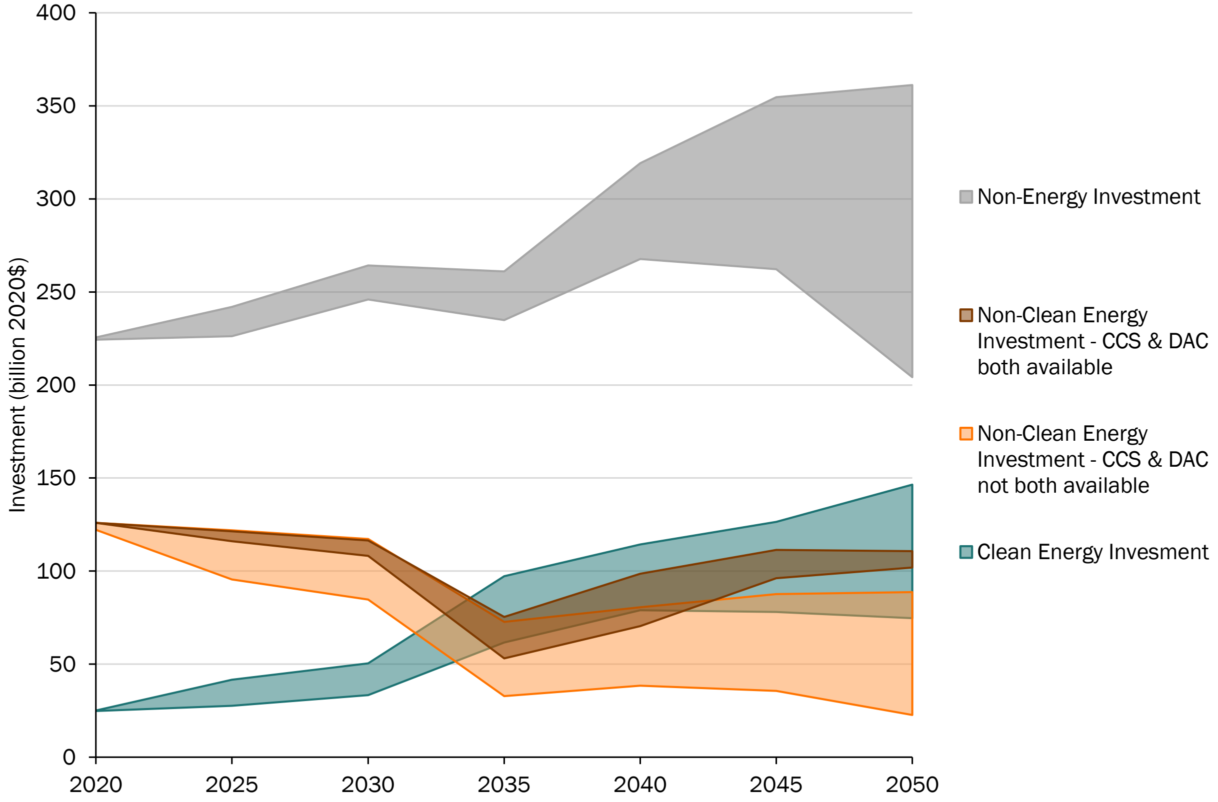
Table 7: Level of adoption of key technologies under all net zero pathways

Clean technology	2020	2030	2040	2050
Direct air capture ($MtCO_{2e}$)	0-0	0-0	0-221	0-426
Carbon capture and sequestration ($MtCO_{2e}$)	0-0	0-38	16-142	10-218
Biofuels and renewable natural gas (PJ)	165-166	224-252	338-1252	321-2153
Renewable electricity (TWh)	395-396	439-536	592-674	606-746
Electric vehicles (% of new market share)				
Personal vehicles	3-4	9-14	56-89	58-100
Medium- and heavy-duty vehicles	0-0	3-4	8-12	7-32
Hydrogen fuel cell vehicles (% of new market share)				
Personal vehicles	0-0	0-0	0-0	0-0.3
Medium- and heavy-duty vehicles	0-0	6-14	30-51	37-72

3.1.3 Clean technology investment

The drivers of emissions reductions across Canada are supported by a shift in investment from non-clean energy such as fossil fuels to clean technologies such as renewable electricity, biofuels manufacturing and electric vehicles (Figure 5). Non-clean energy investment decreases from $126 billion in 2020 to $23-111 billion in 2050 depending on the net zero scenario, while clean energy investment increases from $25 billion in 2020 to $75-146.5 billion in 2050. Investment in clean energy is lowest and investment in non-clean energy is highest when DAC and CCS are available to offset emissions from continued fossil fuel consumption. When DAC and CCS are not available, there is a significant shift away from investment in non-clean energy towards cleaner energy sources, as shown in Figure 5. Regardless of what GHG abatement technologies are used, investment outside of the energy sectors remains much larger than investment within these sectors.

Figure 5: Annual investment in all net zero pathways



Clean energy investment includes investment in clean fuels and technologies. Figure 6 presents how investment in clean fuels varies across net zero pathways and Figure 7 presents the same for investment in clean technologies. Investment in these fuels and technologies varies across net zero pathways. In scenarios in which DAC and CCS are available, for example, significant investment is made in these technologies and less in electricity generation and biofuels. Significant investment is made in electric vehicles across all net zero scenarios and is greatest when DAC and second-generation biofuels are not available. It is also greatest when new non-emitting power generation is low cost, as the availability of cheaper electricity makes the transition to electric vehicles more economic. When available, significant investment is shifted to DAC and CCS to offset emissions across the economy, and less investment is made into other means of decarbonization.

Figure 6: Investment in clean fuels under all net zero pathways

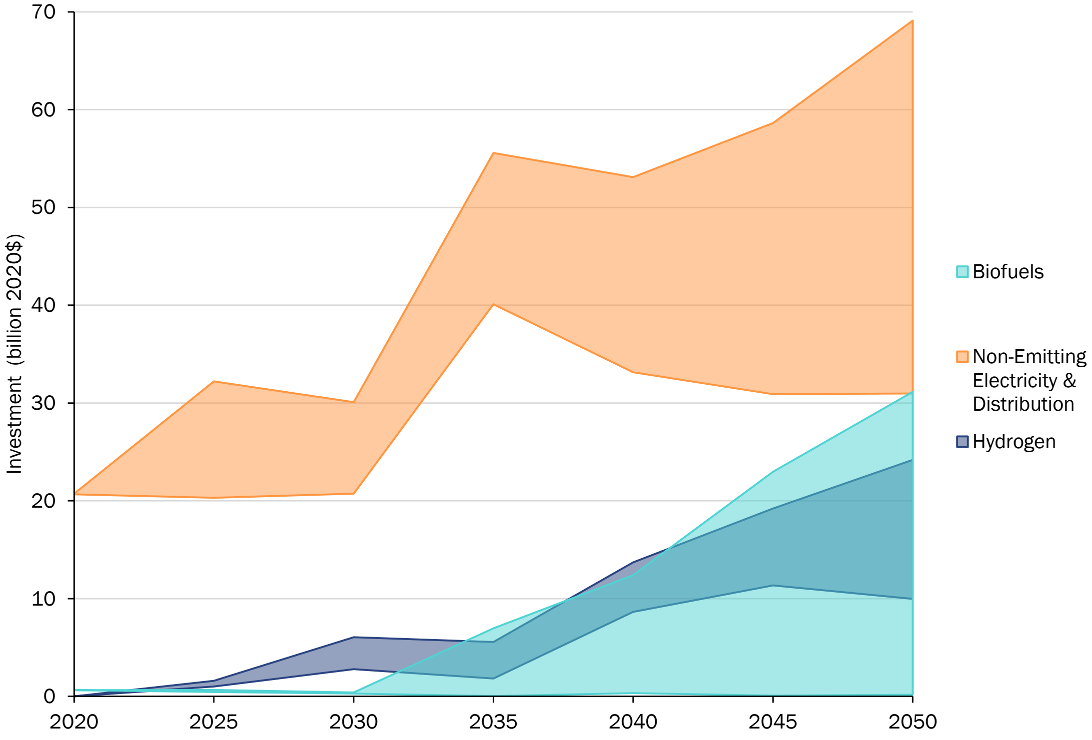
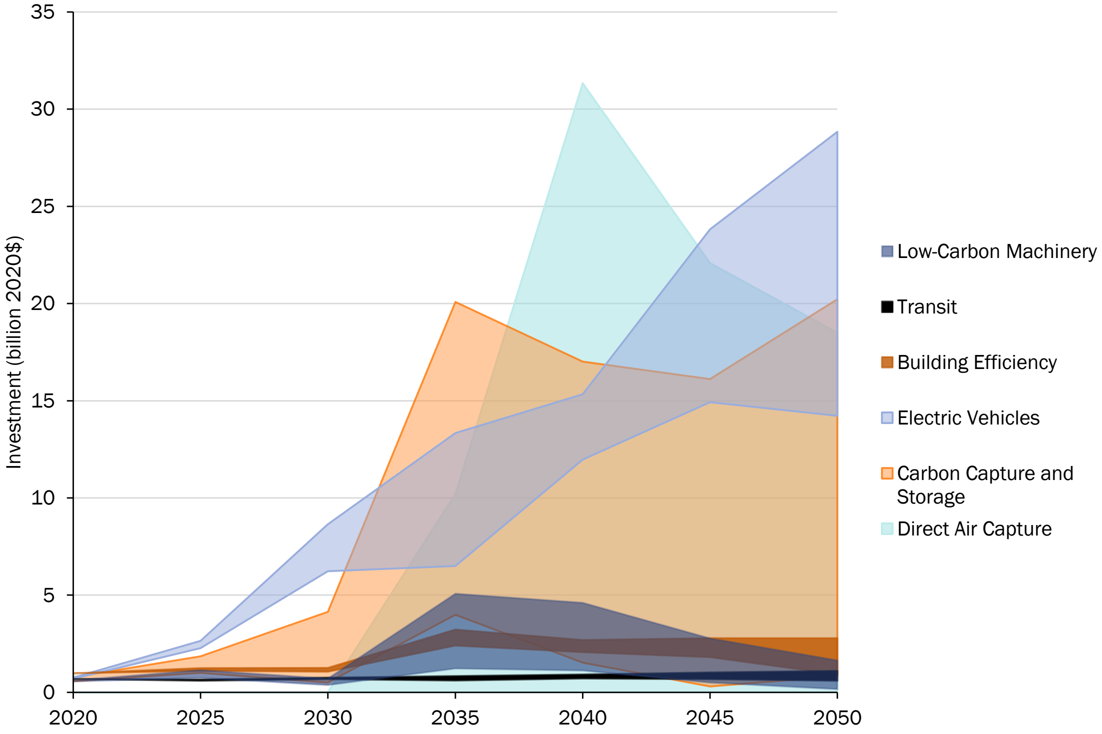


Figure 7: Investment in clean technologies under all net zero pathways



3.2 Drivers of emissions reductions in key sectors

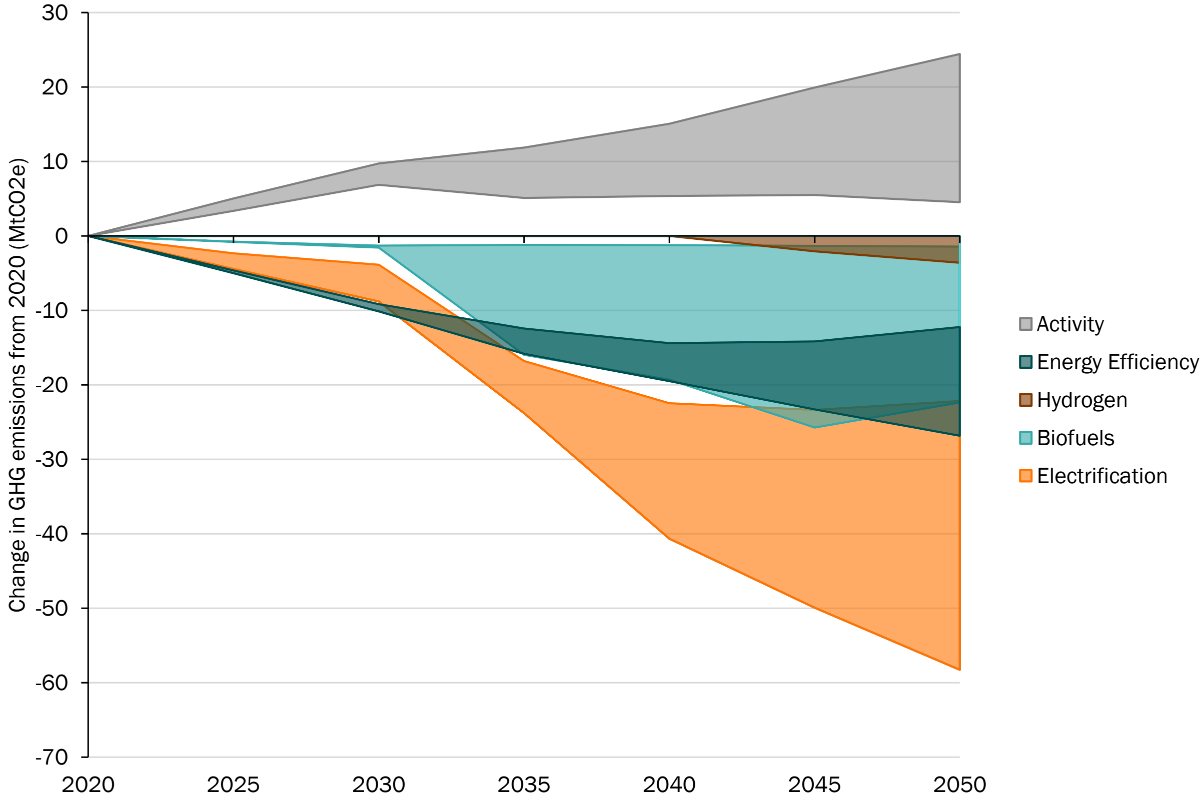
This section focuses on the key drivers of emissions reductions, including changes in energy consumption, by sector.

