Evaluating the Macroeconomic Costs of Climate Change in Canada

Modeling Methodology Report

SUBMITTED TO

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SUBMITTED BY

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Executive Summary

Climate change is expected to have broad-reaching impacts on infrastructure, human health, and natural resources in Canada. CCI has worked to quantify these impacts across almost two dozen impact areas, producing sectoral estimates of climate change impacts in a variety of formats and magnitudes. This report summarizes Navius' approach used to integrate all these costs and benefits into a single macroeconomic model.

Our analysis was conducted using gTech, a computable general equilibrium model representing economic activity in all Canadian provinces, the territories, and the United States. For this project, gTech was customized to run in 10-year increments from 2015 to 2095 and to include new spending categories for climate damages and productivity shocks.

CCI provided estimates for climate change costs/benefits across almost two dozen impact areas, which we aggregated into the 13 categories below. For each impact area, the inputs were translated into an intensity-based change in productivity for a certain industry or spending on a certain good or service.

Table 1: Summary of impact areas considered in Navius' modeling

Impact Aaea	Direction and magnitude of Impact	Navius modeling approach
Agricultural productivity	++	Data inputs used as-is to reflect a productivity change to the sector
Forestry resource reductions	-	Data inputs used as-is to reflect a reduction in resource availability
Tourism	+	Translated to estimates for how exports of services and goods will increase/decrease
Labour productivity	- -	Translated to a reduction in labour productivity using 2016 hours worked
Inland and coastal flooding	-	Translated to a per-m2 cost to buildings and increased over time to reflect asset appreciation
Storms	- - -	Primarily modeled as government procurement of construction funded by higher taxes
Permafrost thaw	-	Translated to a per-m2 cost to buildings; partially funded by government procurement.
Changes to electricity demand for heating and cooling	-	Decreases/increases to the heating and cooling requirements of buildings

Electricity infrastructure damages	-	Translated to a productivity reduction in the electricity distribution sector
Hydroelectric generation	+	Translated to a productivity increase in the electricity distribution sector
Rail damages and delay	-	Translated to a productivity reduction in the rail transportation sector
Road damages and delay	- -	Delay costs were translated to a productivity reduction for freight transportation; damage costs were modeled as government procurement of construction.
Heat- and air quality-related deaths	- -	Data inputs used as-is to reflect a reduction in the labour supply
Healthcare spending	-	Modeled as government procurement of services funded by higher taxes

Climate impacts were scaled up with economic growth and time, in addition to the severity of weather, to reflect increasing costs as Canadians build more roads, houses, and other infrastructure susceptible to damage throughout the 21st century. Damages affecting one specific sector were endogenously increased with the size of that sector in the model. Three asset valuation scenarios related to GDP growth in the model were simulated to account for how asset growth might impact the level of the damages to buildings and infrastructure.

We also simulated 14 difference climate change scenarios (two global emissions scenarios and seven climate models downscaled to Canada) and quantified the individual and combined impact of each impact area across scenarios. We compared key model outputs for GDP, jobs, household welfare with the estimates from the climate-change free reference case.

Given the large timescale and scope of this project, uncertainty is inherently large. Resulting economic impacts are sensitive to the assumptions used for how assets that may be susceptible to climate damages grow relative to economic output. If the economy becomes more intensive of capital inputs that may be subject to damage, impacts are larger. If the stock of capital which weather would damage grows slower than the overall economy, impacts are lower. Areas for future research include stochastic modeling of disaster costs, migration, and trade restrictions.

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1. Overview of Approach

The Canadian Climate Institute (CCI) has conducted research on various ways that climate change may affect Canadians. This includes quantification of the impacts of climate change on human health and labour supply (due to changes in temperature, climate-sensitive vectors for disease and pathogen transmission, and exposure to air pollution), as well as economic costs of damages to infrastructure (i.e., increased costs of protection, repair, or replacement) and agricultural and forestry productivity. The goal of this project is to integrate CCI's estimates of climate change impact groups into one model to understand the macroeconomic costs of climate change, including its effects on GDP, employment, welfare, and other indicators across all regions in Canada.

CCI provided data inputs for a range of climate impact groups, which Navius then translated into inputs for the gTech model. The list of climate impacts considered in our modeling is shown in Table 2.

Table 2: Impact groups included in modeling

Impact area	Direction and magnitude of Impact
Agricultural productivity	++
Forestry resource reductions	-
Tourism	+
Labour productivity	- -
Inland and coastal flooding	-
Weather-related disasters	- - -
Permafrost thaw and Northern infrastructure	-
Changes to electricity demand for heating and cooling	-
Electricity infrastructure damages	-
Hydroelectric generation	+
Rail damages and delay	-
Road damages and delay	- -
Heat- and air quality-related deaths	- -
Healthcare spending	-

We used a modified version of our macroeconomic model, gTech, to simulate how direct costs to households and businesses would affect the economy as a whole. gTech is a computable general equilibrium (CGE) model that simulates economic activity in all ten Canadian provinces, the territories, and the United States. For this project, the model was expanded to operate in 10-year increments from 2015 to 2095 and to include new spending categories for climate damages. These CGE model developments allowed us to quantify the combined impact of all impact groups across a range of 14 different possible climate change scenarios and three asset growth scenarios between now and 2095, with and without adaptation. A total of 84 scenarios plus a stable-climate reference case were simulated. For a detailed discussion of the gTech model, refer to the appendix.

2. Climate Change Scenario Inputs

CCI provided inputs to model a range of climate scenarios intended to reflect differing severities of global climate change, uncertainty in changes to temperature and precipitation at the provincial level, and different levels of proactive adaptation to climate impacts.

The climate change scenarios considered include the IPCC's representative concentration pathways with radiative forcings of 4.5 W/m2 and 8.5 W/m2 (RCP4.5 and RCP8.5). The global mean surface temperature change by end-of-century is estimated to be between 1.1 and 2.6 degrees Celsius and 2.6 and 4.8 degrees Celsius for the RCP4.5 and RCP8.5 scenarios respectively[1]. CCI used downscaled climate models to show how these global scenarios may translate to national and regional impacts in Canada. To capture uncertainty associated with modeling future climate change, seven global climate models were used for each of the RCP8.5 and 4.5 scenarios, resulting in 14 different climate change scenarios. We also simulated all the climate impacts independently with one climate model, CCSM4, to be able to examine their impacts independently.

