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Health-related impacts of decarbonization in Canada

An evaluation of the air pollution, health and economic impacts of achieving net-zero emissions

SUBMITTED TO

Canadian Association of Physicians for the Environment
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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. They 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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1. Introduction

Under the Paris Agreement, Canada has committed to reduce its greenhouse gas (GHG) emissions by 30% below 2005 levels by 2030, and the federal government has announced the goal of achieving net-zero GHG emissions by 2050.[1] Net-zero is achieved when anthropogenic GHGs 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 Association of Physicians for the Environment (CAPE) is an organization of health professionals working to educate on issues of health and the environment. CAPE is undertaking a report on fiscal stimulus spending to support decarbonization of Canada's economy, including the air pollution, health and economic impacts of achieving Canada's 2030 emissions reduction target and 2050 net-zero emissions goal.

This study aims to explore a potential net-zero emissions scenario for Canada that achieves these targets, and to quantify the associated air pollution, health and economic impacts of this scenario as compared to a reference case scenario.

This report is structured as follows:

- Chapter 2 outlines the two scenarios forecasted (reference case and net-zero).
- Chapter 3 summarizes how Canada's air pollution, including key criteria air contaminants, may change through 2050 under net-zero GHG emissions.
- Chapter 4 summarizes the associated health impacts of air pollution changes.
- Chapter 5 summarizes the key economic impacts of a net-zero policy scenario, including quantification of the clean economy.

Additional information about the modelling methodology used for this analysis is provided in the appendices.

[1] Environment and Climate Change Canada. December 16, 2019. "Canada advanced climate action and remains committed to ambitious global action as United national Climate Change Conference concludes". Available at: https://www.canada.ca/en/environment-climate-change/news/2019/12/canada-advanced-climate-action-and-remains-committed-to-ambitious-global-action-as-united-nations-climate-change-conference-concludes.html

2. Forecast scenarios

Two scenarios were forecast for this analysis – a reference case scenario and a net-zero policy scenario. The energy-economy model gTech was used to simulate these two potential pathways for Canada out to 2050. More details about gTech and the modelling methodology used for this analysis can be found in the appendices.

Reference case scenario

A reference case scenario is a forecast of Canada's future under all currently implemented policies and planned policies that have been publicly announced.

To characterize Canada's energy-economy, the reference case is calibrated to a large variety of data sources. GDP and labour force growth forecasts are calibrated to the Parliamentary Budget Office.[2] Historical greenhouse gas emissions are calibrated to Environment and Climate Change Canada's National Inventory Report.[3] Moving forward, modeled emissions are also calibrated to align with historical trends. The ability of the model to replicate historical trends improves our confidence in projections moving forward.

The reference case scenario used in this analysis shows GHG emissions decreasing slightly out to 2030 under existing and planned policy but maintaining relatively flat out to 2050 (Figure 1).

Net-zero scenario

Development of the net-zero policy scenario in this analysis was intended to be policy agnostic, with the only implemented "policy" being a cap on emissions at net-zero in 2050. This provides a vision of one potential net-zero scenario for Canada, including emission, energy, technology and economic outcomes.

To achieve net-zero emissions in 2050, several different abatement options are available in each sector. Abatement options are implemented based on what is behaviourally realistic, technologically available, and most cost effective over time to achieve the required reduction in emissions. These options range from sector

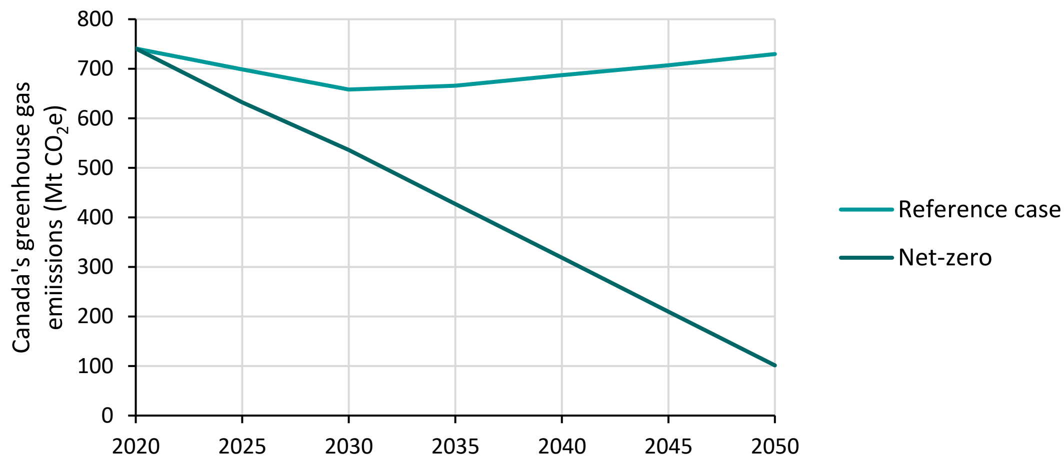
[2] Parliamentary Budget Office, 2020 Fiscal Sustainability Report. Available from: https://www.pbo-dpb.gc.ca/en/blog/news/RP-1920-029-S-fiscal-sustainability-report-2020-rapport-viabilite-financiere-2020

[3] 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

and production changes, to mode, fuel and technology shifting, to income, preference and behavioural changes.