3.2.1 Buildings

In all net zero pathways, more residential and commercial buildings are built to keep up with Canada's growing economy and population. This change in sector activity leads to an increase in emissions, represented by the 'activity' wedge in Figure 8. Emissions rise with increased activity in this sector but are reduced at the same time by improvements in energy efficiency, electrification of heating systems (e.g., with the use of heat pumps), and fuel switching from natural gas to biofuels or hydrogen. All drivers of emissions reductions in residential and commercial buildings are presented in Figure 8.

Electrification is the key driver of mitigation in this sector, leading to 22-58 $MtCO_{2e}$ of emissions reductions in 2050 compared to 2020. The upper end of this range occurs in scenarios in which DAC is unavailable, and as a result, the buildings sector completely decarbonizes, as well as in scenarios in which second-generation biofuels are not available. When available, biofuels are another significant driver of emissions reductions in this sector, leading to up to 22 $MtCO_{2e}$. Biofuels contribute most to emissions reductions in scenarios in which Canada acts ahead of other countries to address climate change, as Canada is not competing with demand for biofuels in the US (i.e., there is more importation of bioenergy from the US), as well as in scenarios where DAC is unavailable to offset emissions, as more fuel switching is required. Efficiency is the third key driver of emissions reductions in buildings, reducing 12-27 $MtCO_{2e}$ in 2050.

Figure 8: Drivers of emissions reductions in residential and commercial buildings



Total energy consumption in residential and commercial buildings decreases in all net zero pathways, by 16-44% from 2020 to 2050 (Figure 9). Along with a reduction in energy consumption, emissions reductions are driven by a transition in fuel use from natural gas to cleaner fuels including electricity and bioenergy (such as RNG). The change in energy consumption by fuel is presented in Figure 10. Natural gas consumption decreases in all net zero pathways but remains highest in scenarios in which DAC is available. In these cases, natural gas is used in the hardest-to-decarbonize portions of the building stock, such as older buildings where fuel switching is more costly. When DAC is not available, fuel switching to electricity and RNG plays a more significant role.

Figure 9: Total energy consumption in residential and commercial buildings

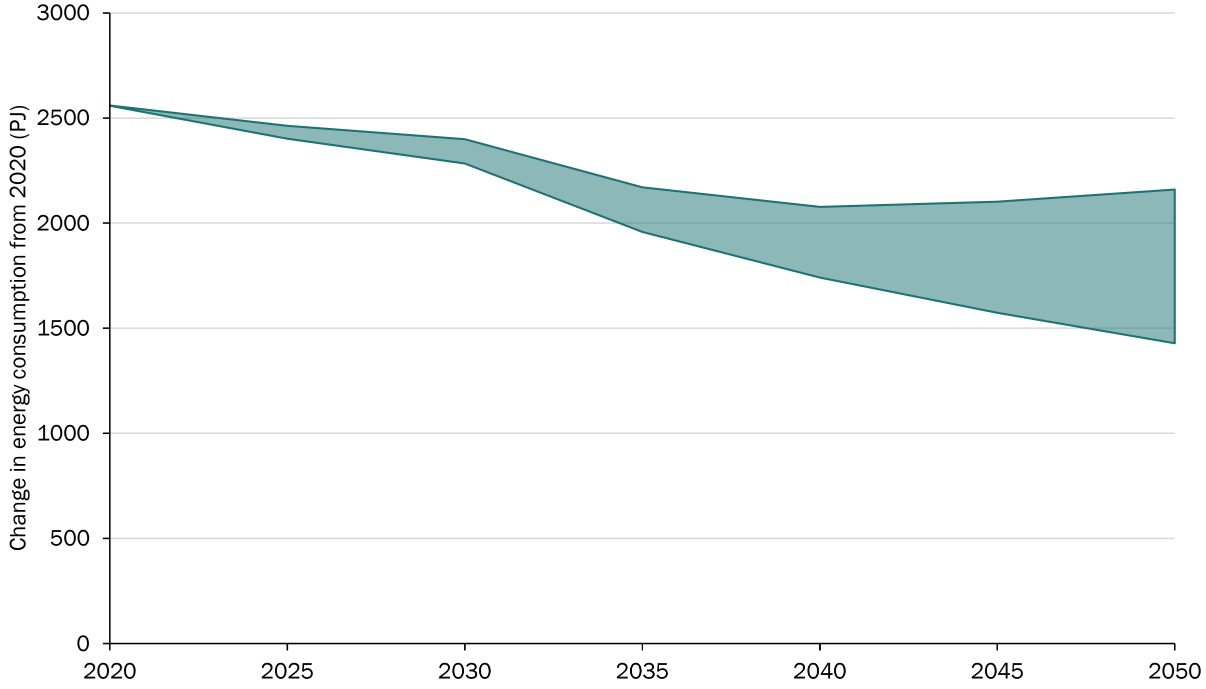
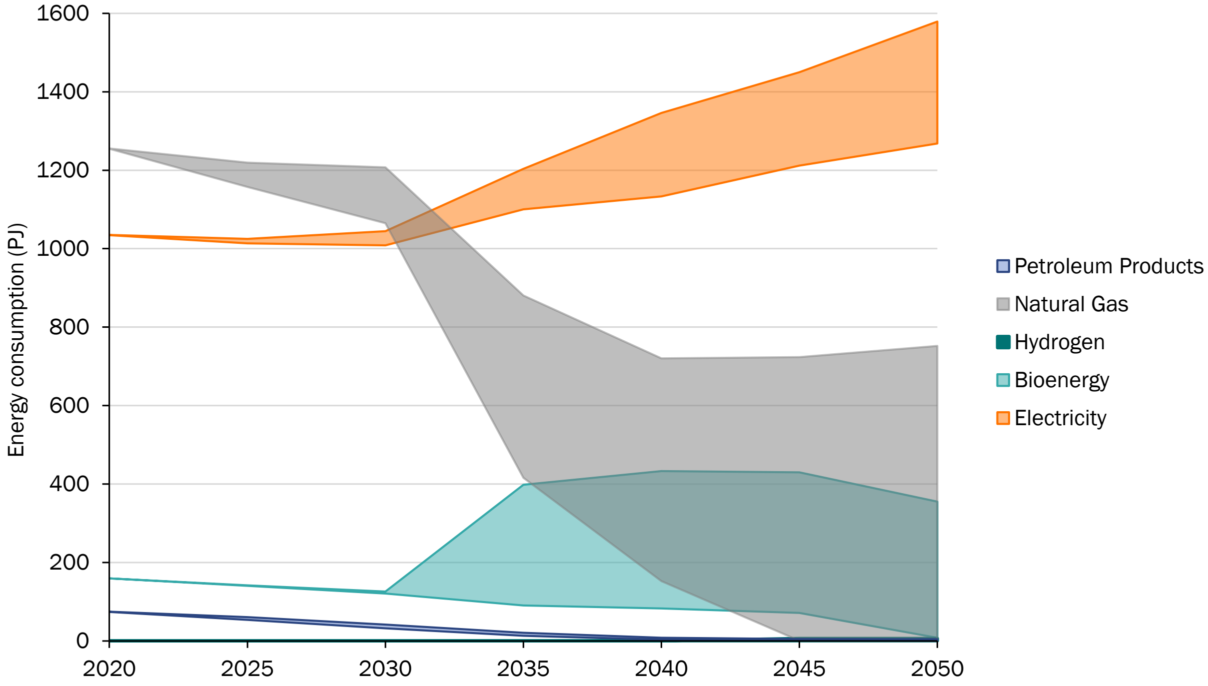


Figure 10: Energy consumption by fuel type in residential and commercial buildings



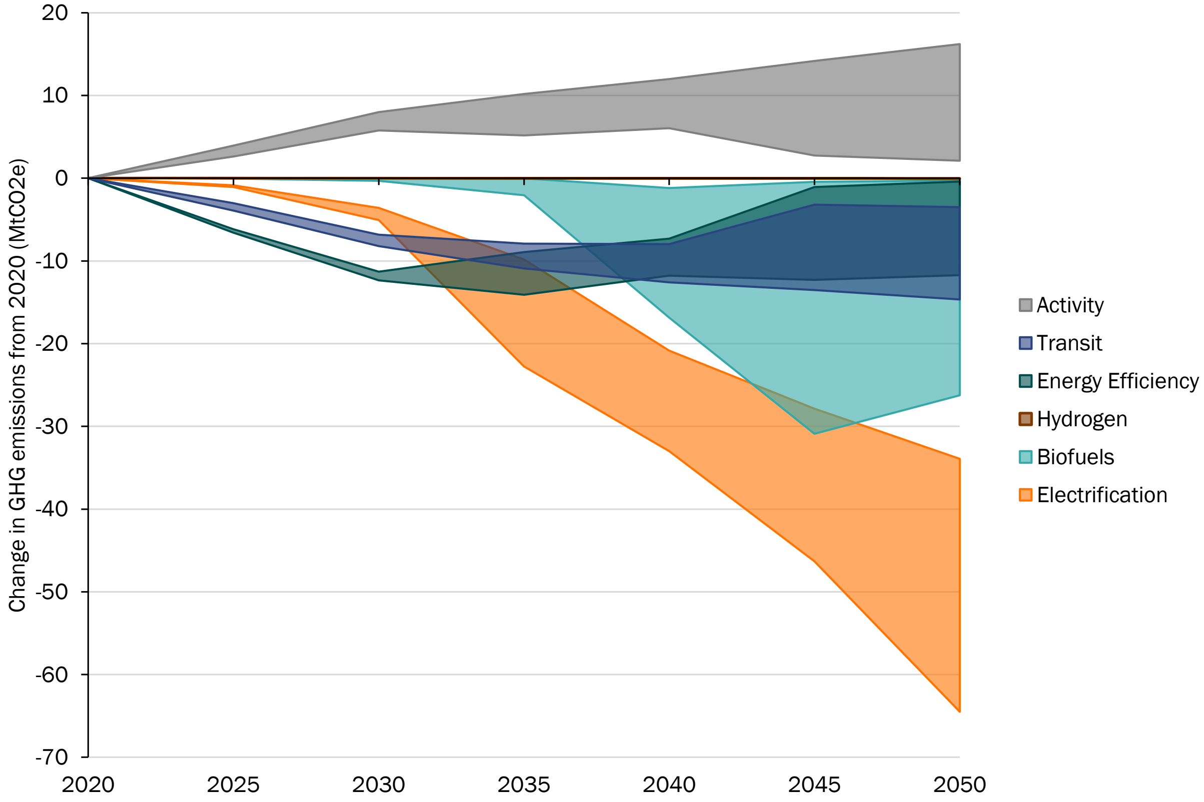
3.2.2 Transport

Personal transport

The number of passenger vehicle kilometers travelled increases in all net zero pathways, as Canada's population and economy grows. While vehicle kilometers traveled increases, emissions from this sector decrease significantly in all net zero pathways, mostly due to adoption of electric vehicles and vehicle efficiency improvements. All drivers of emissions reductions in this sector are presented in Figure 11.

Electrification is the key driver of emissions reductions in personal transport (34-65 $MtCO_{2e}$ in 2050), accounting for more than 50% of reductions in all pathways. The upper end of this range is pathways in which DAC is not available, second-generation biofuels are not available, and the cost of electric vehicles declines more rapidly than expected. When available, biofuels are another key driver of emissions reductions in this sector (up to 26 $MtCO_{2e}$ in 2050). Biofuels contribute most to emissions reductions in scenarios in which Canada implements climate policy ahead of other countries, as there is less competition for biofuels in the US, as well as scenarios in which CCS is not available, as there is also less competition for biofuels for BECCS (bioenergy with CCS). Energy efficiency is another key driver of emissions reductions in some scenarios (up to 12 $MtCO_{2e}$ in 2050), as well as mode shifting from personal vehicles to public transit (3.5-15 $MtCO_{2e}$ in 2050). Hydrogen does not contribute significantly to emissions reductions in passenger vehicles in the net zero scenarios in this analysis but does play a larger role in medium- and heavy-duty vehicles, discussed next.

Figure 11: Drivers of emissions reductions in personal vehicles



Total energy consumption for personal transport decreases in all net zero pathways compared to today, by 56-79% by 2050 (Figure 12). Figure 13 shows how energy consumption changes by fuel type in this sector. There is a significant reduction in the consumption of petroleum products by internal combustion engines in all scenarios, and an increase in battery electric vehicles. The most electricity is consumed in this sector in scenarios in which DAC is unavailable, the cost for electric vehicles comes down faster than expected, second-generation biofuels are not available, and new non-emitting firm power is available at low cost, reducing the cost of electricity. Note that less energy is needed from electricity than gasoline to power the same number of vehicles due to the increased efficiency of electric engines. Bioenergy consumption also increases in this sector, mostly in scenarios in which DAC is not available and the US is not implementing climate policy, so there is less demand for bioenergy in the US (i.e., more bioenergy that can be imported from the US).