For some climate impact areas, CCI was able to quantify reductions in damages associated with proactive adaptation. For this subset of impact areas for which adaptation data was available, we simulated the 14 climate change forecasts for this subset independently along with the same subset's no-adaptation inputs, in order to quantify the benefit of adaptation by excluding influence from climate impacts in which adaptation was not quantified.

CCI previously developed, sometimes with other consultants, estimates of how temperature and precipitation changes in the seven climate models and two emission scenarios (RCP4.5 and RCP8.5) would affect impact areas of interest in the Canadian economy. Data outputs from this work varied in format: infrastructure impact estimates were provided as dollar costs to Canada's 2015 infrastructure stock, some estimates were provided as productivity changes, and others such as healthcare impacts were provided as total cost including consideration of population and economic growth. The description of data inputs for each impact area and how they were translated into a model input is provided in Section 3.

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[1] IPCC AR5 Working Group 1 Summary for Policy Makers (2018), pg. 23. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_SPM_FINAL.pdf

3. Modeling Damages by Impact Area

This section provides a summary of each of the climate impacts considered in this project and how the data provided by CCI was input into gTech to estimate macroeconomic impacts.

3.1. Agriculture

Warmer weather, changes to rainfall patterns, and extreme weather all have the potential to increase or decrease crop yield from Canada's agricultural sector.

Data Inputs

CCI worked with Agriculture and Agri-Food Canada (AAFC) to obtain detailed projections of future yields from their analyses of climate change impacts on yields of key crops (corn, wheat, canola) across Canada. Province-by-province changes in yields from these AAFC modeling scenarios corresponding to the climate models used in the CCI were input directly into the gTech model. Soy yield changes for each province were estimated using agricultural projections from Network for Greening the Financial System (NGFS) climate impacts scenario datasets. Changes to yields of other field crops, which were modeled in aggregate, were estimated using a weighted average of projected climate change yield effects on forage crops (He et al, 2019), potatoes (Brassard and Singh, 2007), and horticultural products (Doria, 2011; McKeown et al, 2005; Stöckle et al, 2010).

Table 3: CCI Data Input Disaggregation for Agriculture

Adaptation data available	No, an adaptation scenario was not developed for agriculture.
Regional disaggregation	Partial. Yield changes for corn, wheat, soy, and canola were provided at the provincial level; data for other field crops was provided at the national level with the same figure used for each province.

Climate model disaggregation	Partial. Yield changes for corn, wheat, soy, and canola were provided by GCM; data for other field crops was provided for the ensemble with same figure used for each GCM.

Modeling Approach

The changes to crop yields provided by CCI were used as-is to represent a productivity increase or decrease to the affected economic sectors (corn, wheat, soy, canola, and other crop production). For example, if input data suggests that canola yields will increase by 50% by 2095, this was modeled as required 50% less of all economic inputs (land, fertilizer, capital, labour) to produce one unit of canola in this year.

3.2. Forestry

Increased temperatures due to climate change will increase forest fire risk and forest productivity, affecting the quantity of standing timber available for the forest industry to harvest.

Data Inputs

CCI worked with another consultant, Green Analytics, to estimate changes to standing timber in each province and territory due to temperature increases associated with each climate scenario, based on Boucher et al (2018).

Table 4: CCI Data Input Disaggregation for Forestry

Adaptation data Available	No, an adaptation scenario was not developed for forestry.
Regional disaggregation	Yes.
Climate model disaggregation	Indirectly. The relationship between standing timber and temperature was derived from Boucher et al. (2018) and extrapolated to other climate models.

Modeling Approach

Prior to assessing climate change impacts, the forestry sector in gTech is provided an endowment of resources (trees) that can be used for productive activity, which is derived from the cost structure of the industry in Statistics Canada's Supply-Use tables. The size of this resource endowment determines how much the industry is able to produce in a given year, and what production will cost.

To incorporate Green Analytics' inputs, the estimates for reductions in standing timber were directly translated to a reduction in resource availability below the reference case level. For example, a 20% reduction in standing timber was interpreted to be a 20% reduction in the resource available to the forest industry, effectively assuming the trees at risk of fire are equally desirable to industry as the average forest[2].

This reduction in resource availability translates closely to a reduction in output (and thus constant-price GDP) from the industry, but not necessarily a reduction in GDP after accounting for price changes. Interestingly, in some scenarios the major construction investments associated with other impact areas coupled with the decrease in forest sector outputs saw a price for wood and wood products increase faster than outputs declined.

3.3. Tourism

Increased temperatures have the potential to push global tourism towards the poles, as high-latitude climates become more temperate and equatorial regions become too hot. This impact area reflects a potential economic benefit to Canada due to increased exports of tourism-related goods and services.

Data Inputs

The Hamburg Tourism Model (HTM) is an econometric model of tourism flows between 207 countries that considers how changes to countries' climates could affect trade flows. Green Analytics used the HTM to estimate changes to foreign tourist arrivals in Canada, provided to Navius as a percent change from 2015, based on average warming across the Canadian landmass associated with each of the climate scenarios.

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[2] One adjustment was made to the GreenAnalytics inputs for 2085 and 2095. In Saskatchewan and Manitoba, for two of the GCMs, raw data inputs showed a 90+% reduction in standing timber. Due to the small size of the sector in these provinces, the model was unable to solve with such a drastic reduction in the already small industry. This data input was reduced to an 80% reduction in timber.

Table 5: CCI Data Input Disaggregation for Tourism

Adaptation data available	No, an adaptation scenario was not developed for tourism.
Regional disaggregation	No. The relative change in foreign tourist arrivals was assumed to apply equally in all provinces.
Climate model disaggregation	Yes.

Modeling Approach

To incorporate relative changes to foreign tourist arrivals, estimates were needed for where tourism money would be spent, what it would be spent on, and how this would change over time. Typically, expenditures by tourists are reflected in Statistics Canada's Supply-Use tables as exports of tourist-related goods and services. For example, a foreign tourist staying in a Canadian hotel is an export of accommodation services. Statistics Canada also publishes data on estimated expenditures by international tourists, allowing tourism-related expenditures to be decoupled for other non-tourism exports.

The following assumptions were used to incorporate changes to tourist arrivals into quantity of goods exported in gTech:

- The regional distribution of tourism expenditures in Canada remains the same 2015-2095 as is shown in Statistics Canada table 24-10-0004-01: Provincial and territorial tourism supply and expenditure.
- The commodity distribution of tourism expenditures (hotels versus car rentals versus food) remains the same as is shown in Statistics Canada table 36-10-0230-01: Tourism demand in Canada.
- Expenditures by tourists in each region on each commodity are scaled up using the change to foreign arrivals provided by Green Analytics to reflect increased arrivals, and the change to US GDP to reflect increased spending power by foreign tourists.

