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Transition Scenarios for Analyzing Climate-Related Financial Risk

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MIT Joint Program on the Science and Policy of Global Change combines cutting-edge scientific research with independent policy analysis to provide a solid foundation for the public and private decisions needed to mitigate and adapt to unavoidable global environmental changes. Being data-driven, the Joint Program uses extensive Earth system and economic data and models to produce quantitative analysis and predictions of the risks of climate change and the challenges of limiting human influence on the environment—essential knowledge for the international dialogue toward a global response to climate change.

To this end, the Joint Program brings together an interdisciplinary group from two established MIT research centers: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at

Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the program's work lies MIT's Integrated Global System Model. Through this integrated model, the program seeks to discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This report is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—*Ronald G. Prinn,*
Joint Program Director

Transition Scenarios for Analyzing Climate-Related Financial Risk

Y.-H. Henry Chen¹, Erik Ens², Olivier Gervais², Hossein Hosseini³, Craig Johnston^{3,*}, Serdar Kabaca⁴, Miguel Molico³, Sergey Paltsev¹, Alex Proulx², Argyn Toktamyssov⁴

Abstract: In November 2020, the Bank of Canada launched a pilot project with the Office of the Superintendent of Financial Institutions aimed at better understanding risks to the economy and the financial system related to climate change. Part of this work included developing a set of Canada-relevant climate transition scenarios that explore pathways consistent with achieving certain climate targets. The scenarios vary in terms of two key drivers of climate transition risk: (i) the ambition and timing of climate policy and (ii) the pace of technological change and availability of advanced technologies. To develop the scenarios, we used a suite-of-models approach that linked a computable general equilibrium energy-economy model with two macroeconomic models. The scenarios focus on Canada and the United States because of the material exposure of the Canadian financial sector to these regions. They capture the evolution of the global economy, summarized across 10 emissions-intensive sectors of the economy and across 8 distinct regions of the world. The analysis illustrated the important sectoral restructuring the Canadian and global economies may need to undertake to meet climate targets. The analysis showed that every sector contributes to the transition and that the financial impacts vary across sectors. These impacts depend on how the sectors are impacted by emissions and capital expenditures costs and on how the demand for their products is affected by decarbonizing of economies. The scenarios also shed light on the risks of significant macroeconomic impacts, in particular for commodity-exporting countries like Canada. The economic impacts for Canada are driven mostly by declines in global prices of commodities rather than by domestic policy decisions. Finally, the analysis showed that delaying climate policy action increases the overall economic impacts and risks to financial stability.

This report is also available at the Bank of Canada [website](#).

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1 Introduction

In November 2020, the Bank of Canada launched a pilot project with the Office of the Superintendent of Financial Institutions (OSFI) aimed at better understanding climate-related risks to the economy and the financial system (Bank of Canada and OSFI 2022). Climate change poses challenges not traditionally encountered by general macroeconomic and financial risk assessments. Concerns centre on the physical and transition risks of climate change and best practices for addressing them. The physical risks associated with climate change include increases in the global average temperature and in the frequency and severity of extreme weather events (e.g., flooding and wildfires). Reducing these physical risks requires efforts to decarbonize our economies and carries economic transition risks. Sudden changes in climate policies, technology or market sentiment could lead to economic dislocation and a rapid repricing of climate-related risks if they are not priced in sufficiently by market participants. This could negatively affect the balance sheets of financial market participants, with potential consequences for financial stability.

While the financial community recognizes these risks, the high degree of uncertainty in how they might evolve makes risk management challenging. The uncertainty surrounding transition risks may be substantial, driven by uncertainty over how future technologies, policies and regulations, economic growth and other aspects of human development will evolve. While assessing the physical risks of climate change is important, the Bank and OSFI pilot focused exclusively on the transition risks of climate change.

The project developed a set of Canada-relevant climate transition scenarios that explore pathways consistent with achieving certain climate targets.¹ Scenario analysis is an approach used to examine different plausible future states of the world to identify what *could* happen rather than predicting what *will* happen. This allows us to evaluate a range of hypothetical outcomes based on different assumptions of what may occur and can assist in evaluating risks to the economy related to climate change, particularly when dealing with high degrees of uncertainty. The scenarios are designed to capture a range of risk outcomes that could be stressful to the economy and the financial system.

The goals of the project were to:

- build the capability of authorities and financial institutions for climate scenario analysis and support the Canadian financial sector in enhancing the disclosure of climate-related risks

¹ The Bank developed its own scenarios for this pilot to provide economic and financial data at the relevant geographic and sectoral levels of Canadian financial institutions.

- increase authorities' and financial institutions' understanding of the financial sector's potential exposure to risks associated with a transition to a low-carbon economy
- improve authorities' understanding of financial institutions' governance and risk management practices around climate-related risks and opportunities

This paper presents the scenario design, key assumptions and modelling approach used in developing the climate transition scenarios. The scenarios focus on Canada and the United States given the Canadian financial sector's material exposure to these regions. The scenarios capture the evolution of the global economy, summarized across 10 emissions-intensive sectors (coal, oil, gas, refined oil, electricity, energy-intensive industries, transportation, forestry, crops and livestock), and across 8 regions of the world (Africa, Canada, China, Europe, India, Japan, United States and Rest of the World). This is one of two technical documents supporting the pilot project. Another report describes the methodologies behind the assessment of climate-related financial risks in more detail (see Hosseini *et al.* 2022).

The next section presents a detailed description of the scenarios and key assumptions supporting their development. Following this is an overview of the modelling framework we used to build the scenarios, which involved linking a sectoral model with two macroeconomic models. We present key results that describe:

- the economic restructuring at the global level
- the financial impacts on the 10 sectors in the analysis
- the macroeconomic implications for Canada and the United States

The results are meant to be a summary of key messages.