Figure 12: Total energy consumption for personal transport

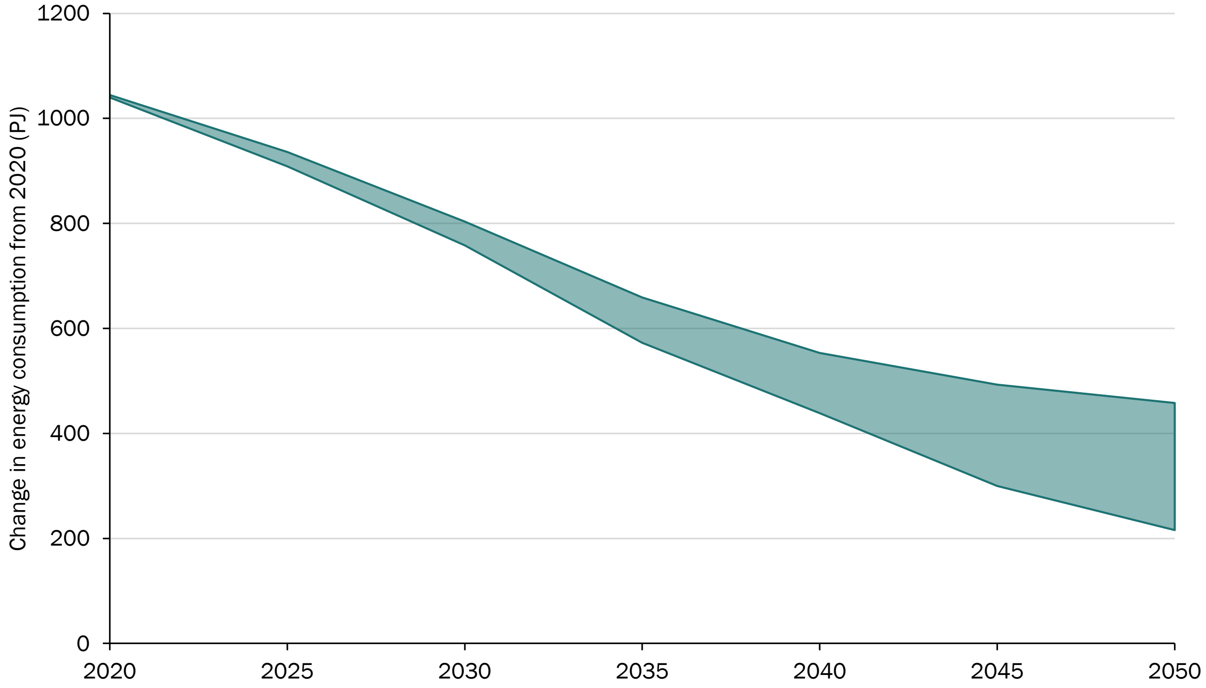
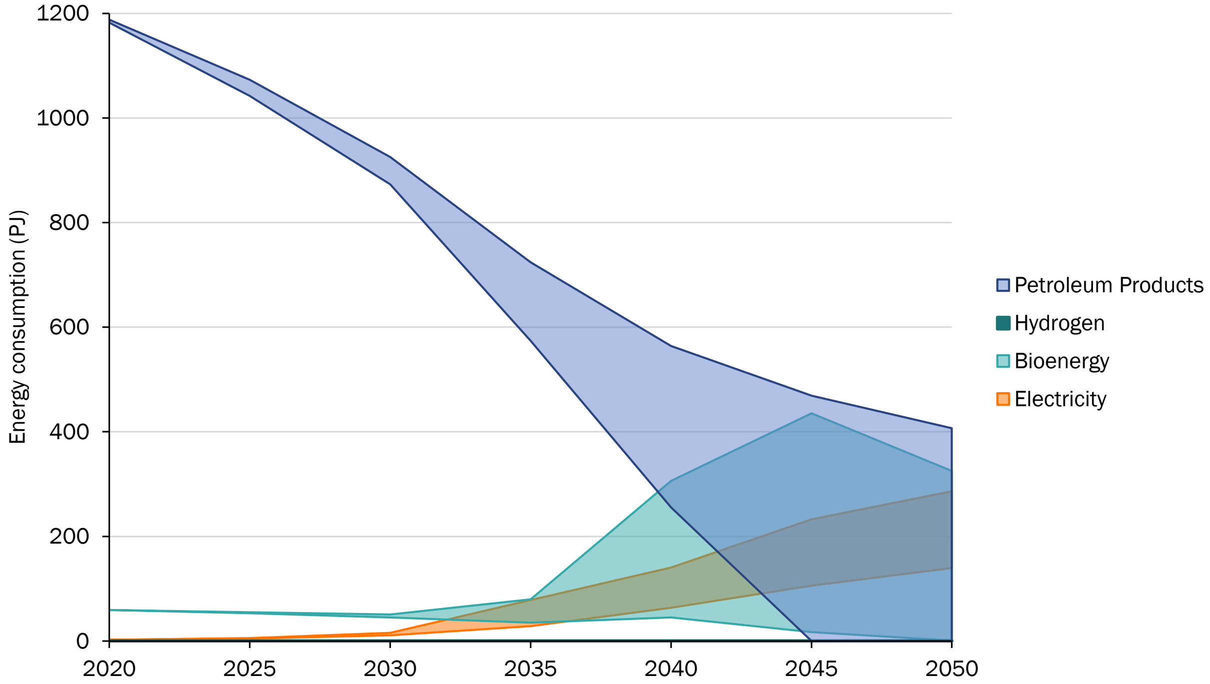


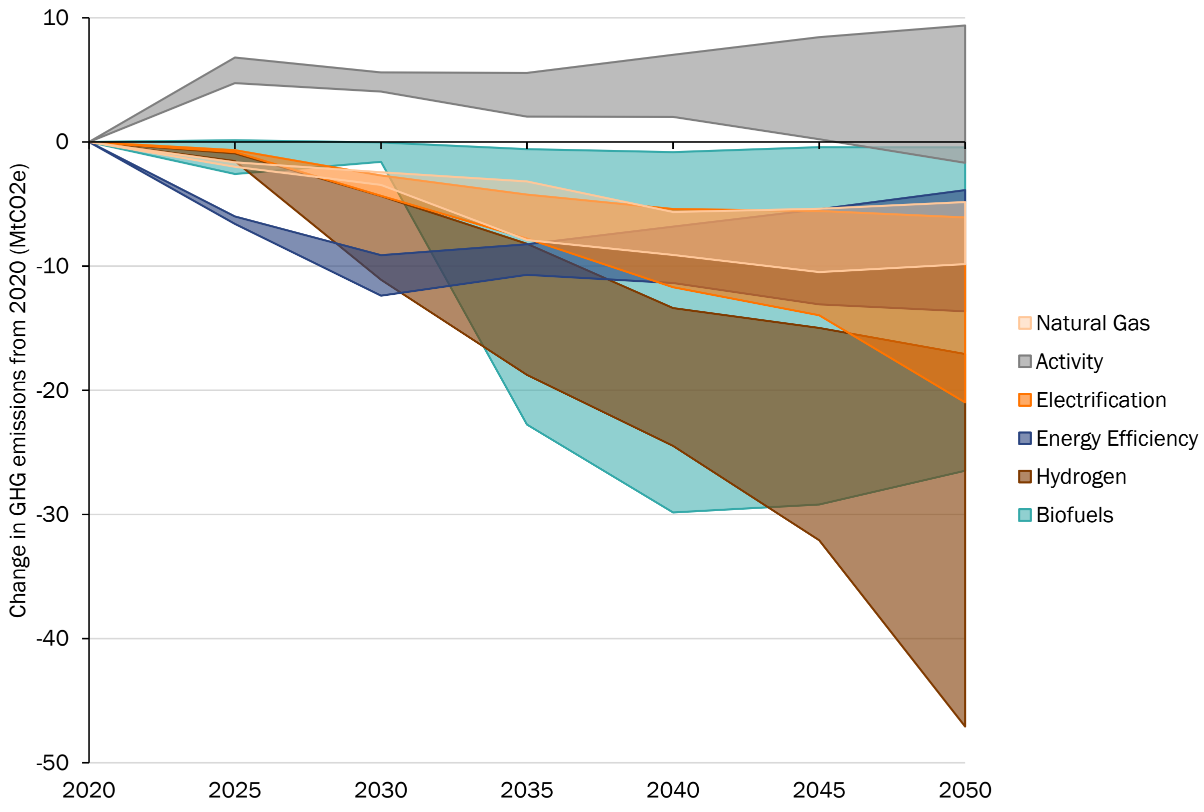
Figure 13: Energy consumption by fuel type in personal vehicles



Medium- and heavy-duty transport

In the medium- and heavy-duty transport sector, bioenergy and hydrogen play a larger role in driving emissions reductions than electrification, due to the challenges in electrifying heavy, long-haul trucking (Figure 14). Bioenergy leads to up to 26.5 $MtCO_{2e}$ of emissions reductions in this sector in 2050, and hydrogen 17-47 $MtCO_{2e}$ in 2050. Similar to the buildings and personal transport sectors, biofuels drive the most emissions reductions in medium- and heavy-duty transport in scenarios in which Canada acts ahead of other major countries in implementing climate policy, as there is less competition for biofuels with the US. When DAC is available, bioenergy is less of a driver of emissions reductions in this sector as it is more cost effective to offset emissions using DAC. Hydrogen becomes the most important driver of reductions by 2050 in scenarios in which DAC is unavailable and the cost of hydrogen fuel cell vehicles declines more quickly than expected.

Figure 14: Drivers of emissions reductions in medium- and heavy-duty vehicles



Total energy consumption in this sector decreases under most net zero pathways (by up to 25% from 2020 to 2050) but stays relatively constant or increases (by up to 2% from 2020 to 2050) in others (Figure 15). In these scenarios, energy consumption starts to increase in 2035 when DAC becomes available and can be used to avoid using high-cost GHG abatement actions. Changes in energy consumption by fuel are provided in Figure 16. This highlights the role of fuel switching in decarbonizing medium- and heavy-duty transport, as this sector moves away from the consumption of gasoline and diesel. In scenarios in which DAC is available, this sector continues to rely on petroleum products, though to a lesser extent, out to 2050. When DAC is unavailable, gasoline and diesel are completely phased out by 2040-2045.