The increased quantity of exported goods due to incremental tourists as a result of climate change was then added to export demand for the relevant commodities (services, food, air travel, and vehicles) in each province.

3.4. Labour Impacts

This impact area is intended to represent reductions in economic output due to reductions in hours worked as a result of extreme heat and other weather events under climate change.

Data Inputs

CCI worked with an external consultant, ESSA Technologies Ltd, to estimate direct effects of climate changes on labour supply. Figures were provided for representative years (2050s and 2080s) under one RCP4.5 and one RCP8.5 scenario. Figures included changes to hours worked (in millions of hours), changes to payroll (in billions of dollars), and changes to GDP (in billions of dollars). Estimates were provided for five aggregated industry groups. For all industries, the figures were reported relative to a 2016 baseline.

To account for potential mitigation of labour supply impacts due to adaptation measures in the workplace, CCI provided data inputs for changes to hours worked, changes to payroll, and changes to GDP due to adaptation, measured as a change from a no-adaptation scenario.

Table 6: CCI Data Input Disaggregation for Labour

Adaptation data available	Partial. Data for increases to hours worked by industry due to adaptation measures (shading and cooling of manufacturing facilities) were provided by GCM, province, and year, for all industries combined.
Regional disaggregation	Yes. All data was provided at the provincial level.
Climate model disaggregation	Partial. Labour supply reductions due to temperature increases were provided for one temperature trajectory in the 2050s and 2080s.

Modeling Approach

The reductions in hours-worked from and the mitigating benefits of adaptation from ESSA were used to represent changes to productivity in each sector. For example, the data suggested lost hours due to climate change in the 2080s would be about 38 million hours per year. Because there were 2.7 billion hours worked in the construction industry in 2016, the model input was then calculated to be a 1.4% reduction (38/2,700) in labour productivity below the no-climate change scenario. Because labour data was provided for the 2050s and 2080s only, data inputs for the intermediary years were produced using linear interpolation.

Productivity increases due to adaptation measures were calculated in a similar manner. Because the increase to hours worked was provided as a total, rather than by industry, the change was apportioned between industries using each industry's share of 2016 hours worked.

Data for changes to payroll and GDP were not inputted into the model in order to avoid double or triple counting the same effect. After modeling the labour productivity changes, we found our estimates for payroll and GDP impacts to be larger than those provided by Industrial Economics, presumably due to differing assumptions about wage growth and indirect equilibrium effects in the CGE model.

3.5. Coastal and Inland Flooding

Sea-level rise, increased precipitation, and warmer weather are expected to increase the severity and frequency of flooding events in Canada.

Data Inputs

CCI worked with an external consultant, Industrial Economics, Incorporated, to estimate the increase to flood-related costs on Canada's 2015 building stock and infrastructure, provided to Navius in millions of 2015 dollars. These costs primarily reflect replacement value of repairing buildings after floods.

Table 7: CCI Data Input Disaggregation for Coastal and Inland Flooding

Adaptation data available	Partial. An adaptation scenario was created for coastal flooding but not inland flooding.
Regional disaggregation	Yes.
Climate model disaggregation	Partial. Inland flooding data was available for all GCMs, while coastal flooding data was only provided for the

	ensemble. The same coastal flooding costs were used for all GCMs.

Costs were divided between the residential and commercial sectors at the provincial level using historic asset valuations. On average, this resulted in 70% of costs being applied to the residential sector, with the rest affecting the commercial sector.

Modeling Approach

In gTech, households and the commercial sector invest in and own buildings, with the cost of different buildings varying by building type and level of energy efficiency. Flood damages were assumed to affect all building types (e.g., detached houses versus apartments, schools versus offices) equally in the residential and commercial sectors. The CCI cost input was translated to a dollar-per-square-meter cost and applied for each year, region, and GCM to all building types in the commercial and residential sectors, with all incremental cost being spent on construction services.

Costs per square meter of floorspace associated with flooding were also increased to reflect historical appreciation of buildings above and beyond increases to building size (building stock grows, but also becomes higher value with time). This approach is discussed in detail in Section 4, Approach to Scaling Damages.

3.6. Weather-Related Disasters

Repair costs on housing, commercial buildings, and public infrastructure were all predicted to increase due to extreme weather events.

Data Inputs

CCI provided data for repair costs due to weather-related damage to buildings and infrastructure for each province, year, and climate model. Future estimates of repair costs were developed by extrapolating recent trends in weather-related disaster damage costs in different regions across Canada, scaled to the rate of climate change projected for each climate model and emissions scenario. Historic data on weather-related disaster costs were obtained from annual Insurance Bureau of Canada summaries of insured catastrophic losses. A simple ARIMA forecast was developed using 1983 to 2021 frequency and disaster cost data. Insured losses were converted to total direct damages according to a scaling factor of 2.11 established from the Parliamentary Budget Office (PBO, 2016). Flood damages already accounted for in the inland and coastal flooding analysis were removed from the weather-related disaster damages to avoid double counting. The forecast costs were adjusted downward to account for the past trend in weather-related disasters costs that would continue in a stable-climate reference case. This adjustment ensures that only the new incremental weather-related disaster costs are included in the analysis.

CCI estimates were produced using 2015 prices and infrastructure, meaning the numbers reflect what it would have cost if the projected future frequency and severity of storms (for example from the 2080s) affected Canadian infrastructure in 2015.

Direct costs associated with storm damages were an order of magnitude larger than any of the other impact areas where economic impact was primarily due to direct damages. Storm damages were the largest determinant of overall macroeconomic impact of climate change. CCI's modeling of impacts to 2015 infrastructure averaged $57 billion per year in the 2090s in the RCP8.5 scenario, with a maximum of $114 billion per year in the GFDL-ESM2M climate model. These inputs were then manipulated and further scaled up to account for asset growth, discussed below.

Table 8: CCI Data Input Disaggregation for Weather-Related Disasters

Adaptation data available	No, an adaptation scenario was not developed for weather-related disasters.
Regional disaggregation	Yes. All data was provided at the provincial level.
Climate model disaggregation	Yes. All data was provided by GCM.

CCI indicated that natural disaster costs should be distributed within the economy with 65% being directly paid for by government, 15% by the commercial sector, and 20% households.