In addition to this document, an accompanying database is available with all the scenarios' data to support other financial institutions in their own assessments of climate transition risks.²

2 Scenarios

To analyze climate transition risks, the Bank developed four climate scenarios over a 30-year horizon, from 2020 to 2050. The scenarios vary in terms of two key drivers of climate transition risk:

- the ambition and timing of climate policy
- the pace of technological change and availability of carbon dioxide removal (CDR) technologies

The scenarios explore different pathways in climate policy, including both immediate and delayed action, toward limiting warming to below 2°C by 2100, as well as a more

² The database is available on the Bank's website.

ambitious scenario to limit warming to 1.5°C by 2100. The scenarios are not meant to be forecasts or to be comprehensive. Rather, they explore different plausible but intentionally adverse global transition pathways consistent with achieving specific climate targets. The scenarios rely conservatively on technologies that are not yet commercially available or that could face scalability issues in the future. **Table 1** provides a brief overview of the scenarios and their key assumptions. A more detailed description follows.

Emissions paths are an input in the development of the scenarios.

The baseline (2019 policies) scenario serves as a benchmark and is assumed to reflect market participants’ expectations of climate policy in 2019. We selected that date to abstract from any effects related to the COVID-19 pandemic. Emissions paths in the baseline (2019 policies) scenario are modelled at the country or regional level, using primary sources for Canada and the United States and estimates from the Climate Action Tracker for the remaining countries and regions.³ The scenario assumes countries continue to pursue their 2019 policy frameworks and take no further policy action to limit global warming. Emissions rise along with global growth in a relatively unconstrained way, implying a further rise in the global average temperature (**Chart 1**).

The below 2°C immediate and delayed scenarios consider a plausible path for global climate policy and greenhouse gas emissions that is likely to be consistent with limiting the increase in global average temperatures to below 2°C by 2100 (**Chart 1**). Both scenarios assume global collective action to reduce emissions, with the immediate scenario assuming action begins in 2020 and the delayed scenario assuming action does not begin until 2030. Because of delayed action, emissions must fall rapidly to make up for lost time and compensate for the additional emissions associated with the delay, implying a large transition through mid-century. The

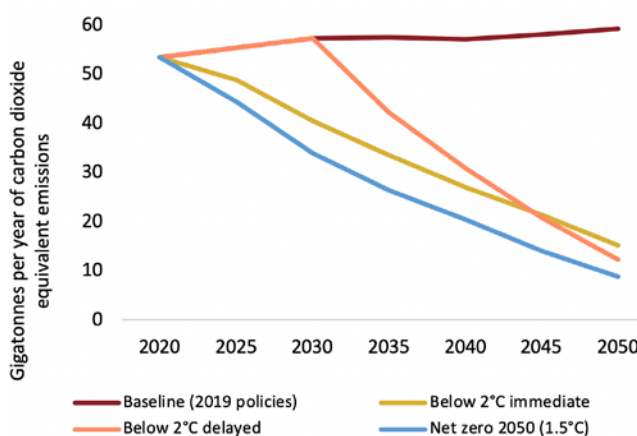


Chart 1. Global greenhouse gas emissions by scenario

3 The Climate Action Tracker summarizes climate policies and emissions based on primary sources.

Table 1. Scenario storylines

Scenario	Climate policy ambition and timing	Technological change
Baseline (2019 policies)	The world follows a path consistent with climate policies in place at the end of 2019, implying a continued rise in emissions and an increase in average global temperatures in the range of 2.9–3.1°C by 2100. Forestry continues on a global trend of being a net source of emissions through mid-century.	The pace of technological change is slow. The availability of carbon dioxide removal (CDR) technologies is limited.
Below 2°C immediate	Starting in 2020, collective global action is taken to reduce emissions toward a target of below 2°C by 2100. Early investments, planning and management allow forests to become a small net sink by mid-century.	The pace of technological change is moderate. The availability of CDR technologies is limited.
Below 2°C delayed	After a decade of following 2019 policy frameworks, collective global action to align with a 2°C target begins in 2030. A steeper transition is needed to make up for the additional decade of a continued rise in emissions. ¹ Delayed investments, planning and management prohibit forests from becoming a net sink by mid-century.	The pace of technological change is moderate. The availability of CDR technologies is limited.
Net-zero 2050 (1.5°C)	Starting in 2020, collective global action is taken to reduce emissions toward a 1.5°C target. Current net-zero commitments by some countries, including Canada, are modelled directly in this scenario. Strong early investments enable forests to become a net sink by mid-century.	The pace of technological change is fast. The availability of CDR technologies is moderate, including bioenergy with carbon capture and storage.

1 Given that climate change is driven by the accumulation of emissions in the atmosphere over time, we must compensate for these additional emissions by converging to a lower path of emissions through mid-century.

emissions paths for the below 2°C immediate and delayed scenarios are based on countries’ nationally determined contributions submissions, scaled to be consistent with the ambition and timing of the respective scenario.

The net-zero 2050 (1.5°C) scenario considers a plausible path for greenhouse gas emissions that is likely to be consistent with limiting the increase in global temperatures to 1.5°C by 2100 (Chart 1). This scenario reaches net-zero global carbon dioxide emissions by mid-century and assumes countries with explicit net-zero greenhouse gas emissions targets meet their commitments. Like the below 2°C immediate scenario, the net-zero 2050 (1.5°C) scenario assumes that global collective action to reduce emissions begins in 2020. However, the net-zero 2050 (1.5°C) scenario requires a larger decline in global emissions.

For countries that have explicit targets along the transition (e.g., 2030 emissions target levels), we include those targets directly in the scenarios. For other countries/regions, we align the net-zero 2050 (1.5°C) scenario emissions pathways with the net-zero scenario of phase II of the Network for Greening the Financial System (NGFS) climate scenarios.⁴

The scenario narratives and the paths for global emissions are generally aligned with those developed by the NGFS. In **Chart 2**, the Bank’s scenarios are given in green, and the three models used within the NGFS are in other colours. The Bank, however, developed its own scenarios for this pilot to provide economic and financial data at the relevant geographic and sectoral level of granularity to assess the exposures of Canadian financial institutions.

2.1 Technology

The availability of technologies, in both the present and the future, plays an important role in the transition to a low-carbon economy. The baseline scenario and the below 2°C immediate and delayed policy action scenarios assume a slow pace of technological progress. In these scenarios, industries can take full advantage of commercially available technologies (e.g., electric vehicles, carbon capture and storage with traditional fossil-fuel energy generation). But industries cannot lean on technologies that are not yet commercially available or that face scalability issues (e.g., bioenergy with carbon capture and storage [BECCS],⁵ direct air capture). The purpose is to look at scenarios where the transition relies on significant structural change

5 BECCS is a potential net negative emissions technology. It refers to the process of converting biomass to energy and capturing and storing the carbon, thereby removing it from the atmosphere.