The net-zero policy scenario modeled in this analysis shows GHG emissions decreasing steadily out to Canada's 2030 emission reduction target (30% below 2005 levels by 2030), and further to achieve net-zero emissions in 2050.

Figure 1: Canada's greenhouse gas emissions[4]



Source: Navius Research, gTech model

Some key assumptions used in the simulation of these scenarios include:

- The cost and availability of several key technologies including electric vehicles, biofuels, hydrogen, and carbon capture and storage. Navius' technology database simulates the cost and availability of a wide variety of technologies available to decarbonize the Canadian economy. These technologies are characterized based on the best available information and literature, as well as expert consultation.
- Canada's reference case economic and labour growth is based on the Parliamentary Budget Office's Fiscal Sustainability Report[5]. GDP by sector is

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[4] The scenarios modeled for this analysis, and presented in this figure, exclude sequestration from land-use, land use change and forestry (LULUCF) and Western Climate Initiative (WCI) emission credits. These were excluded for the purpose of this analysis, which is to evaluate the air pollution and health impacts of a net-zero policy scenario for Canada. LULUCF has little effect on air pollution and most WCI credits represent a reduction in air pollution in California, and therefore any health benefits will be incurred in California. When these two sources of emissions reductions are included in the reference case scenario, WCI credits reduce emissions by 10Mt in 2030 and 4Mt in 2050 and LULUCF reduces emissions by an additional 24Mt in 2030 and 2050 (based on Environment and Climate Change Canada estimates). The net-zero policy scenario assumes 100Mt of additional emission reductions in 2050 due to LULUCF, as explained on the next page. This is the reason why the net-zero policy scenario reaches 100Mt rather than 0Mt in 2050 in this figure.

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).

- Global oil and gas prices were assumed to be the same as in the reference case scenario and are based on US WTI (oil) and Henry Hub (natural gas) prices. Oil prices increase from $52.5/barrel (USD 2015) in 2020 to $79.39/barrel (USD 2015) in 2050. Natural gas prices increase from $2.5/mmBTU (USD 2015) in 2020 to $4.1/mmBTU (USD 2015) in 2050.

- Mitigation potential from land-use, land-use change and forestry are not explicitly modeled in this analysis. Instead, an assumed fixed amount of emission offsets is available in 2050 from land-use and forestry measures. The size of this potential offset was calculated based on literature review and expert consultation to be 100 million tonnes of carbon dioxide equivalents in 2050. This estimate is based on reduction potentials of afforestation[6], forest management[7], and agriculture[8], [9]. The reduction potential of other land uses, such as wetlands, was excluded.

- Non-GHG air pollution projections were calibrated to be consistent with emissions reported by the National Pollutant Release Inventory[10] and align nationwide within 3% of all pollutant emissions reported in this inventory. More details about the assumptions and limitations of this air pollutant forecast are provided in Appendix B.

- Human health impacts of a net-zero climate policy scenario were simulated using Health Canada's Air Quality Benefits Assessment Tool (AQBAT).[11] Further details about this model and assumptions made to quantify health impacts are provided in Appendix C.

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[5] 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
[6] Stephens (2000) Afforestation potential in Canada: A spatial analysis of economic land suitability with carbon sequestration benefits.
[7] Lemprière et al (2017) Cost of climate change mitigation in Canada's forest sector.
[8] ECCC (2016) Specific Mitigation Opportunities Working Group for agriculture
[9] Fan et al. (2019) Increasing crop yields and root input make Canadian farmland a large carbon sink
[10] Government of Canada. (2020). National Pollutant Release Inventory. Available at: https://www.canada.ca/en/services/environment/pollution-waste-management/national-pollutant-release-inventory.html
[11] Health Canada. (2017). Air Quality Benefits Assessment Tool. Available at: https://www.science.gc.ca/eic/site/063.nsf/eng/h_97170.html

3. Air pollution impacts

Criteria air contaminants (CACs) are a set of common air pollutants known to cause negative human health impacts. They are mainly emitted by fossil fuel combustion, but also arise from non-fuel related sources such as the interaction between vehicle tires and roads, industrial processes like the grinding of limestone in the cement sector, as well as from non-anthropogenic sources such as forest fires.