Modeling Approach

Commercial and residential costs from storms were modeled identically as damage to buildings due to inland and coastal flooding, described above.

Most storm costs in CCI's data were to government-owned infrastructure, requiring the government to raise additional revenue to pay for the repairs. An incremental federal tax on personal and corporate income above and beyond existing rates was added to raise 100% of the revenue required for the storm damage. All storm-related costs were treated as consumption of construction services in gTech.

3.7. Permafrost Thaw

This impact area reflects repair costs associated with thawing permafrost damaging buildings, roads, and airports in Canada's North.

Data Inputs

CCI worked with Industrial Economics to generate estimates for future repair costs to roads, buildings, and airports due to permafrost thaw, with 79% of costs associated with road repair, 19% buildings, and 2% airports.

Table 9: CCI Data Input Disaggregation for Permafrost Thaw

Adaptation data available	Yes.
Regional disaggregation	Yes.
Climate model disaggregation	Yes.

Modeling Approach

For costs associated with buildings, these were incorporated using the same method described for Coastal and Inland Flooding in Section 3.5. For roads and airports, these costs were modeled as government expenditure on construction funding by increased personal and corporate income taxes, described above for Storm Damages in Section 3.6.

3.8. Electricity Demand

Milder winters and hotter summers are expected to decrease demand for heating and increase demand for air conditioning in Canada, resulting in some savings on heat and higher expenses on electricity.

Data Inputs

CCI worked with Navius in previous study to assess the effects of projected future changes to heating and cooling degree days for each GCM and region. which were translated to changes in energy use intensities for heating and cooling in residential and commercial buildings using the Navius Integrated Electricity Supply and Demand (IESD) model.

Table 10: Data Input Disaggregation for Electricity Demand

Adaptation data available	No, an adaptation scenario was not developed for electricity demand.
Regional disaggregation	Yes.
Climate model disaggregation	Yes.

Modeling Approach

In gTech, households and the service sector consume energy end uses for heating and cooling. Expenditures on these end uses reflect the fuel/electricity cost, operating costs, and capital expenditure on equipment. In the reference case, the end-use requirement for air conditioning was modeled to increase by a certain amount to account for business-as-usual adoption of air conditioning with growing household incomes.

In each of the climate scenarios, the heating and cooling requirements for all building shells were decreased/increased from the reference case intensity by that climate scenario's change to heating and cooling degree days. A detailed description can be found the in 2020 report *Impacts of climate change on Canada's electricity system.*[3]

[3] Navius Research, 2020, Impacts of climate change on Canada's electricity system. Available at: https://www.naviusresearch.com/wp-content/uploads/2021/09/Electricity-Impacts-of-Climate-Change-Updated-Report-2021-09-01.pdf

3.9. Electricity Infrastructure, Rail Damages, and Road and Rail Delay

Climate change costs for electricity infrastructure, railway damage, and transportation delays due to road and rail demand were all modeled with a similar methodology. These impact areas reflect costs to repair and replace infrastructure due to weather-related damages or a monetized version of how transportation may be delayed due to the infrastructure damage.

Data Inputs

CCI worked with Industrial Economics to generate projections of future costs for climate damages to electricity infrastructure and railways, as well as monetized delay to road transportation and railways. All figures were provided in millions of 2015 Canadian dollars. As with the other impact areas, the total expenditures were reflective of climate damages to Canada's 2015 infrastructure and economic activity, using the expected weather from future years.

Table 11: CCI Data Input Disaggregation for Electricity Infrastructure, Rail Damages, and Road and Rail Delay

Adaptation data available	Yes.
Regional disaggregation	Yes.
Climate model disaggregation	Yes.

Modeling Approach

For all affected sectors, the costs per year were translated into a reduction in productivity for the electricity distribution, rail, trucking freight transportation, and other road transportation economic sectors. The following calculation was used:

$$\text{Productivity Reduction (\%)} = \frac{\text{Climate Damage Cost}}{\text{Total 2015 Supply} + \text{Climate Damage Cost}}$$

Where the climate damage cost was provided for each year, region, and GCM by CCI, and the total 2015 supply is the economic value of all goods produced by that industry in the balanced 2015 supply-use table in the model[4].

The result is that the affected sectors (electricity distribution, rail, trucking freight, and other transportation) require a certain amount more of all their productive inputs (labour, machinery, construction supplies) to produce one unit of output.

3.10. Hydroelectric Generation

Increased or decreased rainfall due to climate change may increase river flows, increasing productivity of Canada's hydroelectric dams. This increased generation would displace more costly thermal generation and result in incremental reductions to electricity supply cost.

Data Inputs

CCI worked with Industrial Economics to generate preliminary estimates of potential future hydroelectric generation from existing hydroelectric assets, measured in terawatt-hours.

Table 12: CCI Data Input Disaggregation for Hydroelectric Generation

Adaptation data available	No. Hydroelectric generation was not included in the adaptation scenarios.
Regional disaggregation	Yes.
Climate model disaggregation	Yes.

[4] In some cases, the balanced supply-use table used in the model differs slightly from the tables published by Statistics Canada in order to align consumption of energy commodities with emissions in Canada's National Inventory Reports. This results in some industries being slightly larger or smaller in our model, or more fuel-intensive, than the published estimates from Statistics Canada. During this process, certain sectors (such as Statistics Canada "Electric power generation, transmission and distribution") are further disaggregated for use in our model (into thermal electricity generation, hydroelectric generation, and electricity distribution as separate sectors).

Modeling Approach

Similar to electricity infrastructure and rail damages discussed above, increased hydroelectric generation was modeled as a productivity increase to the sector, meaning slightly less capital, labour, and other inputs were required for each terawatt-hour of generation. This allowed the sector to generate more electricity with a fixed supply of capital and resources (existing dams).

3.11. Road Damages

Climate change is expected to increase costs for road repair in Canada due to increased events of extreme heat causing cracking, increased precipitation causing erosion, and freeze-thaw cycles damaging road surfaces.

Data Inputs

CCI worked with Industrial Economics to generate estimates of potential future climate-induced costs in millions of 2015 Canadian dollars, reflective of changes to costs on Canada's 2015 road network.

Table 13: CCI Data Input Disaggregation for Road Damages

Adaptation data available	Yes.
Regional disaggregation	Yes.
Climate model disaggregation	Yes.