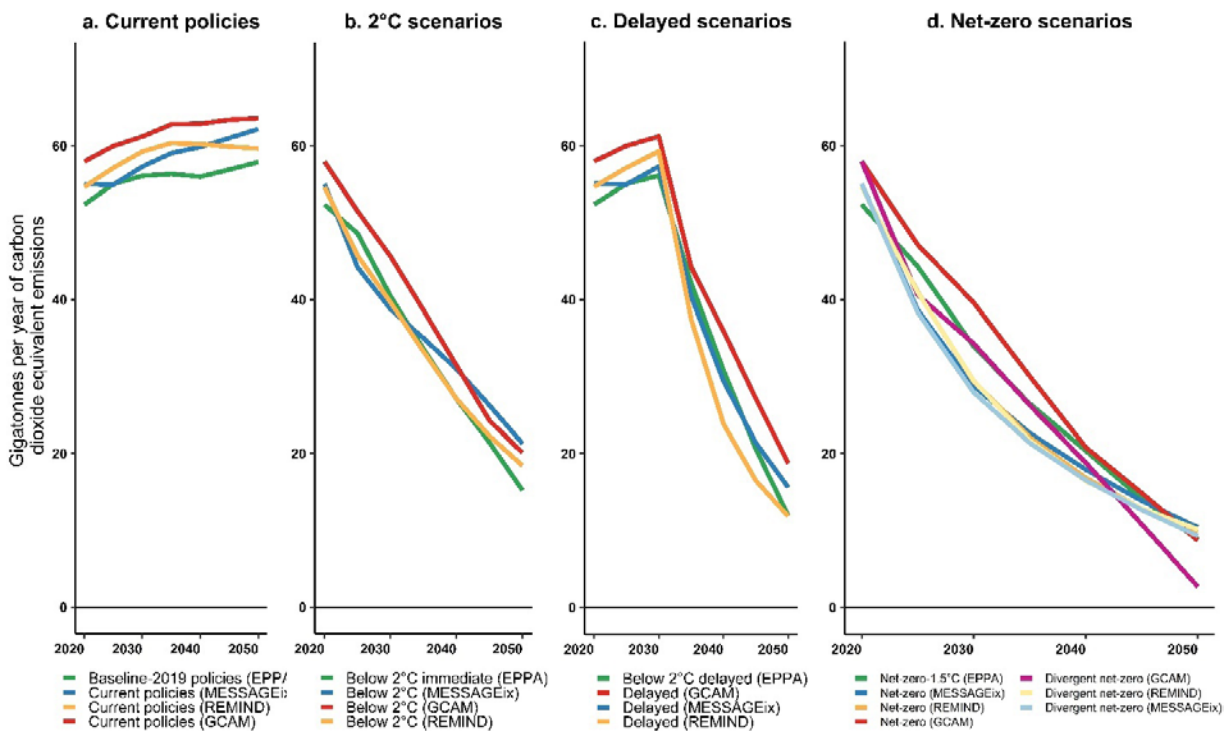


Chart 2. Alignment of global greenhouse gas emissions between the Bank of Canada and the NGFS scenarios

Note: NGFS refers to the Network for Greening the Financial System, EPPA is the Economic Projection and Policy Analysis model, GCAM is the Global Change Analysis Model, REMIND is the Regional Model of Investment and Development, and MESSAGE is the Model of Energy Supply Systems and their General Environment Impact.

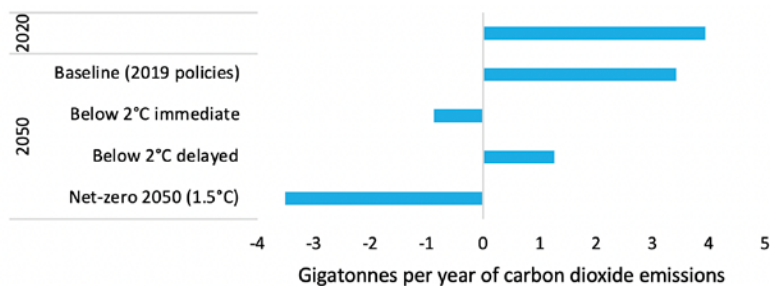


Chart 3. Carbon dioxide emissions/removals from forestry

at the industry level—which is thus potentially stressful to the economy and financial system—and not simply on hypothetical technological progress.

In the net-zero 2050 (1.5°C) scenario, however, we assume that the pace of technological change is faster. Under this scenario, a moderate amount of CDR technology is available, including BECCS. The fast pace of technological progress partially eases the transition in other parts of the economy and supports the achievement of the more ambitious global climate target.⁶

2.2 Nature-based solutions

The scenarios assume modest contributions from expanding natural carbon sinks such as forests—known as nature-based solutions. Emissions in forestry are modelled at the country/regional level. We first leverage estimates of current emissions and removals from forestry from the Massachusetts Institute of Technology (MIT) and primary sources. We then assume in the scenarios that the evolution of these forest-based emissions follows the projections implied from the Global Timber Model across various global climate policy scenarios (see Austin *et al.* 2020). We take the implied relationship between carbon prices and annual forest-based carbon flux driven by reduced deforestation, increased afforestation and improved forest management from the model. We then apply this relationship to the projected path of the shadow carbon price from the scenarios to project forest-based carbon flux consistent with our scenarios.

The world’s forests were a net source of emissions of approximately 4 gigatonnes of carbon dioxide in 2020 (**Chart 3**). The baseline (2019 policies) scenario assumes a continued rise in emissions and little efforts to reduce forest-based emissions through mid-century. Delayed investments and planning in forestry under the below 2°C *delayed* scenario leads to continued emissions from the world’s forests through mid-century. In contrast, the below 2°C *immediate* scenario assumes that early investment and planning in forestry enable the global forest sector to become a net sink of carbon of

around 1 gigatonne of carbon dioxide by 2050. Forest carbon flux plays an even larger role in the net-zero 2050 (1.5°C) scenario, which assumes that similar early investment and planning is paired with greater climate ambition, leading to a removal of nearly 3.5 gigatonnes of carbon dioxide by 2050.