Figure 15: Total energy consumption for medium- and heavy-duty transport

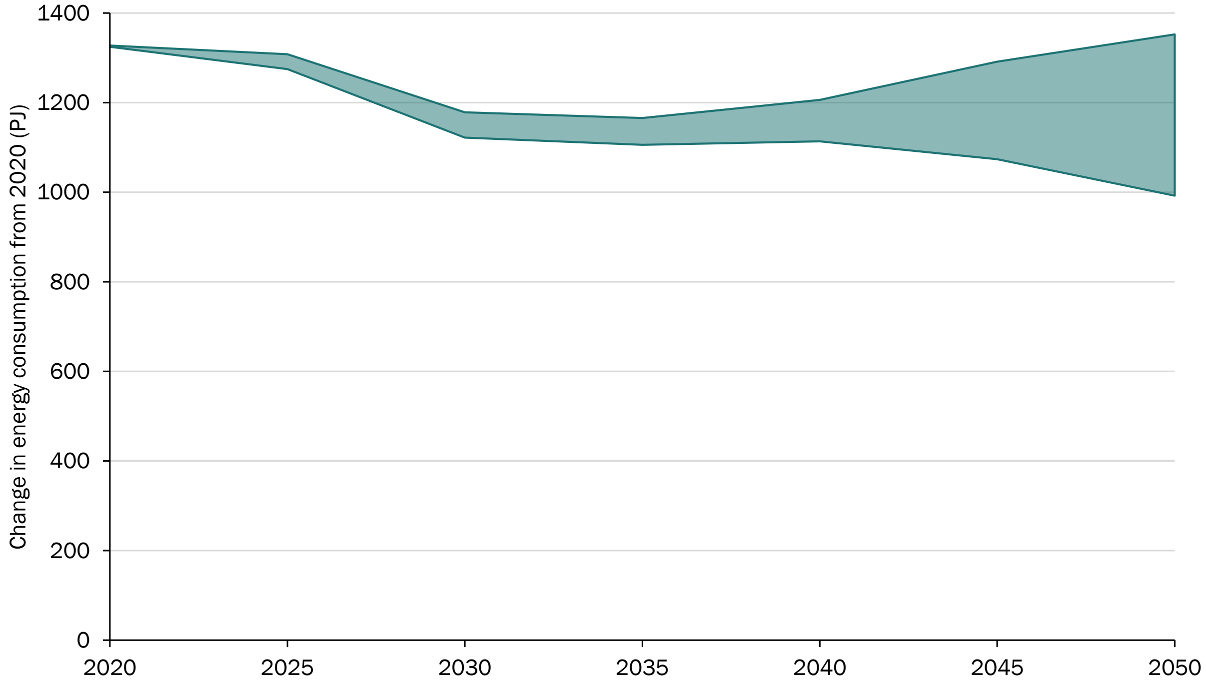
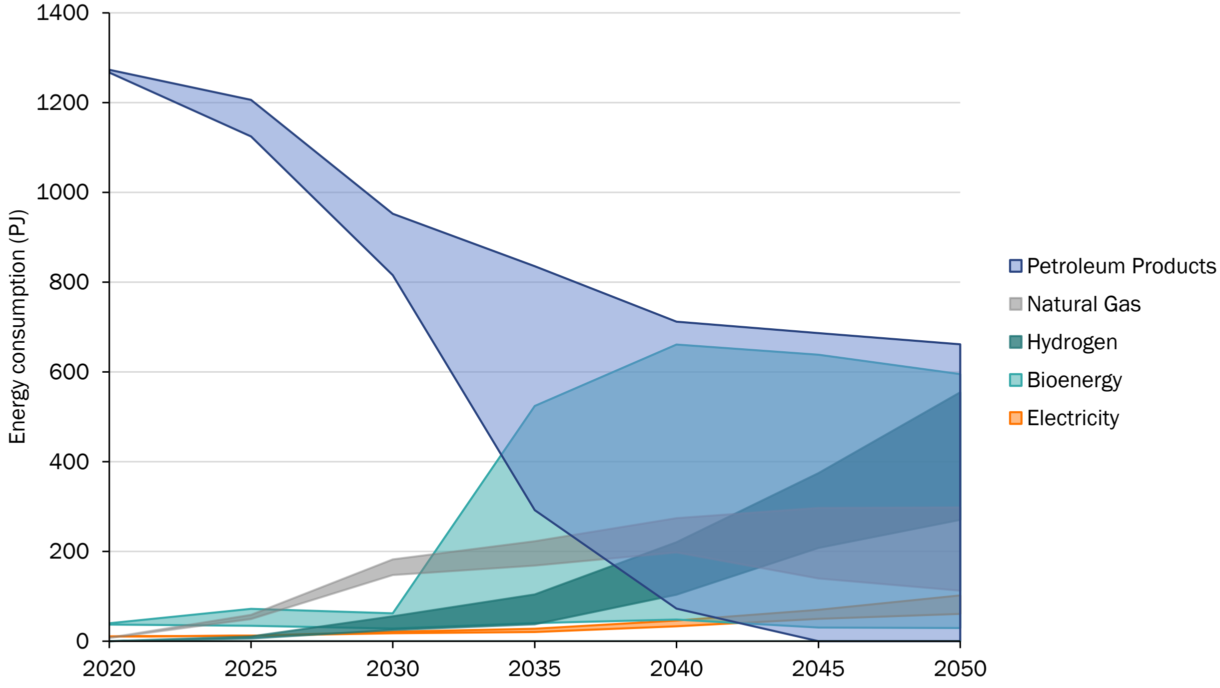


Figure 16: Energy consumption by fuel type in medium- and heavy-duty vehicles

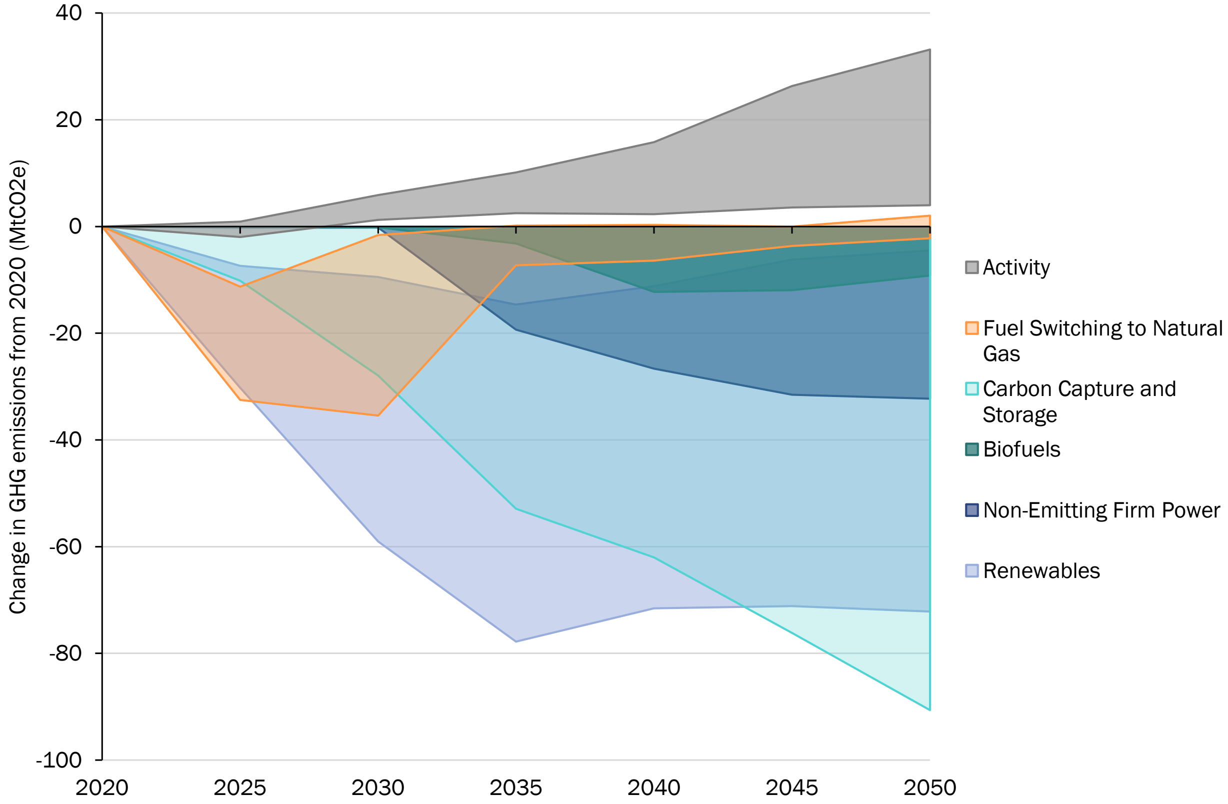


3.2.3 Electricity

Electricity generation increases significantly under all net zero pathways to keep up with increasing demand from clean technologies such as electric vehicles, heat pumps, DAC (when available), and hydrogen production via electrolysis. All scenarios show a reduction in thermal electricity generation and a significant increase in renewable generation. Drivers of emissions reductions in the electricity sector are presented in Figure 17.

The electricity sector completely decarbonizes in scenarios in which DAC is not available. In these pathways, emissions reductions are driven by an increase in renewable electricity generation, such as wind energy (4.5-72 $MtCO_{2e}$ in 2050). The upper end of this range is scenarios in which CCS is not available and renewables become the main driver of mitigation in this sector. When CCS is available, it is a key driver of mitigation, leading to up to 91 $MtCO_{2e}$ of emissions reductions in 2050. If CCS is not available, but new non-emitting firm power, such as nuclear or geothermal, is available at low cost, it becomes an important driver of emissions reductions by 2050. Switching to natural gas from more emissions-intensive fossil fuels such as coal is also an important driver of emissions reductions in some scenarios in the short term (11-32.5 $MtCO_{2e}$ in 2025), but not in the long term.

Figure 17: Drivers of emissions reductions in the electricity sector



Total energy consumption in the electricity sector varies significantly across net zero pathways, increasing by 72% from 2020 to 2050 in some scenarios and decreasing by 72% in others (Figure 18). Energy consumption increases most in this sector in scenarios in which DAC is available, starting in 2035, as electricity is required to power the DAC process. Changes in energy consumption for thermal electricity generation by fuel are presented in Figure 19. Natural gas consumption declines in all scenarios until 2035. At that point, DAC becomes available in some scenarios and natural gas consumption correspondingly begins to increase out to 2050. In scenarios in which DAC and CCS are unavailable, no natural gas is consumed for electricity by 2045. A reduction in consumption of energy for thermal generation is replaced with renewable electricity sources such as wind and solar, as well as non-emitting firm power generation in some scenarios.

Figure 18: Total energy consumption for thermal electricity generation[31]

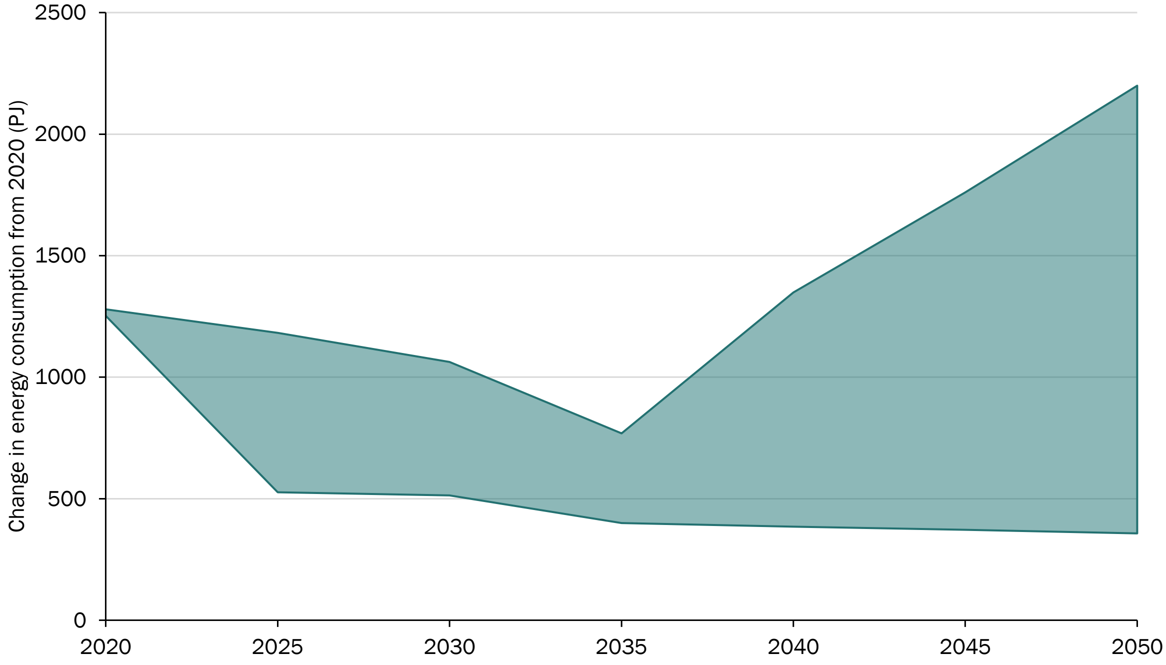
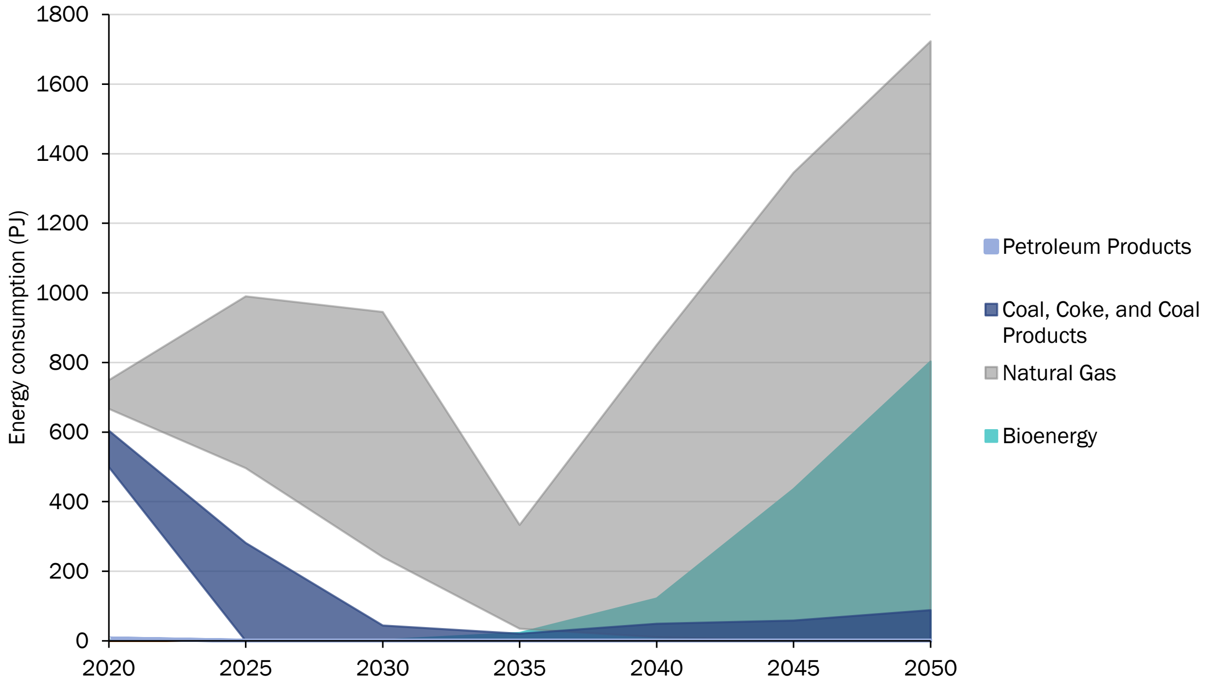


Figure 19: Energy consumption by fuel type for thermal electricity generation[31]



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[31] This figure shows fuel consumption for thermal electricity generation. Consumption of renewables and non-emitting firm generation are excluded.