Modeling Approach

Road damage costs were modeled using the same method as storm damages to government infrastructure (described in Section 3.6 above). This includes increased expenditures on construction services funded by increased personal and corporate income taxes.

3.12. Heat- and Air Quality-Related Deaths

Increased extreme heat events and increased smog due to warmer weather are expected to result in premature deaths attributable to climate change. Quantifying the "cost" of having community members pass away is an ethically complicated economic question. In this study, we have focussed on the direct economic impacts including reduced labour force participation.

Premature deaths will always result in non-monetary costs; loss of life is a tragedy that of which a person's forgone hours of productive labour is certainly not the largest component. The economic impacts presented in this study do not include any estimate of these emotional costs to people's welfare.

Data Inputs

CCI worked with ESSA to generate estimates of monetized deaths using an estimated increased number of premature deaths multiplied by a lifetime earnings of $750k, adjusted upwards in future years to account for expected growth to real earnings. This is a human capital approach to valuation and is commensurate with macroeconomic modeling.

Table 14: CCI Data Input Disaggregation for Premature Deaths

Adaptation data available	No. The health adaptation scenario did not consider reductions in premature deaths.
Regional disaggregation	Yes.
Climate model disaggregation	Yes.

Modeling Approach

In gTech, households are endowed with a certain quantity of labour, which grows in each year to reflect increases to population and worker productivity. The monetized value of premature deaths due to climate change was subtracted from this labour endowment in each year, assumed to be evenly distributed across skill levels (an equal percent reduction in the high-skilled and low-skilled labour that can be provided in each province).

3.13. Healthcare Spending

Data Inputs

Hospitalization and health care expenditures due to extreme heat events are expected to increase with climate change. CCI worked with ESSA to generate estimates for incremental healthcare costs due to climate change-induced heat, air quality, and Lyme disease illness, measured in millions of 2015 Canadian dollars on Canada's 2015 population.

Table 15: CCI Data Input Disaggregation for Healthcare Spending

Adaptation data available	No. The health adaptation scenario did not consider reductions in health care demand or spending.
Regional disaggregation	Yes.
Climate model disaggregation	Yes.

Modeling Approach

Like storms and road damages, incremental healthcare costs were funded by increases to personal and corporate income taxes. All spending was assumed to be on services (health services are aggregated with the rest of the service sector in gTech).

4. Approach to Scaling Damages

For each climate damage or benefit simulated in our model, CCI provided raw data inputs for how expected changes to the climate in each scenario would impose a cost or benefit on Canada's 2015 economy. For example, raw inputs for road damages reflect the cost that the weather of the 2090s would impose on Canada's 2015 road network, raw inputs for labour effects reflect what fraction of 2015's hours-worked would be lost due to heat events, etc. A key methodological decision was how to interpret these numbers and scale them up over time, as Canada will have more roads in the future, more buildings, and more workers.

The areas of climate impacts examined in this project can be grouped into two classes based on how we modeled them: productivity changes and direct expenditures on a good or service. Productivity changes were impacts expected to grow or shrink with a certain sector of the economy in the model (like the value of road delays growing with the size of the transportation sector). The second category, direct expenditures, are areas where money is being spent on a defined capital asset (like buildings or roads).

Impacts Modeled as Productivity Changes

For certain impact areas, like agriculture, raw data inputs were changes to industry productivity for certain outputs. These were used as-is.

For impact areas affecting a specific industry where total costs (in dollars, rather than percent) was provided, we calculated the equivalent productivity reduction using the total supply from the balanced supply-use table used in the model and the formula below.

$$\text{Productivity Reduction (\%)} = \frac{\text{Climate Damage Cost}}{\text{Total 2015 Supply} + \text{Climate Damage Cost}}$$

For example, if total output from trucking freight and other transportation services was \$10 billion in 2015, and CCI estimated that road delays would cost \$100M due to weather events with 2095's climate, this was modeled as a 1% reduction in the industry's productivity. As the economy grows in the model, this cost to the industry would be endogenously scaled up – the 1% productivity reduction would be worth \$200-300M in the second half of the century as the economy grows by a factor of 2 to 3 relative to 2015. The list of the climate impact areas modeled as productivity/intensity changes is provided in Table 16.

Table 16: Climate Impacts Modeled as Productivity Increases and Decreases

Impact area provided by CCI	Primary direction of effect	Scaled in the model using:
Agriculture	+	Canola, soy, corn, wheat, and other crop sector output
Forestry[5]	–	Forestry sector output
Labour[6]	–	Labour demand in affected industries
Electricity Demand	–	Household heating/cooling load in the reference case
Electricity Infrastructure	–	Electricity distribution sector output
Electricity Generation	+	Hydroelectric sector output
Rail damages and delay	–	Rail freight sector output
Road delay	–	Truck transportation and other transportation sector outputs
Tourism[7]	+	Final demand in the United States

For these nine impacts areas, CCI's data inputs were used to calculate a percent reduction or increase in the industry's productivity. As the industries grow from 2015-2095 in the CGE model, the climate damage costs grow at a rate corresponding to the growth rate of the industry.

Impacts Modeled as Direct Capital/Operating Expenditures

Certain climate damages provided by CCI, like those to roads and buildings, reflect repair and maintenance spending on public goods, households, of infrastructure shared by many economic sectors. These damages were scaled up using ranges of plausible growth for increases to asset values for the affected asset types. Because CCI's inputs reflect costs to Canada's 2015 capital stock, these values need to change year-to-year in the model, not just with the severity of climate damages, but also with

[5] Forestry is distinct from the other impacts in this grouping in that the availability of raw resources (trees) was reduced, limiting sector output. This goes a step further from purely an adjustment to productivity. Considering the labour impacts as an example, the construction sector could still increase output from the reference case, the productivity adjustment would simply require a certain amount more labour (due to heat events and lost hours) to achieve a given output.

[6] Included productivity reductions due to weather events and labour supply reductions due to premature deaths.

[7] Tourism was included as an increase to the amount of Canada's tourism-related exports consumed in the United States, as a proxy for international tourists.