As with technological progress, the greater contributions from nature-based solutions may ease the transition in other parts of the economy.

2.3 Policy assumptions

Policy assumptions were modelled following two steps. First, we collected and modelled non-carbon price policies for each distinct region, including specific sectoral mandates, reductions of certain fossil fuel electricity-generating technologies, targets for minimum amounts of renewable energy and other policies that could affect the level of emissions. Second, each country and region in the analysis was subjected to a constraint on the path of emissions consistent with the scenario. This is a model input.

We illustrate this process for Canada and the United States below.

2.3.1 Canada

Climate policies for Canada’s baseline (2019 policies) scenario are based on the “with measures” projections of Environment and Climate Change Canada, as presented in *Canada’s Fourth Biennial Report on Climate Change* (GoC 2019). Canadian climate policies in 2019 are largely a product of the Government of Canada’s Pan-Canadian Framework on Clean Growth and Climate Change, including the following non-carbon tax policies:⁷

- phase out of traditional coal-fired generation of electricity
- renewable shares in electricity generation (see **Chart A1** in the appendix for renewable share targets for all countries and regions)
- Corporate Average Fuel Economy standards for both passenger and commercial vehicles (see **Chart A2** in the appendix)
- regulations on methane emissions

⁶ Similar assumptions are made by the NGFS International Energy Agency (IEA 2021) and the Canadian Institute for Climate Choices (CICC 2021) under their respective net-zero scenarios.

⁷ To see the full list of policies included under the reference scenario, see Table A2.39 in *Canada’s Fourth Biennial Report* (GoC 2019, 146)

In addition, in 2019, Canada's Pan-Canadian Framework outlined a federal backstop carbon pricing scheme that increased in price through to 2023.

The emissions path for Canada's baseline (2019 policies) scenarios follows Environment Canada's reference scenario in 2019,⁸ which projects little additional mitigation (**Chart 4**).

The 2°C *immediate* and delayed scenarios alter the path of emissions to decline with what would be consistent with a global collective action to limit warming to no greater than 2°C by 2100. The 2°C scenarios incorporate the same suite of non-carbon price policies as described in the baseline (2019 policies) scenario but increase their intensity. Emissions in Canada decline sharply across both scenarios (**Chart 4**).

The net-zero 2050 (1.5°C) scenario closely follows Canada's latest climate commitments. In April 2021, the Government of Canada submitted an updated national greenhouse gas emission reduction target to reduce its emissions by 40 to 45 percent below 2005 levels by 2030 and achieve net-zero greenhouse gas emissions by 2050.⁹

As in the below 2°C scenarios, the net-zero 2050 (1.5°C) scenario assumes an increase in the intensity of non-carbon price policies, including the traditional coal phase out, renewable energy standards, fuel efficiency standards and increased ambition for methane emissions. The path of emissions for Canada in the net-zero 2050 (1.5°C) scenario involves a sharp decline in emissions over the coming decade, ultimately reaching net-zero by 2050 (**Chart 4**).

8 Environment and Climate Change Canada, "Greenhouse Gas and Air Pollutant Emissions Projections: 2019."

9 Please refer to Environment and Climate Change Canada's "Canada's Enhanced Nationally Determined Contribution" (April 2021).

2.3.2 United States

Emissions under the baseline (2019 policies) scenario for the United States are derived from the reference case of the Energy Information Administration's 2019 energy outlook (EIA 2019). The baseline (2019 policies) scenario assumes that laws and regulations in effect in 2019 are unchanged throughout the projection period. The climate policies include:

- renewable shares in electricity generation (see Chart A1 in the appendix for renewable share targets for all countries and regions)
- Corporate Average Fuel Economy standards for both passenger and commercial vehicles (see Chart A2 in the appendix)

Like in Canada, in the United States the baseline (2019 policies) scenario projects a continued increase in the level of emissions (**Chart 5**). The 2°C scenarios impose non-carbon price policies similar to those outlined in the baseline (2019 policies) scenario but increase the intensity of the fuel economy standards. The net-zero 2050 (1.5°C) scenario reflects the more recent commitments made by the United States, including a 2030 greenhouse gas emissions reduction target of 50 to 52 percent below 2005 levels by 2030¹⁰ and the achievement of net-zero greenhouse gas emissions by 2050.¹¹

10 Please refer to the United States' most recent National Determined Contribution submission to the United Nations Framework Convention on Climate Change.

11 For more information, see White House Briefing Room, "Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies" and "Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies" (April 22, 2021).

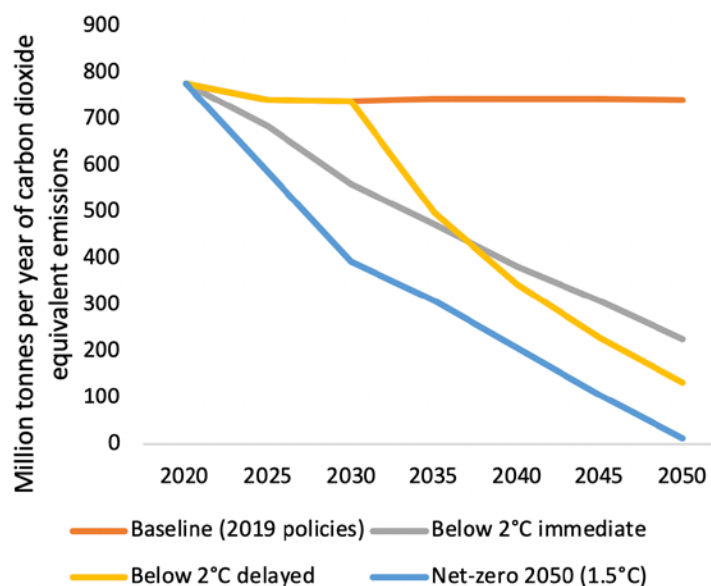


Chart 4. Projected greenhouse gas emissions in Canada across scenarios

3 Modelling framework

In this section, we begin with an overview of the suite-of-models approach used in the development of the scenarios, and then we provide further details on each model. The Bank linked a computable general equilibrium energy-economy model with two macroeconomic models to develop the climate transition scenarios (Figure 1). Recognizing the strengths and weaknesses of different models, we leaned on their comparative advantages to help design the scenarios.