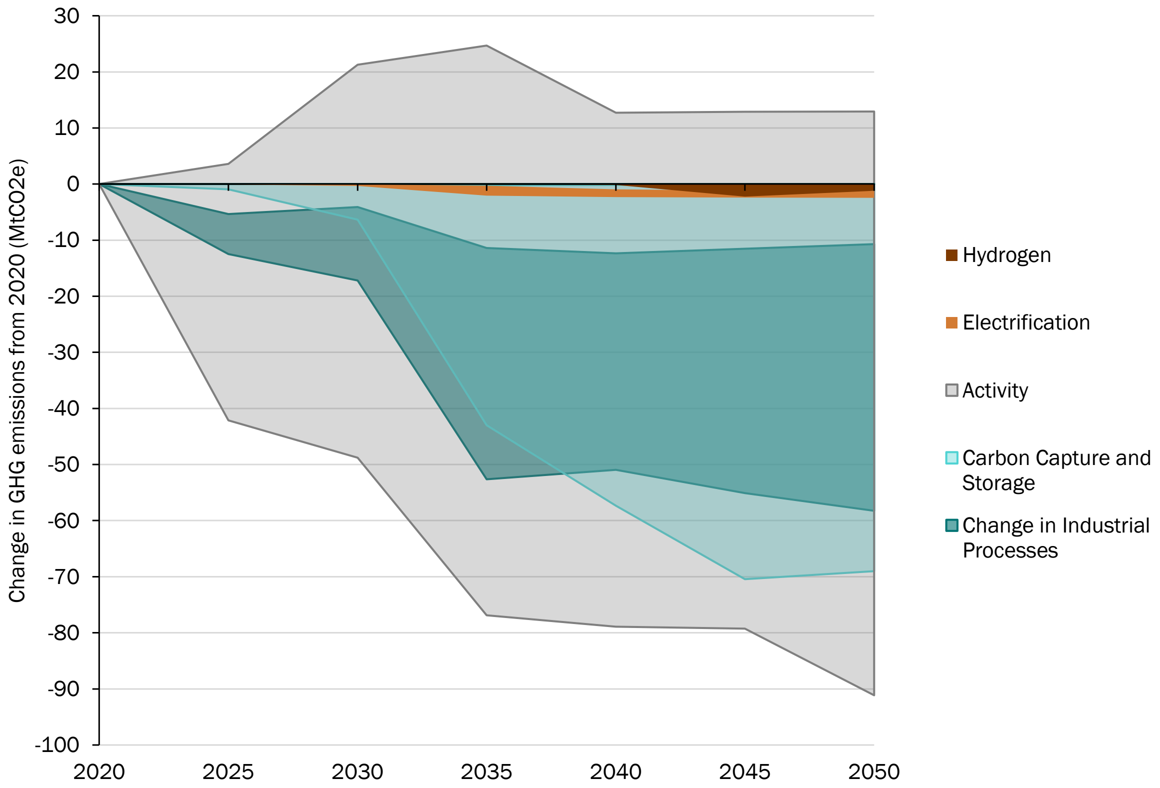
3.2.4 Industry

Oil and gas

Results of this analysis suggest that the future of Canadian oil production is heavily dependent on the net zero pathway that Canada (and the world) pursues. Because of the lifecycle emissions intensity of oil, its production in Canada in 2050 depends both on the availability of DAC technology, as well as the level of climate action globally. All drivers of emissions reductions in this sector (including conventional and oil sands production) are presented in Figure 20.

Activity of the oil sector varies significantly across net zero scenarios. If DAC is not available, a key driver of mitigation is a reduction in oil production. Reduced activity in this sector leads to up to 82 $MtCO_{2e}$ of emissions reductions in 2050 in scenarios in which other major countries implement climate policy, and there is decreased international demand for oil (i.e., a low oil price). In other scenarios in which DAC is available to offset emissions, oil production continues out to 2050, leading to an increase in emissions of up to 13 $MtCO_{2e}$ by 2050 (which are offset by DAC) due to increased production. In scenarios in which CCS is available, it is a key driver of emissions reductions in this sector (up to 69 $MtCO_{2e}$ in 2050). Changes in industrial processes, mostly the management of methane emissions through reductions in venting and flaring, is also a driver of mitigation in this sector (11-58 $MtCO_{2e}$ in 2050).

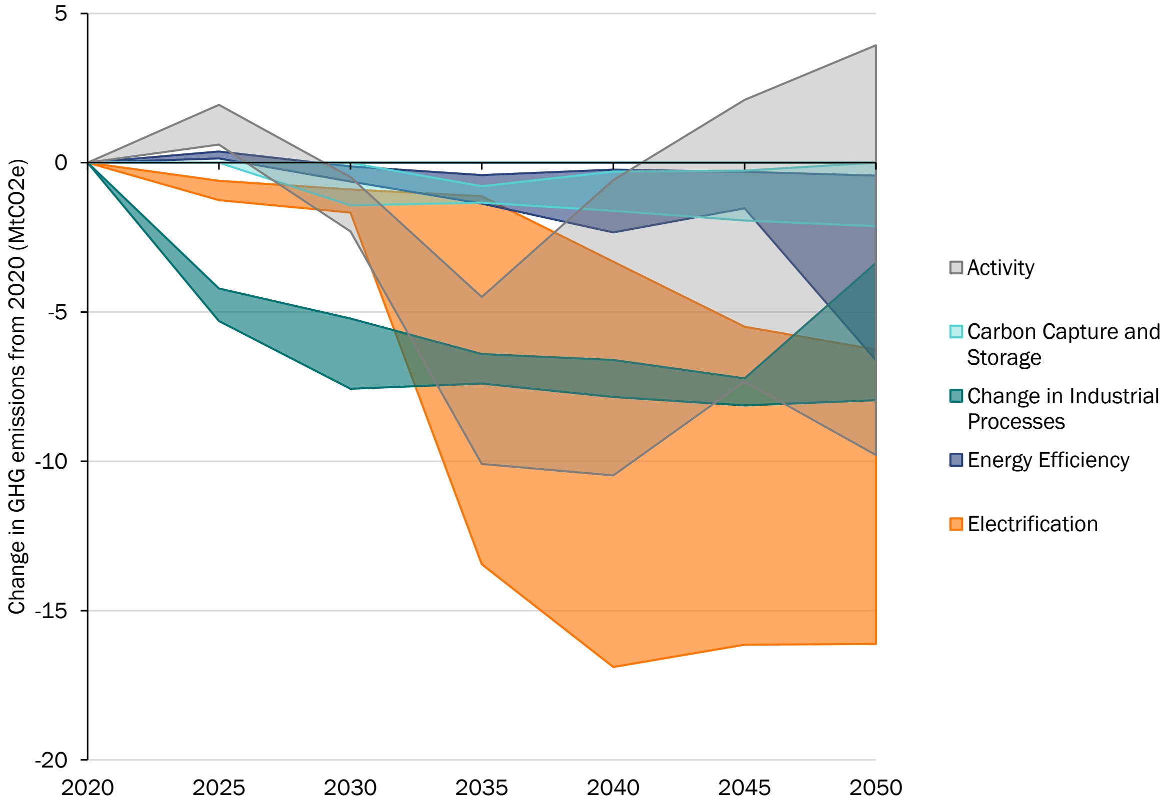
Figure 20: Drivers of emissions reductions in the oil sector



Similar to the oil sector, the future of Canada's natural gas sector is heavily dependent on the net zero pathway pursued by Canada and the world. All drivers of emissions reductions in this sector are presented in Figure 21, which highlights the uncertainty in future natural gas production. In scenarios in which DAC becomes available in 2035, natural gas production increases out to 2050, leading to an increase in emissions of up to 4 $MtCO_{2e}$ in 2050, which are offset by DAC. When DAC is not available, production in this sector decreases, and this reduced activity is a significant driver of emissions reductions (up to 10 $MtCO_{2e}$ in 2050).

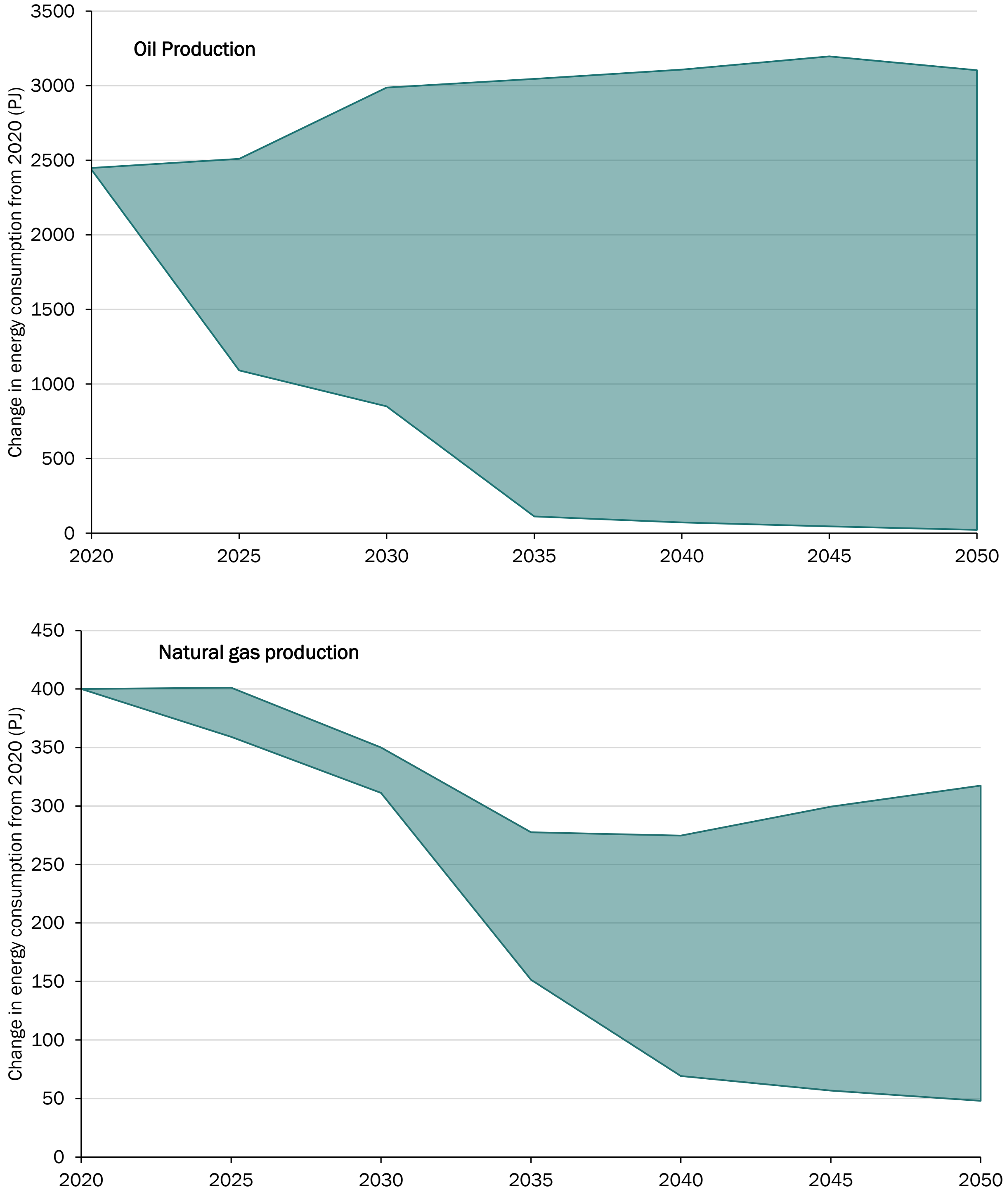
In all net zero scenarios, electrification is a key driver of mitigation in this sector, leading to 6-16 $MtCO_{2e}$ of emissions reductions in 2050. The upper end of this range occurs if DAC is not available and the sector therefore relies on electrification to decarbonize. Changes in industrial processes is another important driver of mitigation in the natural gas sector across all net zero pathways, with most reductions coming from the management of methane emissions.

Figure 21: Drivers of emissions reductions in the natural gas sector



Total energy consumption in the oil and gas sectors vary depending on the amount of continued production out to 2050 (Figure 22). Energy consumption in the oil sector decreases completely (up to 99%) in some scenarios in which activity declines (i.e., when DAC is not available), and increases by up to 27% in others when the availability of DAC allows for continued production. Energy consumption in the natural gas sector decreases in all scenarios compared to today (by 21-88% in 2050).

Figure 22: Total energy consumption in the oil and gas sectors



In scenarios in which production of oil continues out to 2050, there is some fuel switching to electricity, along with the continued use of oil and gas (Figure 23). The natural gas sector continues to use natural gas for energy in all net zero scenarios. Variations in energy consumption across pathways is mainly driven by differing levels of sector activity (Figure 24).