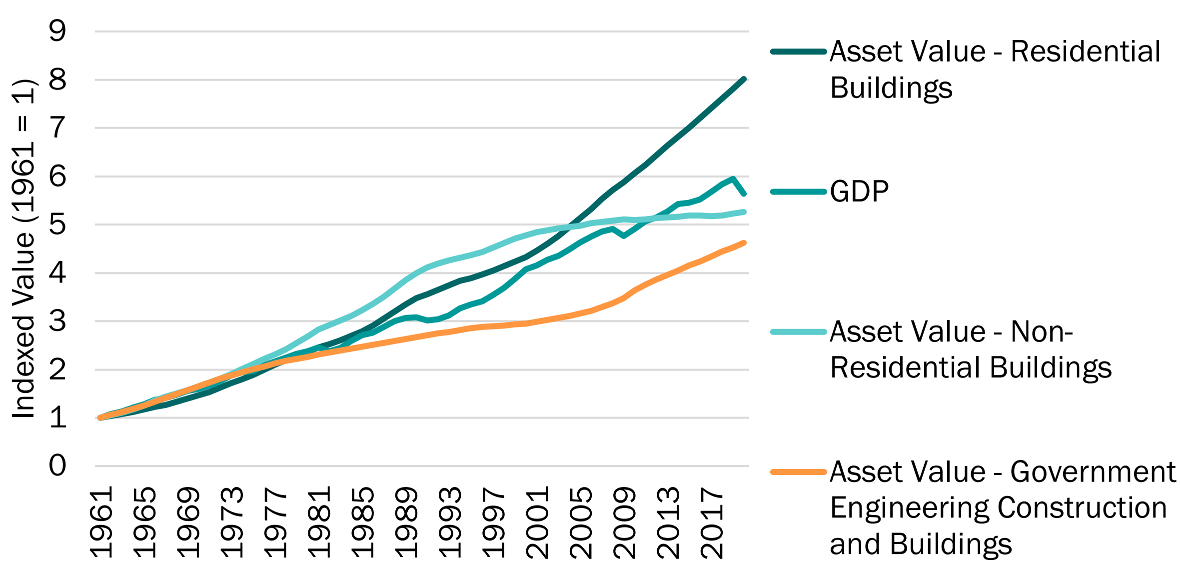
the quantity of capital stock available to be damaged. The climate damages that reflect direct expenditures on certain goods are shown in Table 17 below.

Table 17: Climate Damages Scaled with Asset Values

Damage area	CCI climate damage inputs aggregated in this category	Spending category
Residential buildings	Storms, flooding, and permafrost	Construction
Non-residential buildings	Storms and flooding	Construction
Government spending funded by taxes	Storms, road damage and permafrost	Construction
Government spending funded by taxes	Health care costs associated with extreme heat	Services

Historically, assets that would be affected by climate damages have increased in value with the size of the economy, but not uniformly so. A comparison of residential, commercial, and government capital stocks with historic GDP is shown in Figure 1 below.

Figure 1: Comparing the Size of the Canadian Economy and Capital Stocks



Growth rates in capital stocks compared to the overall size of the economy have varied since 1961 with the macroeconomic era, technological change (businesses now invest a higher fraction in computers compared to 1961), and the political era (e.g., level of deficit spending). Reasonably consistently, increases to the value of residential buildings have outpaced economic growth as people purchase nicer homes with higher incomes. Capital stocks of non-residential buildings and government assets have grown faster than the economy in some periods of high investment, and slower in others. Similarly, the comparison of growth rates varies even more at the provincial level with historic industrial development, real estate cycles, and changes to provincial government spending.

How asset values susceptible to damage by weather events might grow over the coming eight decades is highly uncertain but an important assumption for how weather events could affect the economy. If the capital stocks susceptible to damage that require replacement are large compared to economic output, economic impacts will be large. If capital stocks are smaller compared to economic output because of technological change, economic impacts of replacing vulnerable capital stocks will be smaller.

To reflect this uncertainty, we have scaled damages on buildings and roads by a range of plausible values for how these assets may grow compared to the modeled economy. A time series regression was performed on Canada's historic data from 1961 to present to estimate how a percent change in GDP has historically related to a percent change in residential, commercial, and government asset values. The 95th percentile high and low confidence interval were used for the low and high "bookends" for a sensitivity analysis.

Table 18: Sensitivity analysis for growth in infrastructure climate damages: percent changes in damageable asset value for a percent change in regional GDP

Damage type	Low-growth scenario	Reference-growth scenario	High-growth scenario
Residential buildings	1.20	1.27	1.34
Non-residential buildings	0.94	1.04	1.14

Government spending funded by higher taxes	0.62	0.69	0.76

For example, the model does contain expenditures on residential buildings that grow with time and the size of the economy. However, CCI identified that the model's endogenous growth of housing stock likely understates the growth of housing asset values; the dynamic of people buying more luxurious homes as incomes rise is not fully reflected in the model. Housing stock growth is generally slower than GDP in the model, but historic asset appreciation is faster. To account for this, an adjustment to climate damages was made above-and-beyond the increase to housing stock in the model in order to align growth in climate damages slightly above GDP growth from the previous 10-year period, because historically residential buildings have appreciated at 1.2x the rate of GDP.

5. Limitations

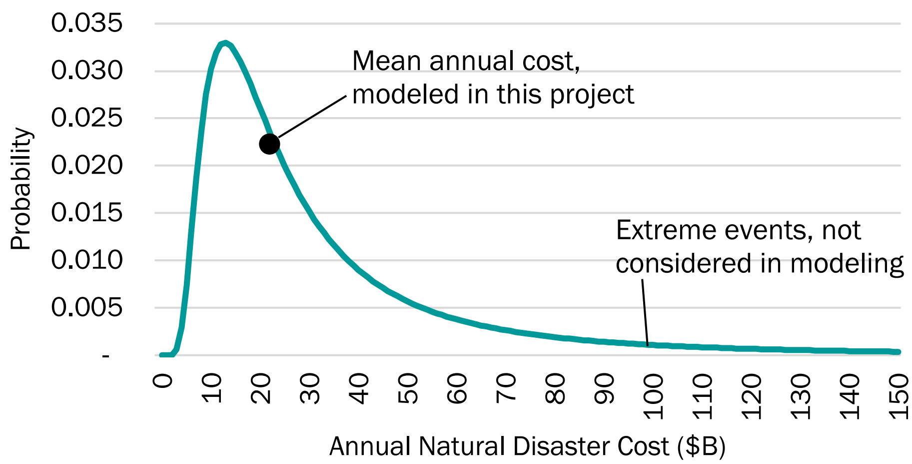
This section discusses key uncertainties and limitations of the modeling approach.

Randomness of Climate Disasters

This project took a deterministic approach to assessing the economic impact of climate disasters within each climate scenario. For each impact area, our model inputs were expected annual costs, estimated using precipitation and temperature outputs from climate models. We did not model the economic impacts of possible catastrophic events or the possibility of years with no disasters at all.