To develop the sectoral-level scenarios, we worked closely with MIT, using its Economic Projection and Policy Analysis (EPPA) model. The model tracks emissions as they relate to economic activity and has firms making cost-minimiz-

ing decisions over time. The MIT-EPPA model represents the world's economy across several countries/regions and sectors relevant to the Canadian financial system. In addition, the model has a rich representation of technologies, including traditional fossil fuels, as well as more advanced backstop technologies, including BECCS.

The MIT-EPPA model provides important information about the sectoral restructuring along the transition. This information helped the financial institutions that participated in the pilot to assess the impacts of the transition scenarios on their portfolios: namely, the impacts on credit and market risk. However, to place the sector-level analysis in a larger macroeconomic context, we also used two of the Bank's macroeconomic policy models to analyze the impact on the Canadian, US and global economies. These

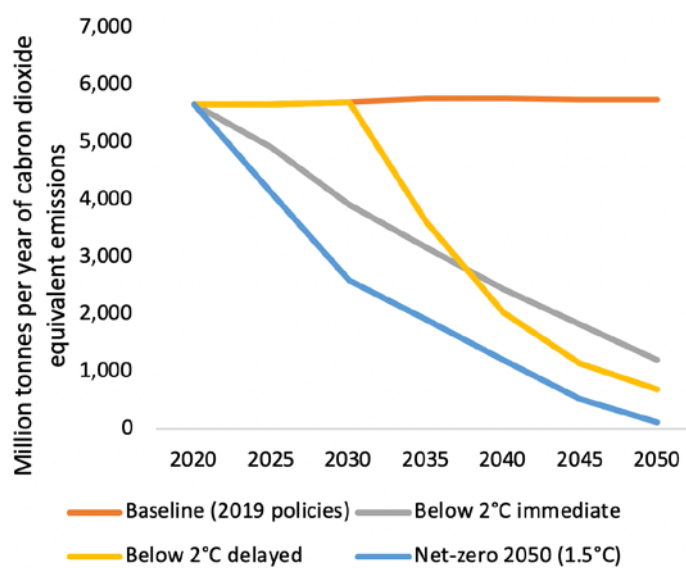


Chart 5. Projected greenhouse gas emissions in the United States across scenarios

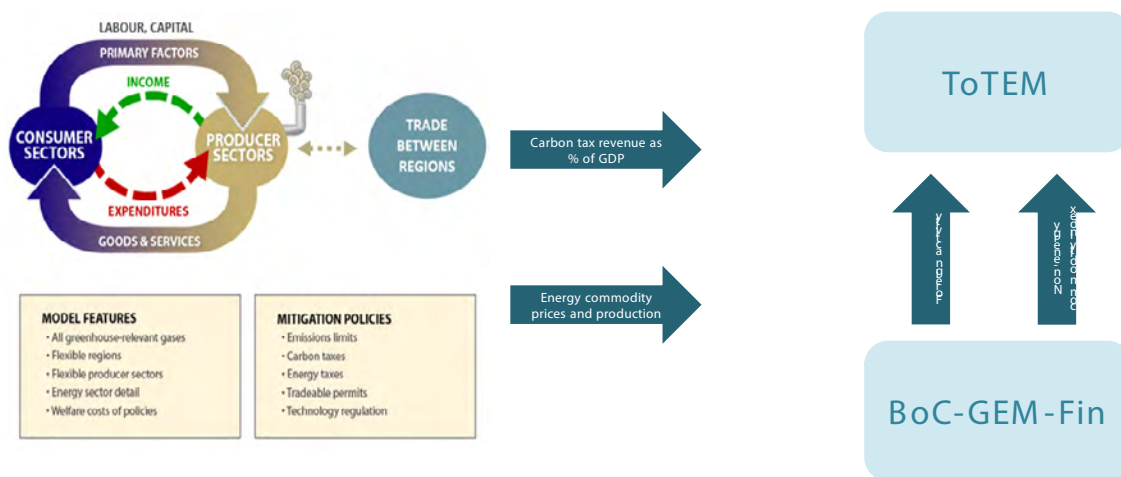


Figure 1. Representation of the suite-of-models approach used in the Bank of Canada's climate scenario development

Note: ToTEM refers to the Terms-of-Trade Economic Model, and BoC-GEM-Fin is the Bank of Canada's Global Economy Model with Financial Frictions.

are the Terms-of-Trade Economic Model (ToTEM) III, the Bank's main structural model for the Canadian economy (Corrigan et al. 2021), and BoC-GEM-Fin, a five-region model for the global economy (De Resende and Lalonde 2011; Lalonde and Muir 2007).

Both models are dynamic stochastic general equilibrium frameworks in which the behaviour of firms and households is largely micro-founded. The supply sides of both models are quite rich, with dedicated raw materials sectors responsible for producing commodities and a variety of intermediate goods feeding into the production of final goods. This detailed supply structure makes the models useful laboratories for exploring the effects of taxes on firms' energy inputs. This specifically involves imposing tax-rate profiles on Canada and each region of BoC-GEM-FIN to match profiles generated by the MIT-EPPA model for carbon tax revenues as a share of gross domestic product (GDP). In addition, the macroeconomic policy models took information regarding energy commodity markets from the MIT-EPPA model as inputs.

While the modelling framework determines the substitution away from carbon-rich commodities, we emphasize that there are two-sided risks to the scenarios. For example, the scenarios do not consider the upside risks of innovation in new products or services or the creation of new industries/sectors that might accompany the transition and productivity spillovers from investments in green technologies. On the downside, the models might fail to fully capture all the labour market adjustment costs and frictions along the transition.