This study quantified the anthropogenic sources of CACs and how they are expected to change over time. Under a net-zero GHG emissions scenario, CAC emissions are expected to decline as a result of a reduction in fossil fuel combustion through, for example, technology and fuel switching, efficiency gains, changes in sector output, or changes in industrial processes.

The CACs explored in this study include the following:

- Nitrogen oxides (NOx) are produced during fossil fuel combustion. NO_2 is a primary contributing pollutant to the formation of ground level ozone.
- Sulphur oxides (SOx) are also produced during fossil fuel combustion from smelters, power plants, refineries and internal combustion engine vehicles.
- Particulate matter (PM10 and PM2.5) are airborne particles in solid or liquid form and include dust from roads and fugitive dust from construction and mining. They are categorized by size, which largely determines the extent of environmental and health damage. PM10 is particulate matter with a mass median diameter less than 10 microns and PM2.5 is less than 2.5 microns.
- Volatile organic compounds (VOCs) are carbon-containing gases and fumes such as gasoline fumes and solvents which come from the transportation sector, industrial processes and residential wood burning. VOCs are a primary contributing pollutant to the formation of ground level ozone.
- Carbon monoxide (CO) is produced by incomplete combustion of fuels and is mainly released from the tailpipes of internal combustion engine vehicles.
- Ammonia (NH_3) is emitted from livestock waste management and fertilizer production in the agricultural sector.

In a scenario where Canada achieves net-zero GHG emissions in 2050, all CAC emissions decrease out to 2050. Some pollutants, such as NOx, SOx and CO, decrease more than others under net-zero climate policy. This is due to a reduction in fossil fuel combustion as the transportation sector switches over to electric vehicles and as the activity of certain sectors, such as oil and gas production, is reduced over time. CACs that are emitted mainly from sources other than fossil fuel combustion, such as PM and NH_3, show less of a decrease over time under net-zero climate policy, as their main sources of emissions such as construction, road dust and agricultural processes remain.

The projected change in CAC emissions from 2015 levels in 2050 is presented in Figure 2 for both scenarios. Figure 3 presents the projected change in CAC emissions in the net-zero policy scenario compared to reference case emissions in 2030 and 2050.

Figure 2: Change in air pollutant emissions from 2015 levels in 2050

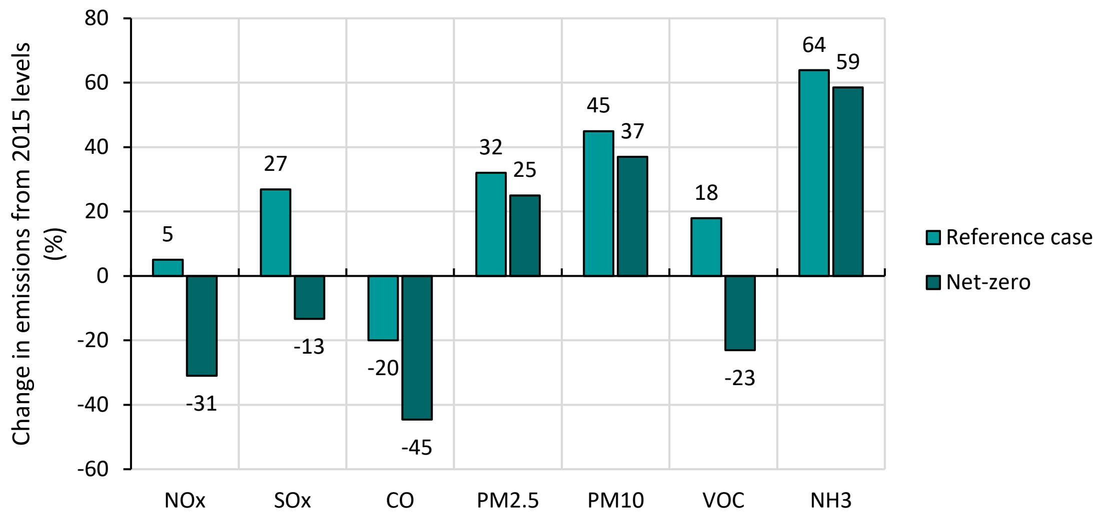
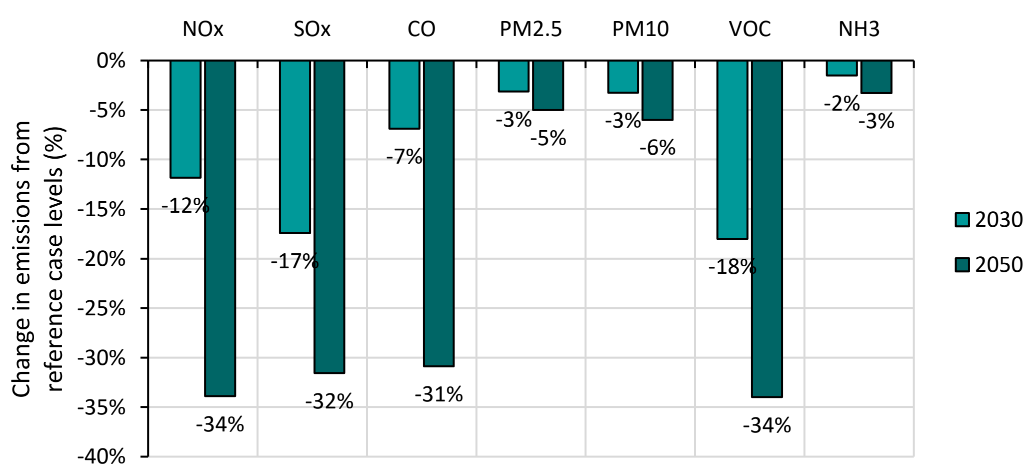