Figure 23: Energy consumption by fuel type in the oil sector

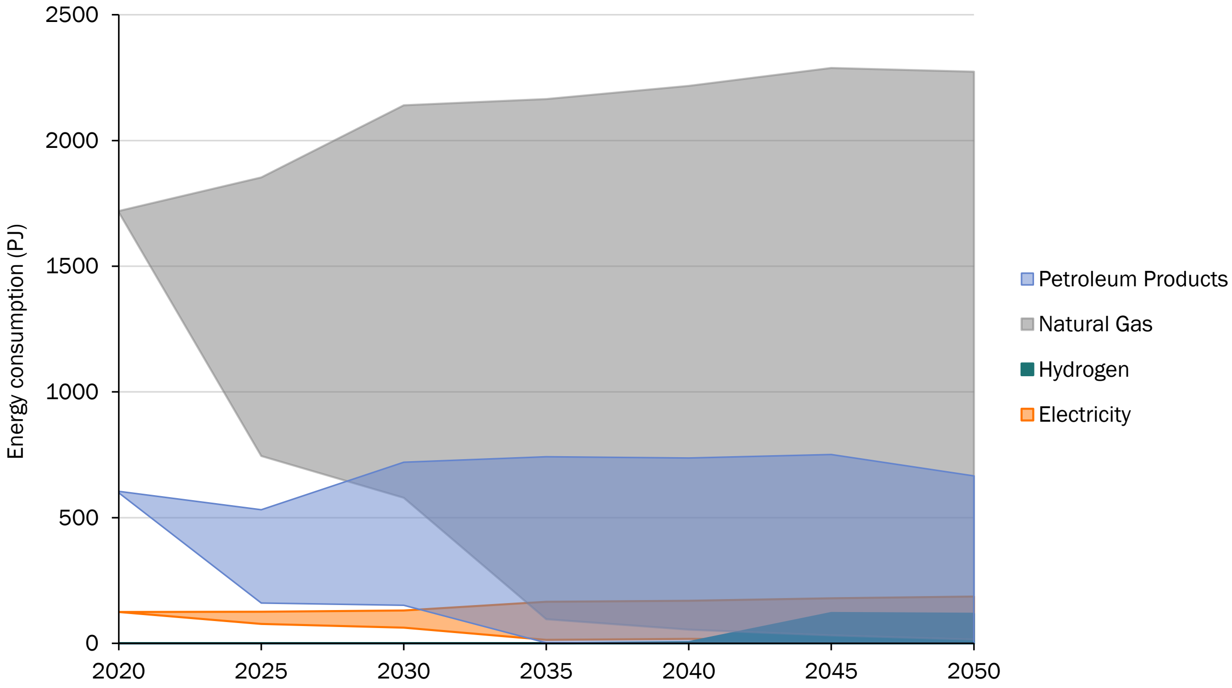
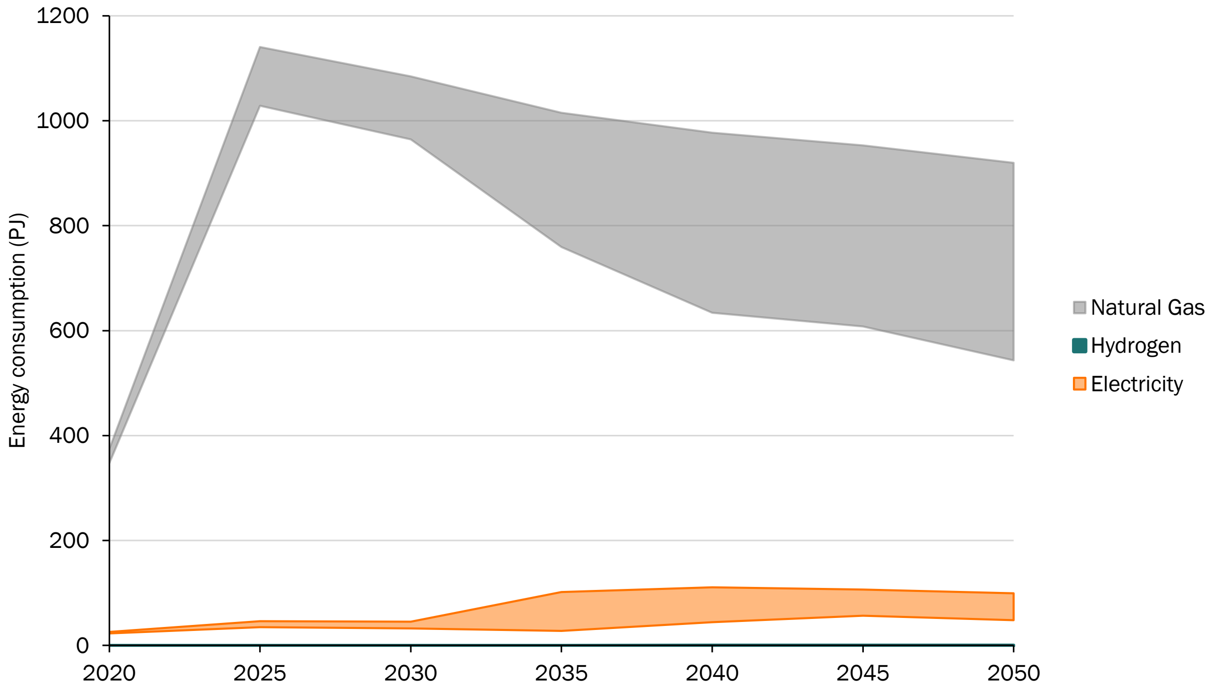


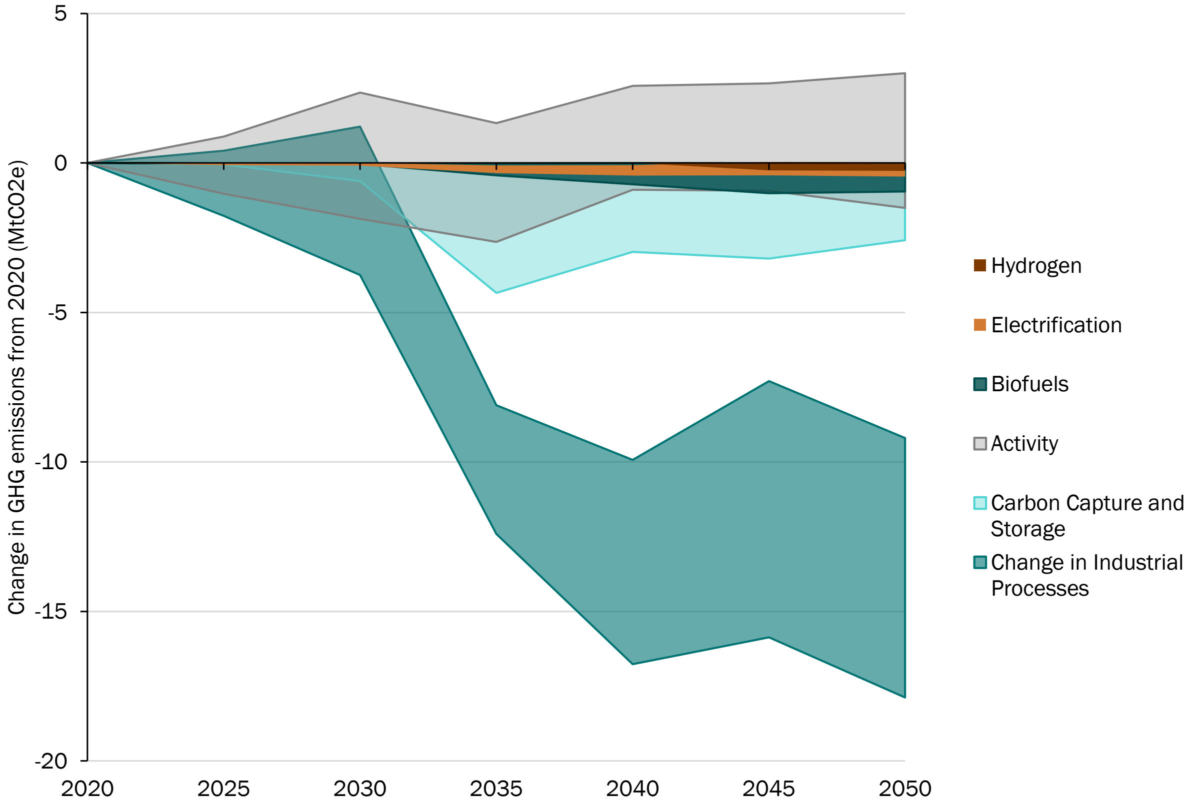
Figure 24: Energy consumption by fuel type in the natural gas sector



Iron and steel

Canada's iron and steel sector completely decarbonizes in all net zero pathways due to the availability of economical abatement options. Iron and steel production remains relatively constant in all pathways, and emissions reductions are driven mostly by process changes, as well as CCS when available. Emissions are mitigated through changes in the production process, away from more emissions-intensive BOF (basic oxygen furnace) steel production to cleaner production using DRI (direct reduced iron) powered by either natural gas or hydrogen, as well as greater production from recycled steel. The use of hydrogen to produce decarbonized steel via DRI and EAF (electric arc furnace) in Ontario will require increased electricity for the production of clean hydrogen, or the long-distance transport of clean hydrogen from western Canada. These process changes lead to 9-18 $MtCO_{2e}$ of emissions reduction in 2050 compared to 2020. All drivers of emissions reductions in this sector are presented in Figure 25.

Figure 25: Drivers of emissions reductions in iron and steel



Total energy consumption in this sector increases in some scenarios (62% from 2020 to 2050) and decreases by up to 79% from 2020 to 2050 in others (Figure 26). As iron and steel production completely decarbonizes by 2050, this sector switches away from the consumption of coal to natural gas, bioenergy and electricity (Figure 27). Natural gas consumption is highest in scenarios in which CCS is available and can be used to capture all remaining emissions. When CCS is unavailable, this sector uses electricity and bioenergy.

Figure 26: Total energy consumption in the iron and steel sector[32]

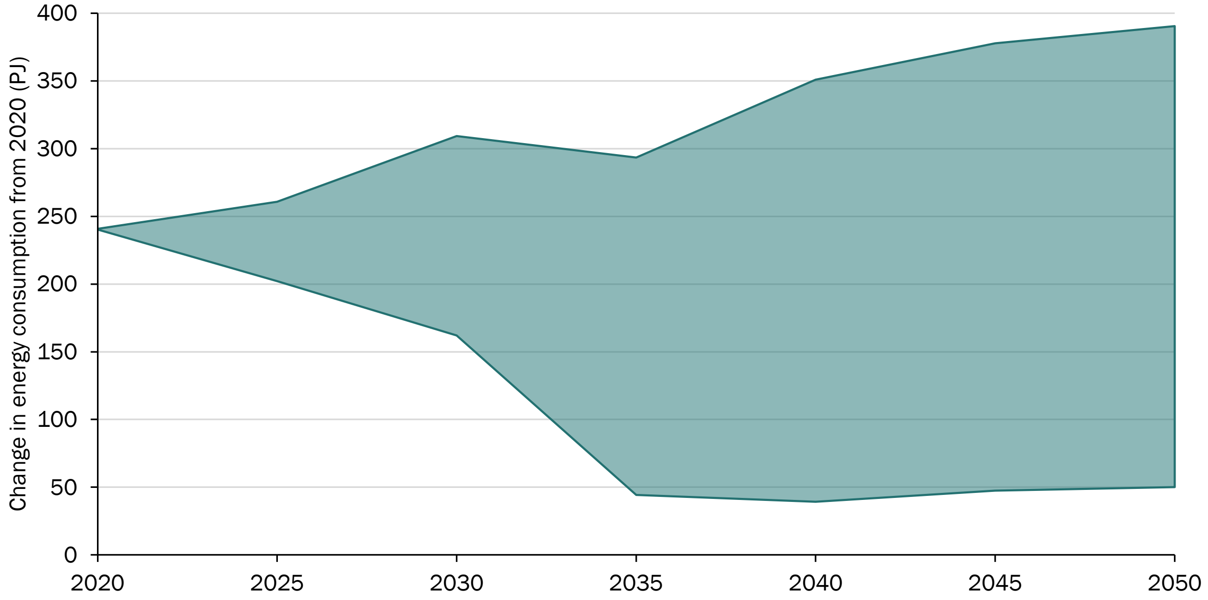
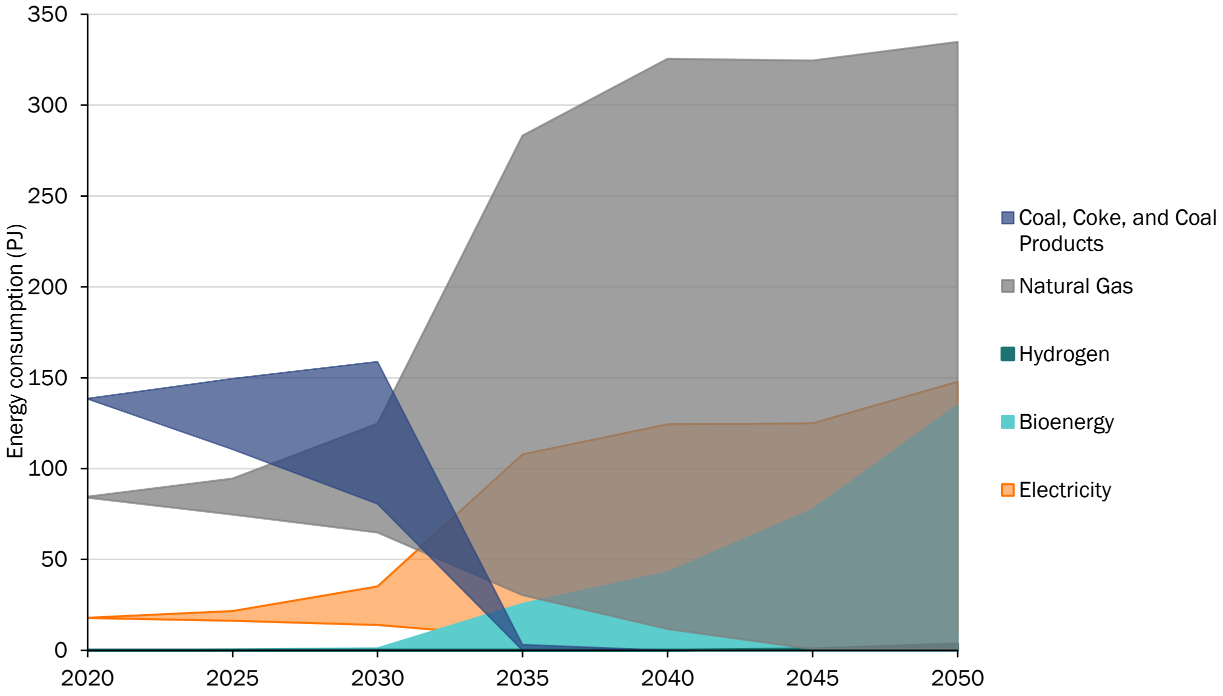


Figure 27: Energy consumption by fuel type in the iron and steel sector[32]



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[32] This figure includes 61 of the 62 net zero scenarios simulated for this analysis. One scenario has been excluded as a significant outlier.