3.1 MIT-EPPA model

The MIT-EPPA model is the part of the MIT Integrated Global Systems Model (IGSM) that represents human systems (Paltsev et al. 2005; Chen et al. 2016). The EPPA model is a recursive-dynamic, multi-region, multi-sector, dynamic general equilibrium model of the world economy, which is built on the Global Trade Analysis Projection dataset (Aguar et al. 2019) and additional data for greenhouse gas and urban gas emissions, taxes and details on selected economic sectors. Provision is made for analysis of uncertainty in key human influences, such as the growth of the population and economic activity and the pace and direction of technical advances. The model is designed to develop projections of economic growth, energy transitions and human-induced emissions of greenhouse gas and air pollutants.

The model projects economic variables and emissions of greenhouse gases¹² and other air pollutants from combustion of carbon-based fuels, industrial processes, waste handling, agricultural activities and changes in land use.¹³ Regional representation in the main version of the MIT-EPPA model is provided in **Figure 2**. While the model tracks the economic activity across 18 distinct countries and regions, the Bank scenarios summarize this information across 8 regions of the world (Africa, Canada, China, Europe, India, Japan, United States and Rest of the World). The data

12 This includes carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride.

13 This includes carbon monoxide, volatile organic compounds, nitrous oxide, sulphur dioxide, ammonia, black carbon and organic carbon.

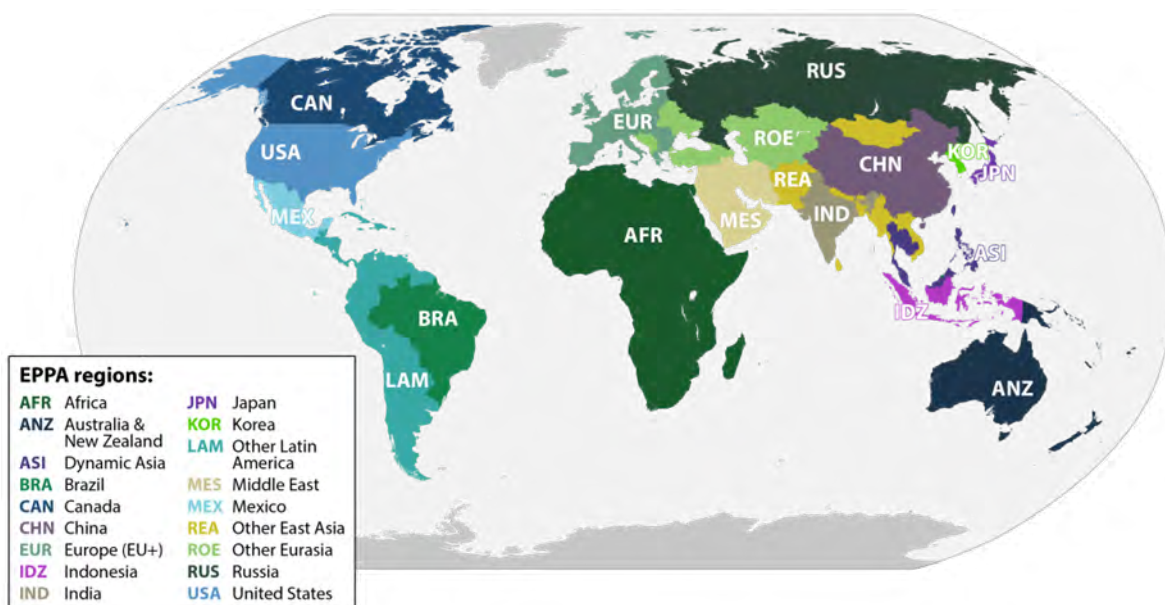


Figure 2. Regions in MIT's Economic Projection and Policy Analysis model

behind these 8 regions are provided in an accompanying database.¹⁴

Sectoral representations of the version used in this paper are provided in **Table 2**.¹⁵

The MIT-EPPA model represents interactions among three types of agents: households, firms and the government. Households own the primary factors of production (e.g., labour, capital and natural resources), which they rent to firms; households then use this income to purchase goods and services. In each sector of the model, firms produce commodities by combining factors of production and intermediate inputs (i.e., goods produced by other sectors). The government sets policies and collects tax revenue and then spends the revenue on providing goods and services for households and on transfer payments to households. In addition, a carbon price is imposed on all greenhouse gas emissions, with the revenues raised redistributed back to households via lump-sum transfers. Equilibrium is obtained through a series of markets (for both factors of production and goods and services) that determine prices so that supply equals demand.

The EPPA model chooses the least-cost production opportunities based on market clearance conditions (supply must equal demand), normal profit conditions (the cost

of inputs should not exceed the price of the output) and income balance conditions (expenditures must equal income, accounting for savings, subsidies and taxes). Growth in population and economic activity (as measured by GDP) are the key drivers of changes over time. For population growth, we adopt a central estimate from the United Nations (UN 2019), which projects that the world population will increase from 7.8 billion in 2020 to 9.7 billion in 2050 (**Table 3**). The fastest growth is expected to occur in Africa, the Middle East and Australia/New Zealand, where the model assumes average annual population growth rates of 2.1 percent, 1.2 percent and 1 percent, respectively, over the 2020–50 time frame. Some countries—such as Japan, Russia, China and South Korea—are projected to experience negative population growth over this period.

For near-term GDP growth, we rely on forecasts from the International Monetary Fund (IMF 2021) and then follow assumptions about long-term productivity growth from the MIT Joint Program on the Science and Policy of Global Change (MIT Joint Program 2021). This results in an assumed average annual growth rate of world GDP of about 2.5 percent for the 2020–50 study period. We assume slower growth in advanced economies than in developing economies (**Table 4**). While we assume the same population growth in all scenarios, GDP growth is affected by economic and climate policies and is different in different policy scenarios.

An important characteristic of the MIT-EPPA model is the representation of links among sectors through each firm's use of intermediate inputs. Purchases of intermediate inputs are captured in input-output tables used to calibrate the models. For each sector, these tables list the value of output produced and the value of each input used, which can be linked to physical quantities (e.g., tonnes of coal).