A simplified depiction of this dynamic is shown in Figure 2 below. In a majority of years, the disaster cost will be less than the mean value considered in our modeling, with more modest economic impacts. In a small minority of years, the cost could be many times larger. Conducting stochastic modeling that includes variation in annual storm costs is a strongly suggested area for future work.

Figure 2: Illustrative distribution for storm damages

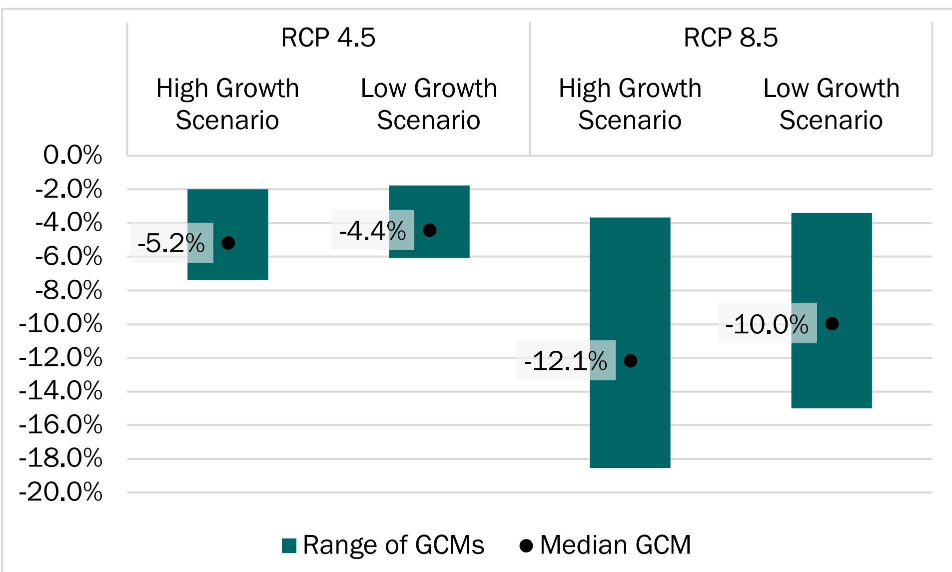


Growth in Climate Damages

A major uncertainty in our methodology is the approach to increasing climate damages with the size of the economy. Across all climate impacts considered in this project, CCI worked with other contractors to estimate how expected future weather would pose a cost (or benefit) to Canada's 2015 infrastructure and population. For example, road repair costs are based on the known kilometers of roads that existed in 2015 and building repair costs are based on the stock of 2015 buildings. To fully capture how these impacts would affect the economy, we need to estimate growth in roads, buildings, and other assets subject to damage.

Different asset classes with different susceptibility to climate damages will grow more or less rapidly than GDP. We relied on how buildings and engineering construction-type assets (e.g., roads) have historically appreciated relative to GDP growth in Canada to scale up climate damages endogenously within the model. As GDP in the model grows, damages were scaled up to reflect plausible ranges of asset appreciations associated with that level of GDP growth (discussed in Section 4 above). Due to the uncertainty as to how assets susceptible to damage will grow, we performed a sensitivity analysis. A comparison of the "High Damage Growth" and "Low Damage Growth" outputs are shown below.

Figure 3: Sensitivity of GDP Effect to Assumption about Growth in Damageable Asset Value



There is further uncertainty in the degree to which appreciation of assets due to economic growth will translate to increased climate damages. Repairing a flooded luxury house will certainly cost more than repairing a simple one. However – especially for multi-story buildings – the link between overall asset value and repair cost would not be one-to-one.

Uncertainty in Climate Damages

Incorporating uncertainty for how economic variables may be affected by a given change to weather is an area for future work.

We view there to be effectively three layers of uncertainty in how climate change may affect the Canadian economy. First, there is uncertainty in how severe climate change will be globally. This project has addressed this via modeling both RCP4.5 and RCP8.5 scenarios.

Second, there is uncertainty in how average changes to global radiative forcing will affect Canadian precipitation and temperature. We have addressed this via using inputs from seven different climate models.

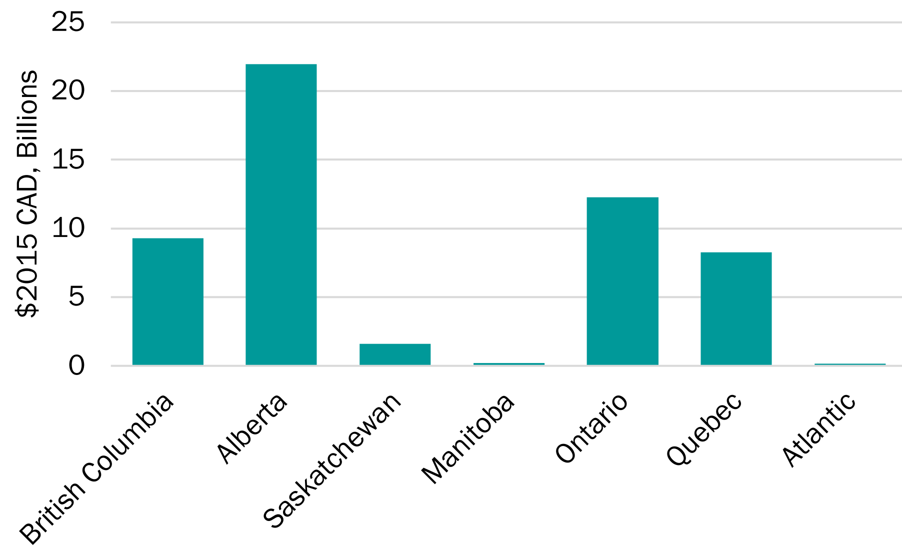
Third, there is potentially quite large uncertainty in how a given change to temperature and precipitation will translate into economic impacts. This uncertainty has generally not been incorporated in the modeling. For each impact area, the uncertainty is likely large for the effect of a given GCM's temperature change on productivity. In this project, confidence intervals were not available for cost estimates for all impact areas with the exception of labour productivity. Developing confidence intervals for cost estimates for a single GCM and evaluating how these high and low bounds affect results is an area for future study.

Interprovincial and International Migration

Changes to Canada's population and the regional distribution of labour were not considered as a climate impact in this analysis. Incorporating the ability of people to move in response to climate changes and associated economic activity would likely mute macroeconomic impacts.