Figure 3: Change in air pollutant emissions under net-zero policy compared to reference case levels



4. Health impacts

All air pollutants quantified in Chapter 3 are known to have harmful impacts on human health. A reduction in emissions of these pollutants under net-zero climate policy is therefore expected to result in positive health impacts for Canadians. These health impacts were quantified in this analysis using Health Canada's AQBAT model.[12] More detail about this model and the quantification of health impacts can be found in Appendix C.

In a scenario where Canada achieves net-zero GHG emissions in 2050, the associated reduction in CAC emissions leads to significant health benefits, including reductions in premature mortalities due to chronic or acute exposure. Table 1 summarizes the health benefits under a net-zero policy scenario compared to the reference case. Results show that reductions in CAC emissions lead to $30.5-100.1 billion ($2015) in avoided costs (based on valuation of all health endpoints by Health Canada, including mortalities, hospital emissions, emergency room visits, and illnesses, symptoms and poor air quality restricted days) and 5,687-11,118 avoided premature mortalities in 2050. This is a mean cumulative impact of 112,081 (90% confidence interval: 75,839 – 148,466) lives saved from air-pollution related mortalities between 2030 and 2050 under net-zero climate policy.

Table 1: Avoided health impacts under net-zero climate policy relative to reference case[13]

	2030		2040		2050	
	Mean	**90% CI**	**Mean**	**90% CI**	**Mean**	**90% CI**
Cost (billion 2015 $)	16.1	7.8 - 25.5	42.6	20.6 - 67.5	63.1	30.5 - 100.1
Chronic and acute mortalities (number/year)	2,136	1,451 - 2,823	5,655	3,820 - 7,496	8,397	5,687 - 11,118
Hospital admissions (number/year)	436	218 - 651	1,150	572 - 1,722	1,800	871 - 2,720
Emergency room visits (number/year)	1,647	803 - 2,482	4,007	1,971 - 6,020	6,038	2,914 - 9,123

12 Health Canada. (2017). Air Quality Benefits Assessment Tool. Available at: https://www.science.gc.ca/eic/site/063.nsf/eng/h_97170.html

13 90% CI means that there is a 90% probability the value is within this confidence interval.

5. Economic impacts

Key economic impacts of a net-zero emission scenario are provided in this chapter. The “clean” portion of the economy has also been quantified. Clean gross domestic product (GDP) and employment are attributed to one of three categories:

- Direct - This category includes GDP and employment of (1) sectors producing clean energy services (e.g., renewable electricity generation and transit) and (2) value-added associated with the use of clean technologies in other sectors. For example, an electric vehicle may be used to provide courier services. Likewise, a clean building may be used to provide real estate services.
- Construction and services - This category includes construction and services required to install a given clean energy technology.
- Manufacturing - This category includes any manufacturing value-added (e.g. manufacturing an electric vehicle, if it occurs in Canada).

Clean investment is defined in this study as:

- Any investment into a sector that produces clean energy services. These sectors include renewable electricity generation, nuclear electricity generation, electricity transmission and distribution, bioenergy supply, transit and rail.
- Investment into a technology or process determined to be clean. These technologies 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”.

The methodology used to quantify the clean economy in this analysis builds on a 2019 analysis completed for Clean Energy Canada[14,15].