4. Key insights

Results of this analysis provide four key insights that we highlight below.

Insight 1: Canada can achieve net zero emissions by mid-century via more than one pathway.

Canada's net zero goal is achievable. Currently known and available technologies and industrial abatement options can be used for Canada to reach net zero emissions by 2050. What Canada looks like at net zero depends heavily on two key factors:

- **The cost and availability of negative emission technologies.** Whether or not Canada transforms its energy system to suit a net zero world, or relies on large-scale implementation of DAC and CCS, or finds an intermediate pathway somewhere in between, has a significant impact on what Canada's net zero economy looks like.
- **International demand for Canadian oil and gas.** Whether the rest of the world implements strong climate policy or continues to demand oil and natural gas as Canada moves towards net zero emissions is a key determinant of whether Canada's oil and gas sector continues to grow or sees a significant decline in production.

Insight 2: An emissions backstop will likely be needed for Canada to achieve net zero emissions.

Some sectors, such as agriculture and cement, are unable to achieve zero emissions given a lack of abatement options. Therefore, some form of negative emission technology, such as DAC and/or CCS and/or land use or forestry sequestration is likely needed for Canada to achieve net zero emissions. The technology that is most widely available, scalable, and cost-effective will play a crucial role in decarbonizing Canada's economy.

When DAC is made available in this analysis, it is implemented at a large scale and allows more carbon-intensive sectors and end-uses to continue out to 2050. However, as a pre-commercial technology, there is no guarantee that the assumptions made about the cost and availability of DAC in this study will pan out. This means that, to have the best chance of achieving its net zero goal, Canada must proceed as if these technologies are not available. Canada should pursue a net zero pathway that does not rely on large scale deployment of negative emission technologies, until more information about these options is available to inform adjustments in its plan.

Insight 3: The future of Canada's oil and gas sector is uncertain.

Canada's oil and gas sector cannot be sustained without negative emission technologies, either DAC or CCS. If Canada transitions to net zero emissions ahead of other major countries, such that significant global demand for fossil fuels persists, negative emission technologies can help Canada to continue production and export of oil and natural gas to meet global demand, while remaining consistent with its own net zero target. If, on the other hand, global demand decreases as a result of climate policy implementation in other major countries, then significant production declines are likely in this sector.

In all pathways to net zero emissions, however, carbon dioxide reductions become a valuable commodity. If DAC or CCS are available, the storage of carbon dioxide becomes a valuable market and requires the transport of carbon dioxide to locations where it can be stored. This creates a new asset and opportunity in western Canada where oil and gas production currently occur, as there is significant geological storage potential in these locations.

Insight 4: Decisions being made today will determine which net zero pathway Canada takes.

There are some common actions that will be required for any of the net zero pathways simulated in this analysis to become a reality:

- **Significant increase in electricity generation capacity** for the electrification of transport, home heating, and some industrial processes, as well as to support potentially significant use of DAC in western Canada.
- **Large increase in biofuel manufacturing** to support the increased use of biofuels in transportation and RNG in buildings.
- **Increased investment in clean energy technologies** including electric vehicles, electricity distribution infrastructure, DAC and wind generation.
- **Increased investment in capacity for GHG sequestration** such as the build out of pipelines to carry carbon dioxide from across the country to western locations where it can be stored.
- **Switch to fully decarbonized steelmaking** using direct iron reduction or steel recycling.

Appendix A: Covered sectors, fuels and end-uses

Table 8: Sectors

Sector name	NAICS code
Soybean farming	11111
Oilseed (except soybean) farming	11112
Wheat farming	11114
Corn farming	11115
Other farming	Rest of 1111
Animal production and aquaculture	112
Forestry and logging	113
Fishing, hunting and trapping	114
Agriculture services	115
Natural gas extraction (conventional)	211113
Natural gas extraction (tight)	
Natural gas extraction (shale)	
Light oil extraction	
Heavy oil extraction	
Oil sands in-situ	211114
Oil sands mining	
Bitumen upgrading (integrated)	
Bitumen upgrading (merchant)	
Coal mining	2121
Metal mining	2122
Non-metallic mineral mining and quarrying	2123
Oil and gas services	213111 to 213118
Mining services	213119
Fossil-fuel electric power generation	221111
Hydro-electric and other renewable electric power generation	221112 and 221119
Nuclear electric power generation	221113
Electric power transmission, control and distribution	22112
Natural gas distribution	222
Construction	23
Food manufacturing	311
Beverage and tobacco manufacturing	312

Sector name	NAICS code
Textile and product mills, clothing manufacturing and leather and allied product manufacturing	313-316
Wood product manufacturing	321
Paper manufacturing	322
Petroleum refining	32411
Coal products manufacturing	Rest of 324
Petrochemical manufacturing	32511
Industrial gas manufacturing	32512
Other basic inorganic chemicals manufacturing	32518
Other basic organic chemicals manufacturing	32519
Biodiesel production from canola seed feedstock	
Biodiesel production from soybean feedstock	
Ethanol production from corn feedstock	
Ethanol production from wheat feedstock	
HDRD (or HRD) production from canola seed feedstock	
Renewable gasoline and diesel production	
Cellulosic ethanol production	
Resin and synthetic rubber manufacturing	3252
Fertilizer manufacturing	32531
Other chemicals manufacturing	Rest of 325
Plastics manufacturing	326
Cement manufacturing	32731
Lime and gypsum manufacturing	3274
Other non-metallic mineral products	Rest of 327
Iron and steel mills and ferro-alloy manufacturing	3311
Electric-arc steel manufacturing	
Steel product manufacturing from purchased steel	3312
Alumina and aluminum production and processing	3313
Other primary metals manufacturing	3314
Foundries	3315
Fabricated metal product manufacturing	332
Machinery manufacturing	333
Computer, electronic product and equipment, appliance and component manufacturing	334 and 335
Transportation equipment manufacturing	336
Other manufacturing	Rest of 31-33
Wholesale and retail trade	41-45
Air transportation	481
Rail transportation	482
Water transportation	483

Sector name	NAICS code
Truck transportation	484
Transit and ground passenger transportation	485
Pipeline transportation of crude oil	4861 and 4869
Pipeline transportation of natural gas	4862
Other transportation, excluding warehousing and storage	4867-492
Landfills	Part of 562
Services	Rest of 51-91

Table 9: Fuels

Fuel
Fossil fuels
Coal
Coke oven gas
Coke
Natural gas
Natural gas liquids
Gasoline and diesel
Heavy fuel oil
Still gas
Electricity
Electricity
Hydrogen
Hydrogen produced from steam methane reformation
Hydrogen produced from electrolysis
Hydrogen produced from biomass gasification
Renewable fuels (non-transportation)
Spent pulping liquor
Wood
Wood waste (in industry)
Renewable natural gas
Renewable fuels (transportation)
Ethanol produced from corn
Ethanol produced from wheat
Cellulosic ethanol
Biodiesel produced from canola
Biodiesel produced from soy
Hydrogenated renewable diesel (“hdrd”)
Renewable gasoline and diesel from pyrolysis of biomass
Renewable natural gas

Table 10: End uses

End use
Stationary industrial energy/emissions sources
Fossil-fuel electricity generation
Process heat for industry
Process heat for cement and lime manufacturing
Heat (in remote areas without access to natural gas)
Cogeneration
Compression for natural gas production and pipelines
Large compression for LNG production
Electric motors (in industry)
Other electricity consumption
Transportation
Air travel
Buses
Rail transport
Light rail for personal transport
Marine transport
Light-duty vehicles
Trucking freight
Diesel services (for simulating biodiesel and other renewable diesel options)
Gasoline services (for simulating ethanol options)
Oil and gas fugitives
Formation co2 removal from natural gas processing
Flaring in areas close to natural gas pipelines
Flaring in areas far from natural gas pipelines
Venting and leaks of methane (oil and gas sector)
Industrial process
Mineral product GHG emissions
Aluminum electrolysis
Metallurgical coke consumption in steel production
Hydrogen production for petroleum refining and chemicals manufacturing
Non-fuel consumption of energy in chemicals manufacturing
Nitric acid production
Agriculture
Process CH4 for which no know abatement option is available (enteric fermentation)
Manure management
Agricultural soils
Waste
Landfill gas management

End use
Residential buildings
Single family detached shells
Single family attached shells
Apartment shells
Heat load
Furnaces
Air conditioning
Lighting
Dishwashers
Clothes washers
Clothes dryers
Ranges
Faucet use of hot water
Refrigerators
Freezers
Hot water
Other appliances
Commercial buildings
Food retail shells
Office building shells
Non-food retail shells
Educational shells
Warehouses (shells)
Other commercial shells
Commercial heat load
Commercial hot water
Commercial lighting
Commercial air conditioning
Auxiliary equipment
Auxiliary motors (in commercial buildings)

Appendix B: Decomposition of emissions methodology

Greenhouse gas emissions can change for a variety of reasons, and these reasons can happen simultaneously. As an example, the adoption of electric vehicles may increase at the same time as fuel suppliers increase the renewable concentration of gasoline. As such, it is difficult to assign a change in GHG emissions to a particular driver.

To overcome this challenge, Navius' decomposition analysis employs the logarithmic mean Divisa index (LMDI) method[33], which disaggregates a given change in GHG emissions into the following five factors:

$$GHG = O \times \sum_{j} \frac{S_j}{O} \times \sum_{eu} \frac{EU_{j,eu}}{S_j} \times \sum_{t} \frac{T_{j,eu,t}}{EU_{j,eu}} \times \frac{GHG_{j,eu,t}}{T_{j,eu,t}}$$

GHG emissions from producing a good or service are decomposed as follows:

1. Output (O in the equation above). Everything else being equal, an increase in output typically (but not always) leads to an increase in GHG emissions. In this case, output is the total production of a good or service.
2. Sector share of output (S_j/O). Some commodities can be produced by more than one sector. For example, BC has three natural gas producing regions and methods of production (i.e., conventional, Montney and Horn River), each with distinct greenhouse gas profiles. An increase in the share of natural gas production from the Montney region (which has relatively lower carbon intensity) relative to the other regions would reduce GHG emissions. Similar to natural gas production in BC, hydrogen, steel and cement can be produced by distinct sectors.
3. End-use efficiency ($EU_{j,eu}/S_j$). If a sector (S_j) consumes less of a GHG-emitting end-use ($EU_{j,eu}$), GHG emissions are reduced. For example, if households choose to drive less per level of income, GHG emissions are reduced.

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[33] Ang, B.W. 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Policy, 33, 867-871.

4. Technology share ($T_{j,eu,t}/EU_{j,eu}$). Increasing the share of a low-emission technology ($T_{j,eu,t}$) used to meet the demand for an end-use ($EU_{j,eu}$) reduces GHG emissions.

5. GHG intensity ($GHG_{j,eu,t}/T_{j,eu,t}$). Any decline in the GHG intensity of a technology reduces GHG emissions. For example, the GHG intensity of a given gasoline vehicle can decline if a greater share of biofuels is blended into the gasoline used.

Using results from this decomposition analysis allows us to build a detailed narrative about why GHG emissions change with an increase in policy stringency. Figure 28 provides an example of this. The diagram on the left-hand side illustrates the nesting of decisions for the personal transportation sector modeled within gTech. At the top-level, households must decide whether to use their incomes for transportation services or for other consumption (e.g., going to a restaurant). The next decision simulates whether households take transit or a passenger vehicle. The following decisions reflect choices for vehicle size, motor type and finally the type of fuel.