For an example, consider the magnitude of the storm damages in Alberta in the 2090s in the RCP 8.5 scenario. Estimates for annual storm damages range in the climate models to between $1.7B and $47B per year, with an average of $22B, representing what damages would be to the 2015 stock of buildings, roads, and other assets. This results in economic impacts which are highly regionally concentrated, with long-term economic impacts potentially large enough to spur out-of-province migration. Incorporating this into the model would likely result in lower national and per-capita GDP impacts, but larger regional effects.

Figure 4: Annual Storm Damages to 2015 Capital Stocks in 2090s, RCP 8.5 Average



Similarly, the economic impact of international migration into Canada due to climate change was not included in this analysis.

Impacts on Trade

The potential for climate damages to restrict the physical flow of goods between regions was not considered in this analysis. Incorporating these risks would increase economic impacts of road and rail damages, flooding, and storms.

The economic impact of damages to transportation infrastructure was reflected as a repair cost, borne by government, and a productivity impact for the freight transportation sector. While the result of the productivity reduction would be higher prices for transportation services, recovered from industries that ship goods, this approach does not physically restrict the ability for goods to flow between regions, as would temporarily be the case following a disaster.

Unquantified and Non-Economic Impacts

Finally, this project only considered the areas of climate impacts of which we are aware and can reasonably be quantified from an economic perspective. Unknown climate impacts that scientists have not yet discovered, global conflict, non-financial costs to ecosystems and animals, and impacts to Canadian emotional wellbeing are not within the scope of our analysis.

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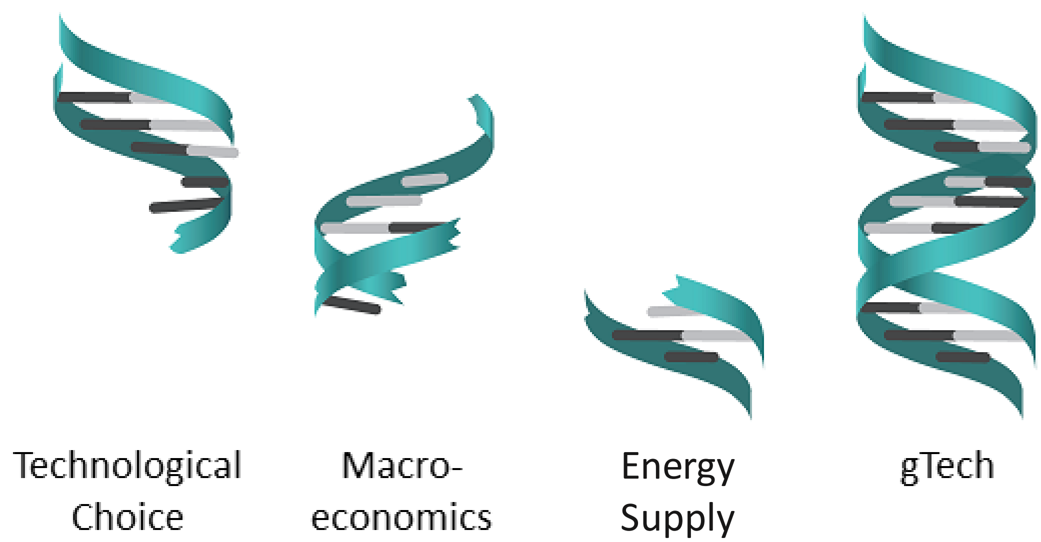
Appendix: Model Background

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 greenhouse gas emissions;
- An exhaustive accounting of the economy at large, including how 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 5. 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.

Understanding 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 19.

Table 19. 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 is likely to 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 labor 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 80 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.
Labor and capital markets	Labor and capital markets must also achieve equilibrium in the model. The availability of labor 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 labor 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 province in the model interacts with other regions via (1) the trade of goods and services, (2) capital movements, (3) government taxation and (4) various types of "transfers" between regions (e.g., the federal government provides transfers to provincial and territorial governments). The version of gTech used for this project accounts for the 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.

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

Dynamic	Description
Households	On one hand, households earn income from the economy at large. On the other, households use this income to consume different goods and services. gTech accounts for each of these dynamics, and how either change with policy.

Simulating technological choice

Technological choice is one of the most critical decisions that influence greenhouse gas 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 200 technologies across more than 50 end-uses (e.g., light-duty vehicle travel, residential space heating, industrial process heat, management of agricultural manure).

Naturally, technological choice is influenced by many factors. Table 20 summarizes key factors that influence technological choice and the extent to which these factors are included in gTech.

Table 20. 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 are fixed, but the price for energy is determined by the model. The method of "solving" for energy prices is discussed in more detail below.

Criteria	Description
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 significantly higher rates.[9] The implication is that using a financial discount rate would overvalue future savings relative to revealed behaviour and provide a poor forecast of household and firm decisions.
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[10]. gTech quantifies these technology-specific preferences as "non-financial" costs, which are added to the technology choice algorithm.
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[11]. As a technology becomes increasingly costly relative to its alternatives, that technology earns less market share.

[9] 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.

[10] 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.

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

Criteria	Description
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[12]. 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. gTech simulates the combined effects of all these policies implemented together.

Understanding 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.

gTech: 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.

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

First, gTech can provide insights related to technological change by answering questions such as:

- How do policies affect technological adoption (e.g., how many electric vehicles are likely to be on the road in 2030)?
- How does technological adoption affect greenhouse gas emissions and energy consumption?

Second, gTech can provide insights related to macroeconomics by answering questions such as:

- How do policies affect national and provincial gross domestic product?
- How do policies affect individual sectors of the economy?
- Are households affected by the policy?
- Does the policy affect energy prices or any other price in the model (e.g., food prices)?

Third, gTech answers questions related to its energy supply modules:

- Will a policy generate more supply of renewable fuels?
- Does policy affect the cost of transporting refined petroleum products, and therefore the price of gasoline in Canada?

Finally, gTech expands our insights into areas where there is overlap between its various features:

- What is the effect of investing carbon revenue into low- and zero-carbon technologies? This question can only be answered with a model like gTech.
- What are the macroeconomic impacts of technology-focused policies (e.g., how might a zero-emissions vehicle standard impact GDP)?
- Do biofuels-focused policies affect (1) technological choice and (2) the macroeconomy?

This modeling toolkit allows for a comprehensive examination of the impacts of Canada's net-zero emission pathways.