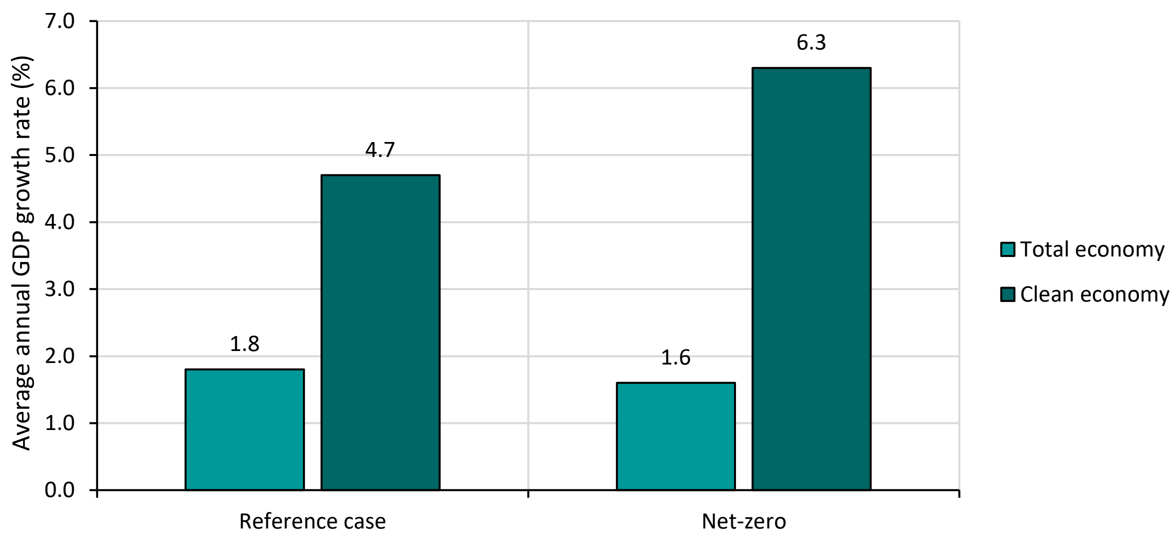
[14] Note that a more restrictive definition of clean jobs has been used in this analysis compared to the 2019 study. This analysis also uses updated data and assumptions.

[15] Navius Research (2019). Quantifying Canada’s clean energy economy. Available at: https://www.naviusresearch.com/publications/clean-energy-economy/

GDP

A common way of measuring economic activity is GDP. GDP is the value of goods and services produced in a given region over the course of the year. Figure 4 presents average annual GDP growth rates for the reference case and net-zero policy scenarios. When Canada achieves net-zero emissions in 2050, GDP grows at an average annual rate of 1.6%. Clean GDP rises from $45.8 billion (2015$) in 2020 to $286.4 billion (2015$) in 2050 in this scenario, reflecting an average annual growth rate of 6.3%.

Figure 4: Canada's average annual GDP growth rate from 2020 to 2050

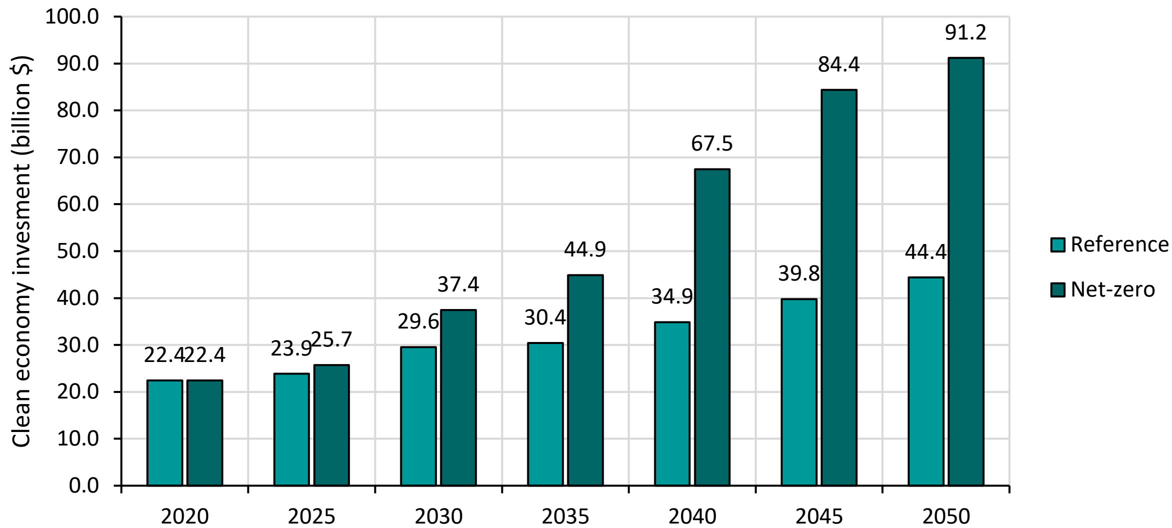


Note that these estimates do not reflect the potential costs of climate change (e.g. flooding) or the potential benefit from global climate mitigation efforts (e.g. reduced flooding).

Investment

Clean investment increases from 2020 to 2050 in both the reference and net-zero policy scenarios, although more significantly in the net-zero scenario. In this scenario, investment in the clean economy increases from $22.4 billion (CAD 2015) in 2020 to $91.2 billion in 2050, compared to clean investment of $44.4 billion in 2050 in the reference case (Figure 5). This is a 3-fold increase in clean investments in the net-zero scenario over this time period, compared to a 1-fold increase in the reference case scenario.