Emissions are decomposed into the five factors (in this case of passenger transportation, the sector share term can be ignored) at each level in the decision structure. The GHG reduction narrative is then built as follows:

A) GHG reductions attributed to the output decision of the vehicle size choice (i.e., trucks vs. cars) explains how changes in household income affects the decision whether or not to drive.

B) GHG reductions attributed to the end-use efficiency decision of the vehicle size choice explain how households choose to take more transit or consume other services instead of drive, when faced with more stringent climate policy.

C) GHG reductions attribute to the technology share decision for vehicle size is due to household purchasing smaller or larger vehicles.

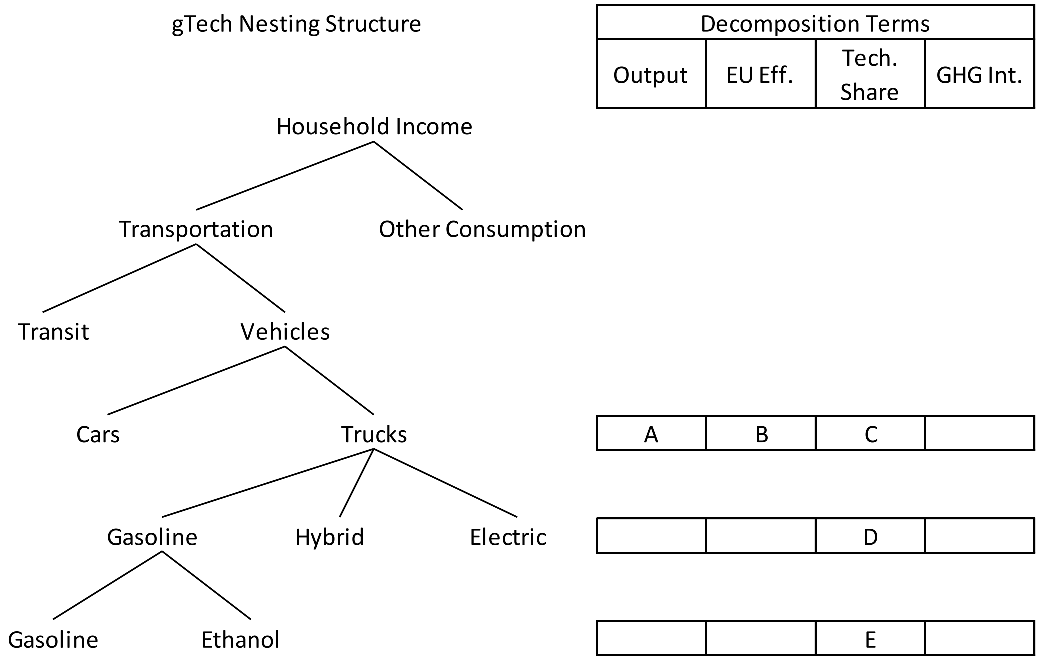
   - Note that the GHG intensity for all sizes of vehicles changes if households purchase different motors or consume greater biofuel blends. However, the reductions for these are best measured at decisions below.

D) GHG reductions attributed to the technology share decision for motor choice is used to describe how households purchase different types of vehicles (e.g., electric vs. internal combustion engines).

   - The output and end-use efficiency terms are ignored here because they are a function of the decisions occurring at the vehicle size level.

E) Finally, GHG reductions attributed to the technology share decision for the fuel choice (e.g., gasoline vs. ethanol) describes how households reduce emissions via blending higher levels of biofuels.

Figure 28: Example of decomposition structure for the personal transport sector



Appendix C: Abatement opportunities by sector

Table 11: Abatement opportunities in industry

Economic Sector	Key GHG abatement opportunities	Data sources
Stationary Combustion		
Electric generation	Renewables	IESD
	Electricity efficiency	EIA (2019)
Process heat (high-grade heat)	Fuel switching	Park et al (2017), CIMS
	Carbon capture and storage	CIMS
	Renewables (Biomass and RNG)	DENA (2016)
	Electric resistance	Park et al (2017), CIMS
Process heat (low-grade heat)	Fuel switching	Park et al (2017), CIMS
	Carbon capture and storage	CIMS
	Renewables (biomass and RNG)	DENA (2016)
	Electric heat pumps	Onmen et al (2015)
Compression	Electrification	Greenblatt (2015)
	Electrification of LNG	ABB (2010)
Industrial cogeneration	Cogeneration	gTech
Steel production	Natural gas direct reduced iron	Fischedick et al. (2014).
	Hydrogen direct reduced iron	Vogl et al. (2018)
Fugitive Sources		
Coalbed methane	No abatement available	
Vents and leaks	Various leak detection and reduction measures	ICF International (2015), Clearstone Engineering (2014)
Formation CO_2	Carbon capture and storage	CIMS
Flaring	For oil facilities: Natural gas production For natural gas facilities: no abatement	Johnson & Coderre (2012)
Industrial Processes		
Hydrogen production	Carbon capture and storage	US DOE (2014)
	Electrolysis	US DOE (2014)
Limestone calcination	No abatement available	
Aluminum CO_2	No abatement available	
Aluminum PFCs	Computer controls to reduce PFCs	CIMS
Other process	No abatement available	
Agriculture		
Enteric fermentation	No abatement available	
Manure management	Anaerobic digestion to produce RNG	IEA ETSAP (2013)
Agricultural soils	No abatement available	
Atmospheric sequestration		
Atmospheric sequestration	Direct Air Capture	Fasihi et al. (2019), Keith et al. (2019)

Table 12: Abatement opportunities in transportation

Greenhouse gas source	Key abatement opportunities	Data sources
Energy – Transport		
Light and heavy-duty vehicles	Efficiency improvements	EIA (2019)
	Natural gas and renewable gas	IRENA (2013), APEC (2010), AAFC (2017), Kludze et al (2013), Yemshanov et al (2014), Petrolia (2008), (S&T)[2] Consultants (2012), Chavez-Gherig et al (2017), G4 Insights (2018), IEA ETSAP (2013), Hallbar Consulting (2016)
	Electrification	Bloomberg (2019), Moawad et al (2016), Argonne (2018), Curry (2017), US DOE (2013), Bloomberg (2018), ICCT (2017), ICCT (2019), Fries (2017), Mayor's Council (2018)
	Renewable fuels	IRENA (2013), APEC (2010), AAFC (2017), Kludze et al (2013), Yemshanov et al (2014), Petrolia (2008), (S&T)[2] Consultants, (2012), Chavez-Gherig et al (2017), G4 Insights (2018), IEA ETSAP (2013), Hallbar Consulting (2016)
	Hydrogen	SA Consultants (2017), SA Consultants (2019), IEA (2019), NREL (2013), NREL (2019A), NREL (2019B)
Domestic navigation	Efficiency improvements	CIMS
Domestic aviation	No abatement options are available	CIMS
Railways	Renewable fuels	See list for renewable fuels above
Industrial Processes and Product Use		
Light and heavy-duty vehicles	Abatement is fixed to align with the federal policy to reduce HFCs	

Table 13: Abatement opportunities in buildings and communities

Greenhouse gas source	Key abatement opportunities	Data sources
Stationary combustion		
Space heating	Thermal improvements to building shells	RDH (2018)
	More energy efficient natural gas furnaces and boilers	EIA (2016), NREL (2018)
	Renewable gas	IRENA (2013), APEC (2010), AAFC (2017), Kludze et al (2013), Yemshanov et al (2014), (S&T)^2 Consultants, (2012), Chavez-Gherig et al (2017), G4 Insights (2018), IEA ETSAP (2013), Hallbar Consulting (2016)
	Electric space and water heating (resistance and heat pump)	EIA (2016), NREL (2018)
Water heating	More energy efficient natural gas water heaters and boilers	EIA (2016), NREL (2018)
	Renewable natural gas	See list for renewable gas above
	Electric water heaters (resistance and heat pump)	EIA (2016), NREL (2018)
Cooking	Electric ranges or renewable gas	EIA (2016), NREL (2018)
Industrial Processes		
Air conditioning	Thermal improvements to building shells	RDH (2018)
	Abatement is fixed to align with the federal policy to reduce HFCs	
Auxiliary equipment	Efficiency	CIMS
Waste		
Waste	Capture of methane for flaring, generating electricity or supply into natural gas distribution network	BC MOE (2017)
	Organic waste diversion	BC MOE (2017)

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Appendix D: List of all net zero scenarios

Scenario	Assumption																						
	Cost of battery electric vehicles		Cost of hydrogen fuel cell vehicles		Cost of hydrogen fuel production		Hydrogen blending rate limit		Availability of new low-emitting, firm power		Net zero climate policy implemented in the rest of the world		Availability of CCS for combustion emissions		Availability of DAC		Global price of oil		Competitiveness protection measures		Availability of second-generation biofuels		Emissions intensity improvement of oil sands sector	
	Ref	Low	Ref	Low	Ref	Low	Ref	High	No	Yes	No	Yes	No	Yes	No	Yes	Ref	Low	Off	On	No	Yes	Ref	Accelerated
1	✓		✓		✓		✓		✓		✓			✓		✓	✓		✓			✓	✓	
2	✓		✓		✓		✓		✓		✓		✓		✓		✓		✓			✓	✓	
3	✓		✓		✓		✓		✓			✓		✓		✓	✓		✓			✓	✓	
4	✓		✓		✓		✓		✓			✓	✓		✓			✓	✓			✓	✓	
5	✓		✓		✓		✓			✓	✓		✓		✓		✓		✓			✓	✓	
6	✓		✓		✓		✓			✓		✓	✓		✓			✓	✓			✓	✓	
7		✓	✓		✓		✓		✓		✓			✓		✓	✓		✓			✓	✓	
8		✓	✓		✓		✓		✓		✓		✓		✓		✓		✓			✓	✓	
9		✓	✓		✓		✓		✓			✓		✓		✓	✓		✓			✓	✓	
10		✓	✓		✓		✓		✓			✓	✓		✓			✓	✓			✓	✓	
11		✓	✓		✓		✓			✓	✓		✓		✓		✓		✓			✓	✓	
12		✓	✓		✓		✓			✓		✓	✓		✓			✓	✓			✓	✓	
13		✓		✓		✓		✓	✓		✓			✓		✓	✓		✓			✓	✓	
14		✓		✓		✓		✓		✓	✓		✓		✓		✓		✓			✓	✓	
15		✓		✓		✓		✓	✓			✓		✓		✓	✓		✓			✓	✓	
16		✓		✓		✓		✓		✓		✓	✓		✓			✓	✓			✓	✓	
17	✓		✓		✓		✓		✓		✓			✓		✓	✓			✓		✓	✓	
18	✓		✓		✓		✓		✓		✓		✓		✓		✓			✓		✓	✓	
19	✓		✓		✓		✓		✓			✓		✓		✓	✓			✓		✓	✓	
20	✓		✓		✓		✓		✓			✓	✓		✓		✓			✓		✓	✓	
21	✓		✓		✓		✓			✓	✓		✓		✓		✓			✓		✓	✓	
22	✓		✓		✓		✓			✓		✓	✓		✓			✓		✓		✓	✓	
23		✓	✓		✓		✓		✓		✓			✓		✓	✓			✓		✓	✓	
24		✓	✓		✓		✓		✓		✓		✓		✓		✓			✓		✓	✓	
25		✓		✓		✓		✓	✓		✓			✓		✓	✓			✓		✓	✓	
26		✓	✓		✓		✓		✓			✓		✓		✓	✓			✓		✓	✓	
27		✓	✓		✓		✓		✓			✓	✓		✓			✓		✓		✓	✓	
28		✓		✓		✓		✓	✓			✓		✓		✓	✓			✓		✓	✓	
29		✓	✓		✓		✓			✓	✓		✓		✓		✓			✓		✓	✓	
30		✓		✓		✓		✓		✓	✓		✓		✓		✓			✓		✓	✓	
31		✓	✓		✓		✓			✓		✓	✓		✓			✓		✓		✓	✓	
32		✓		✓		✓		✓		✓		✓	✓		✓			✓		✓		✓	✓	
33	✓		✓		✓		✓		✓		✓			✓	✓		✓		✓			✓	✓	
34		✓	✓		✓		✓		✓		✓			✓	✓		✓		✓			✓	✓	

Scenario	Assumption																							
	Cost of battery electric vehicles		Cost of hydrogen fuel cell vehicles		Cost of hydrogen fuel production		Hydrogen blending rate limit		Availability of new low-emitting, firm power		Net zero climate policy implemented in the rest of the world		Availability of CCS for combustion emissions		Availability of DAC		Global price of oil		Competitiveness protection measures		Availability of second-generation biofuels		Emissions intensity improvement of oil sands sector	
	Ref	Low	Ref	Low	Ref	Low	Ref	High	No	Yes	No	Yes	No	Yes	No	Yes	Ref	Low	Off	On	No	Yes	Ref	Accelerated
35	✓		✓		✓		✓			✓	✓			✓	✓		✓		✓			✓	✓	
36		✓	✓		✓		✓			✓	✓			✓	✓		✓		✓			✓	✓	
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62		✓	✓		✓		✓			✓	✓			✓	✓		✓			✓	✓		✓	

At Navius, we offer our clients the confidence to make informed decisions related to energy, the economy, and the environment.

We take a collaborative approach to projects, drawing on a unique suite of modeling, research and communication tools to provide impartial analysis and clear advice.

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