14 The database is available on the Bank's website.

15 Different versions of the EPPA model have been formulated for targeted studies, such as decarbonization of light-duty vehicles (Ghandi and Paltsev 2020), BECCS (Fajardy *et al.* 2021), use of natural gas and oil as feedstocks (Kapsalyamova and Paltsev 2020), options for emission reductions in hard-to-abate industrial sectors (Paltsev, Morris *et al.* 2021; Paltsev, Gurgel *et al.* 2021), scenarios for carbon capture and storage deployment (Morris *et al.* 2021), outlook for energy, managed resources and policy prospects (MIT Joint Program 2021) and others.

Table 2. Sectors in the MIT's Economic Projection and Policy Analysis model

Sectors			
Energy-intensive industries	Oil production	Wind electricity	Advanced natural gas
Other industries	Refining	Solar electricity	Private transportation: gasoline and diesel vehicles
Services	Natural gas production	Biomass electricity	Private transportation: electric vehicles
Crops	Coal electricity	Wind combined with gas backup	Commercial transportation
Livestock	Natural gas electricity	Wind combined with biofuel backup	First-generation biofuels
Forestry	Petroleum electricity	Coal with CCS	Advanced biofuels
Food processing	Nuclear electricity	Natural gas with CCS	Oil shale
Coal production	Hydro electricity	Advanced nuclear electricity	Synthetic gas from coal

Note: CCS is carbon capture and storage.

Table 3. Population (in millions) in the Economic Projection and Policy Analysis model regions

	2015	2020	2025	2030	2035	2040	2045	2050
AFR	1,182.4	1,340.6	1,508.9	1,688.3	1,878.2	2,076.8	2,281.5	2,489.3
ANZ	39.9	42.7	45.3	47.9	50.4	52.8	55.1	57.4
ASI	230.3	241.4	251.6	260.4	267.8	273.4	277.4	279.8
BRA	204.5	212.6	219.0	223.9	227.2	229.1	229.6	229.0
CAN	36.0	37.7	39.3	40.8	42.2	43.5	44.6	45.7
CHN	1,414.0	1,446.8	1,465.7	1,472.4	1,469.2	1,457.2	1,437.4	1,410.5
EUR	523.2	528.4	529.2	528.6	526.9	523.9	519.8	514.4
IDZ	258.4	273.5	287.1	299.2	309.8	318.6	325.7	330.9
IND	1,310.2	1,380.0	1,445.0	1,503.6	1,553.7	1,592.7	1,620.6	1,639.2
JPN	128.0	126.5	124.0	120.8	117.2	113.4	109.5	105.8
KOR	50.8	51.3	51.3	51.2	50.7	49.8	48.5	46.8
LAM	297.0	311.8	326.9	340.9	352.8	362.9	371.2	377.7
MES	239.9	261.0	284.6	305.1	323.0	339.7	355.4	369.7
MEX	121.9	128.9	135.3	140.9	145.8	149.8	152.9	155.2
REA	637.2	683.6	728.6	769.6	806.1	838.5	867.2	891.5
ROE	240.4	251.1	257.0	262.0	266.9	271.3	274.8	277.2
RUS	145.0	145.9	145.1	143.4	141.1	139.0	137.3	135.8
USA	320.9	331.0	340.4	349.6	358.7	366.6	373.3	379.4
World	7,379.8	7,794.8	8,184.4	8,548.5	8,887.5	9,198.9	9,481.8	9,735.0

Data source: UN (2019)

Table 4. Annual average GDP growth in the Economic Projection and Policy Analysis model regions (percent)

	2015	2020	2025	2030	2035	2040	2045	2050
AFR	3.5	1.1	4.8	4.0	4.3	4.2	3.9	3.6
ANZ	2.8	0.6	3.7	2.6	2.6	2.6	2.4	2.3
ASI	3.9	1.9	5.0	3.4	2.7	2.6	2.6	2.6
BRA	1.5	-0.8	3.3	2.7	3.0	2.9	2.9	2.9
CAN	2.3	0.2	2.7	2.4	2.4	2.4	2.2	2.1
CHN	7.5	5.3	4.3	3.8	2.3	2.3	1.6	1.6
EUR	0.9	0.5	2.1	1.4	1.4	1.4	1.3	1.3
IDZ	5.6	3.2	5.8	3.6	3.2	2.9	2.4	2.5
IND	6.6	5.3	6.5	5.8	4.4	4.5	3.7	3.7
JPN	0.8	-0.9	1.7	0.8	1.3	1.2	1.2	1.2
KOR	3.1	0.9	4.0	3.3	2.7	2.6	2.5	2.6
LAM	3.3	-0.9	3.8	2.9	3.3	3.2	3.1	3.0
MES	3.6	-1.7	3.2	2.5	3.3	3.3	3.1	3.0
MEX	2.9	0.8	3.6	3.0	3.1	3.2	3.1	3.0
REA	5.4	4.0	6.8	4.1	4.4	4.1	3.6	3.4
ROE	3.5	1.8	4.6	3.2	3.2	3.2	3.0	3.0
RUS	1.1	0.0	2.2	1.7	1.6	1.5	1.4	1.4
USA	2.3	0.2	2.7	1.7	1.9	1.9	2.0	2.0
World	2.6	1.2	3.3	2.6	2.4	2.4	2.2	2.2

Data source: MIT Joint Program (2021)

For example, the coal power sector will use inputs of capital and labour and output from the coal mining sector along with other intermediate inputs to produce electricity. These links across sectors allow the model to evaluate how policy changes will propagate throughout an economy.

Other key features of the MIT-EPPA model include the representation of competition across technologies/sectors and substitution possibilities among inputs. For instance, an increase in the price of coal-based electricity will provide

scope for the expansion of electricity generation from other sources, such as renewable electricity. At the same time, an increase in electricity prices will encourage firms to use electricity more efficiently by investing in more efficient plants, at an additional cost, than they would have without the price increase.