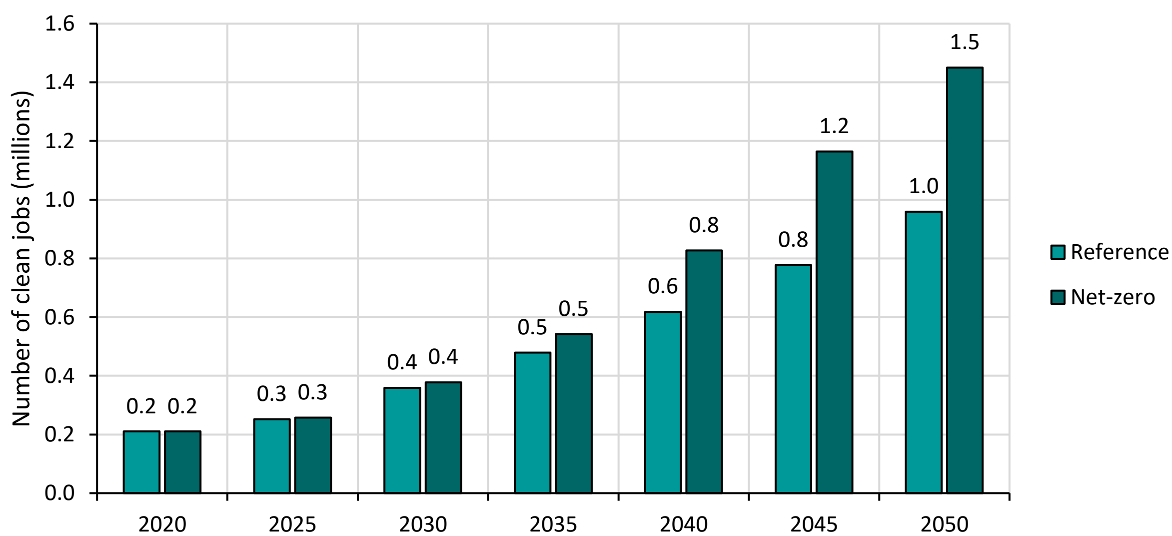
Figure 5: Clean economy investment in Canada



Jobs

In a scenario where Canada achieves net-zero GHG emissions in 2050, total jobs increase from 19.5 million full-time equivalent positions in 2020 to 23.6 million in 2050. Of these, clean jobs increase from 210,000 full-time equivalent positions in 2020 to 1.5 million in 2050 (Figure 6). This corresponds to 500,000 more clean jobs in 2050 in the net-zero scenario than in the reference case scenario.

Figure 6: Number of clean jobs in Canada



Appendix A: Introduction to energy-economy modeling

Canada's energy-economy is complex. Energy consumption, which is the main driver of anthropogenic greenhouse gas 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 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.

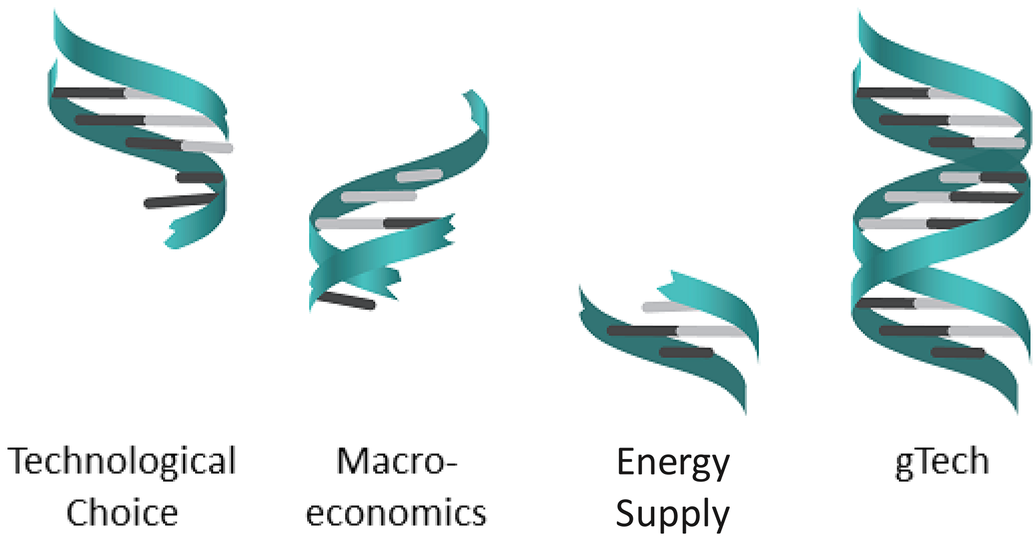
Introduction to gTech

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 7: 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.

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 2 summarizes key factors that influence technological choice and the extent to which these factors are included in gTech.

Table 2: 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.
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.[16] 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.

[16] 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[17]. 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[18]. 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[19]. 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.

[17] 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.

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

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

Criteria	Description
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 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 3.

Table 3: 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[20]. 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).

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

Dynamic	Description
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". Capital markets are introduced in more detail below.
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.
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 changes with policy.

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.

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.

Limits to energy-economy forecasting

Despite using the best available forecasting methods and assumptions, the evolution of our energy economy is uncertain. In particular, forecasting greenhouse gas emissions is subject to two main types of uncertainty.

First, all models are simplified representations of reality. Navius' 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 (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.

However, Navius' tools do not account for every dynamic that will influence technological change. For example, household and firm decisions are influenced by many factors, 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 models 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.

The uncertainties inherent in the forecast presented in the following sections could be examined in detail in the future if desired.

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, greenhouse gas emissions, the economy. The methodology used to incorporate criteria air contaminant forecasts into gTech is provided in Appendix B and the methodology for using gTech forecasts to estimate associated health impacts is provided in Appendix C.

Appendix B: Air pollution modeling methodology

gTech forecasts emissions of non-GHG air pollutants, which change over time and under different policy scenarios due to changes in fuel consumption, technology adoption, and sector activity. The GREET[21] model was used as a source of emission intensity factors for air pollutants and provides emission factors by sector and by fuel type. Since these emission factors are not Canada-specific and only capture CAC emissions from fuel combustion, 2015 pollutant emissions were calibrated to align with Canada's National Pollutant Release Inventory,[22] which includes all sources of CAC emissions.

The criteria air contaminants (CACs) forecasted by gTech include:

- Nitrous oxides (NOx)
- Sulphur oxides (SOx)
- Carbon monoxide (CO)
- Particulate matter (PM2.5 and PM10)
- Volatile organic compounds (VOCs)
- Ammonia (NH_3)

The heavy metal pollutants forecasted by gTech include:

- Cadmium (Cd)
- Mercury (Hg)
- Lead (Pb)

These pollutants are disaggregated in gTech by:

- Pollutant (9 listed above)
- Region (10 Canadian provinces and the territories)

[21] Argonne Research Lab. (2019). GREET Model. Available at: https://greet.es.anl.gov/
[22] Government of Canada. (2020). National Pollutant Release Inventory. Available at: https://www.canada.ca/en/services/environment/pollution-waste-management/national-pollutant-release-inventory.html

- Sector (based on NAICS economic sectors)
- Source (fuel, process, or technology)

There are a few key limitations in the use of an energy-economy model like gTech to forecast air pollutant emissions. The most important is that gTech is not an air dispersion model. The concentration of CACs in the atmosphere depends on geolocation of the emission source, timing of the emissions, interactions between CACs in the atmosphere under certain atmospheric conditions, and dispersion of the pollutants. This means that a reduction in air pollutant emissions in Canada as a result of climate policy will not correlate perfectly to a reduction in the concentration of pollutants in Canada's atmosphere. The CAC emissions forecast by gTech are reported in units of annual average mass by province. The associated health impacts of CAC emissions are dependent on ambient air concentrations at a more granular spatial and temporal resolution. Therefore, the use of gTech outputs to estimate health impacts requires some key simplifying assumptions, which are outlined in Appendix C.

In addition, the quantification of CAC emissions in this analysis may not fully capture the impacts of policy and regulation on the pollutant emission intensities of certain technologies over time. After a review of current policies and regulations expected to impact CAC emissions, the policies that have been captured in this analysis include:

- Tier 3 emission standards for light-duty vehicles[23] , which require a reduction in CAC emissions from vehicles over time.
- Canada's oil and gas sector methane regulations[24], which prevent leaking and venting of some VOCs from the upstream oil and gas sector.

Conservative assumptions were made about other key sources of air contaminants, such as PM emissions from the agricultural sector and VOC emissions from architectural coatings in buildings, which were assumed to decouple from economic growth over time. However, additional policies implemented to address non-GHG air pollution, such as industry, electricity or additional vehicle requirements, are not captured in this analysis, and may lead to a further reduction

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[23] Government of Canada. (2017). Guidance document on Off-Road Compression-Ignition Engine Emission Regulations: chapter 6. Available at: https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/publications/guidance-document-engine-emission-regulations/chapter-6.html

[24] Government of Canada. (2018). Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector). Available at: https://pollution-waste.canada.ca/environmental-protection-registry/regulations/view?Id=146

in CAC emissions. New technologies that may emerge as a result of stricter air quality control regulations are also not captured in this analysis.

Finally, there are some known interactions between climate policy and CAC emissions that have not been captured in this analysis. Increased demand for biofuels, for example, could lead to a reduction in CAC emissions from the agricultural sector as agricultural residue is used to produce biofuels rather than burned. Lower temperatures resulting from increased climate action will also impact CAC emissions, for example by reducing the occurrence of forest fires. The extent of this impact depends on climate policy implementation globally and is therefore highly uncertain. As a result of these missing interactions, and the other limitations discussed above, this analysis likely underestimates the reduction in CAC emissions under net-zero climate policy.

Appendix C: Health impact modeling methodology

To quantify the associated health impacts of the CAC emissions forecasted by gTech, the Air Quality Benefits Assessment Tool (AQBAT) was used. This model was developed by Health Canada to estimate the human health impacts of changes in Canada's ambient air quality. AQBAT includes historical pollutant concentration data, annual baseline health endpoint occurrence rates, and Health Canada endorsed concentration-response functions and health endpoint valuations. It estimates health impacts based on 5 input pollutants (CO, NO_2, O_3, SO_2, PM2.5) and simulates 19 health endpoints, including exposure mortality. It utilizes the @Risk add-in software in Excel to perform Monte Carlo simulations to examine the effects of uncertainties on estimated health impacts. Please see Health Canada's AQBAT documentation for more details about this model. [25]

Health impacts of the net-zero policy scenario compared to the reference case were estimated in AQBAT using the percentage change in air pollutants from 2015 concentrations in the reference case and net-zero policy scenario. The resulting health impact estimates are then based on the difference between the reference case and policy case using default concentration response functions and health endpoint evaluations.

There are some key assumptions made in the estimation of health impacts:

- The biggest assumption made in this analysis is that the change in annual pollutant emissions forecast by gTech are assumed to correspond to a change in concentrations of these pollutants and are applied to each AQBAT census division across each province. In other words, it is assumed that changes in emissions at a provincial level generally equate to changes in pollution concentration at a census division level. The only exception is in Ontario where it is assumed that half of the air pollution concentration relates to emissions in the US[26], which follows a reference case CAC forecast, and in

[25] Health Canada. (2017). Air Quality Benefits Assessment Tool. Available at: https://www.science.gc.ca/eic/site/063.nsf/eng/h_97170.html

[26] Ontario Ministry of Environment, Conservation and Parks. (2010). Where does smog come from? Available at: http://www.airqualityontario.com/science/transboundary.php

Quebec where it is assumed that 16% of air pollution concentration relates to dispersion from Ontario[27], and therefore 8% from the US.

This assumption is important because the health impacts of a given amount of CAC emissions depends on the geolocation of the emission source (i.e., proximity to the population), atmospheric conditions (such as heat and sun, which react with NO_x and VOC to produce O_3, and wind that can disperse or concentrate pollutants), and the time at which emissions occur (for example, air pollution is highest in summer due to the presence of heat and sunlight leading to production of O_3 and secondary PM). All of these factors interact to create episodic events in which air quality levels are poor in densely populated regions and the resulting health impacts are significant. Without the use of an air dispersion model, some of these dynamics have not been captured in this analysis. This means that if most pollution is reduced in densely populated areas under net-zero climate policy, this analysis could underestimate health impacts; if most pollution is reduced in sparsely populated areas, this analysis could overestimate health impacts.

- O_3 is a secondary pollutant formed from VOCs and NO_x and is not simulated directly by gTech. Instead, the change in O_3 concentrations were assumed to be proportional to the change in NO_x and VOC emissions. O_3 concentrations are usually limited by VOC in urban areas and NO_x in other areas. For this reason, O_3 concentrations in the census divisions at the core of Census Metropolitan Areas (which covered 61% of the population) were defined as changes in VOC emissions (which covers 61% of the population). In all other census divisions, changes in O_3 concentrations were defined by changes in annual emissions of NO_x.
- This analysis accounts for impacts of certain pollutants where there is a strong empirical basis for health impacts. There could be further health impacts related to other pollutants (e.g. mercury) or health endpoints (e.g. PM2.5 impact on brain cancer rates) that are not accounted for in these results. This analysis also does not account for the health benefits of lower temperatures as a result of climate action, such as fewer heat stroke days. The extent of this impact depends on climate policy implementation globally and is therefore highly uncertain.

As a result of these assumptions, as well as the CAC emission forecast limitations discussed in Appendix B, there are uncertainties in this methodology that may lead to either overestimation or underestimation of health impacts. Overall, we estimate

[27] Ontario Ministry of the Environment. (2005). Transboundary air pollution in Ontario. Available at: http://www.airqualityontario.com/science/transboundary.php

that this analysis is conservative in its quantification of health impacts as assumptions that may lead to underestimation of health impacts are greater than those that may overestimate impacts.

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