In the MIT-EPPA model, technological change is an important source of growth in the economy, such as capital

accumulation. The MIT-EPPA model represents technology change in three ways:

- exogenous augmentation of the supplies of labour and natural resources
- exogenous reduction of energy use per unit of output through time
- introduction of energy technologies (also known as backstop technologies) that are currently unused but that come into play as supplies of current energy resources deplete (causing a rise in prices) or as policies penalize the greenhouse gas emission of conventional energy sources

The time of entry for backstop technologies in a simulation depends on their cost relative to the cost of current fuels because they change endogenously in the simulations from the MIT-EPPA model. The costs of advanced technologies in the model change endogenously based on technology-specific factors that represent multiple dynamics related to the diffusion of new technology. These include:

- sunk investments in existing technology
- monopoly rents associated with the new technology
- adjustment costs related to expanding the new technology
- short- and long-run pricing of the output of the new technology
- the rate of diffusion of the new technology and how it is influenced by economic factors

The MIT-EPPA model also has a vintaging structure to address the issues related to a lock-in in a particular technology. The model tracks the age of particular investment choices for certain technology types and divides the capital into a malleable portion and a vintaged non-malleable portion.

Production technologies are chosen based on their relative competitiveness. We define the initial relative costs of technologies and input shares. Sectoral and regional prices then change endogenously over time in the model, affecting the

relative costs of technologies and the resulting technology mix. Costs of light-duty transportation are described in Ghandi and Paltsev (2020). Costs of electric power technologies (**Table 5**) are based on the Energy Information Administration's 2020 energy outlook (EIA 2020) and scaled geographically based on the cost of capital and fuel costs as described in Morris *et al.* (2019). Representation of BECCS is based on Fajardy *et al.* (2021), where economic implications of BECCS deployment under the net-zero 2050 (1.5°C) scenario is considered, including revenue sources for BECCS. Some deployment options suggest lower capital cost for BECCS (Clayton 2021) due to designs with energy efficiencies closer to coal-based generation. However, the trade-off is in higher fuel costs due to the required pre-treatment of inputs. These counter-balancing adjustments do not substantially impact BECCS deployment paths in aggressive decarbonization scenarios.

Formulating a mathematical problem using general equilibrium involves modelling the economy as an optimization problem and seeking the solution to the problem through a large non-linear program in which an objective function is maximized or minimized subject to a set of constraints. In EPPA, we use a mixed complementarity approach to solve the model. Starting in 2020, the model solves at five-year intervals up to 2100, with economic growth and energy use for 2015–20 calibrated to the data from the International Monetary Fund (IMF 2021) and the International Energy Agency (IEA 2020). The structure of production functions and the values of elasticities (which describe substitution possibilities when facing a price change) are the same in this version of EPPA as they are in the EPPA6 version of the model, as described in Chen *et al.* (2015, 2016).

As noted above, instead of directly imposing an exogenous path of carbon prices, our models aim to reduce emissions by a pre-determined amount (see **Table A-1** in the appendix). This is done in the following way. The model first incorporates non-carbon tax policies at the country/regional level, contributing to reducing emissions.

Table 5. Cost characteristics of new electricity-generating technologies

	Overnight Cost (2019\$/kW)	Variable O&M (2019\$/MWh)	Fixed O&M (2019\$/kW)
Advanced coal	3,661.0	4.5	40.4
Coal with CCS	5,997.0	10.9	59.3
Advanced gas	1,079.0	2.5	14.0
Gas with CCS	2,569.0	5.8	27.5
Wind	1,319.0	-	26.2
Solar	1,331.0	-	15.2
Nuclear	6,317.0	2.4	121.1
Biomass	4,104.0	4.8	125.2
Biomass with CCS	8,867.0	8.7	169.0

Note: O&M stands for operation and maintenance costs; kW is kilowatt; MWh is megawatt hour; CCS is carbon capture and storage. Data source: EIA (2020) and Fajardy *et al.* (2021).

Then, to fully meet the pre-determined emissions path, the model calculates a shadow price of carbon that captures the remaining stringency required in government climate policy to come up with the rest of the mitigation.¹⁶

3.2 The Bank's macroeconomic policy models

To complement the MIT-EPPA model, we use two of the Bank's macroeconomic policy models to analyze the impacts of the three scenarios on a set of aggregate economic variables for Canada, the United States and the global economy. In the macroeconomic modelling, climate policy is mainly modelled as carbon taxes rebated to households through lump-sum transfers.¹⁷ Profiles for carbon tax revenues as a fraction of GDP and energy commodity prices from the MIT-EPPA sectoral model are used as inputs into the macroeconomic models to align narratives. In this section, we describe the models used for this exercise and explain how these models capture the impact of emissions mitigation policies on the Canadian and global economies.

Recall that the scenarios are not forecasts but plausible paths designed to capture tail risks to the economy and the financial system. These are not most likely scenarios; rather, they are meant to test the resilience of the financial system.

3.2.1 Canadian implications of the emissions mitigation scenarios: Insights from ToTEM III

To assess the effect of the scenarios on the Canadian macroeconomy, we rely on the Bank's main dynamic stochastic general equilibrium model of Canada, ToTEM III (see Corrigan *et al.* 2021). This is an open-economy micro-founded model where the behaviour of most variables is traceable

to a set of fundamental assumptions about the underlying structure of the Canadian economy. It has four types of households (restricted and unrestricted lifetime income consumers, hand-to-mouth consumers, and borrowers) that supply labour and demand consumption goods and housing. On the supply side, the model has five sectors of finished-goods production (consumption, residential investment, business investment, government and a non-commodity sector). Each sector uses commodities as inputs.

The detailed supply side of the economy allows us to implement a tax on the use of those commodities that will affect the firms' optimal behaviour in choosing the amount of labour, capital and commodities. To simulate the macroeconomic effect of the scenarios on the Canadian economy, we:

- impose specific tax-rate profiles to match EPPA-consistent carbon tax revenue paths under the scenarios described in previous sections
- impose the global effects of emissions mitigation policies imposed in other countries (covered in the next section)

Note that we also add some negative judgment on commodity exports to reflect EPPA's predictions of the impact of non-price policies.

Overall, three main channels affect the Canadian economy: the domestic increase in carbon taxes and other carbon-reduction policies, lower foreign demand for Canadian goods and lower commodity prices.

Channel 1: Increase in the domestic carbon tax and other emissions reduction policies

The increase in the domestic carbon tax (and other emissions-related policies) is the most direct channel affecting the Canadian economy. **Figure 3** provides a stylized overview of how a carbon tax affects the Canadian economy:

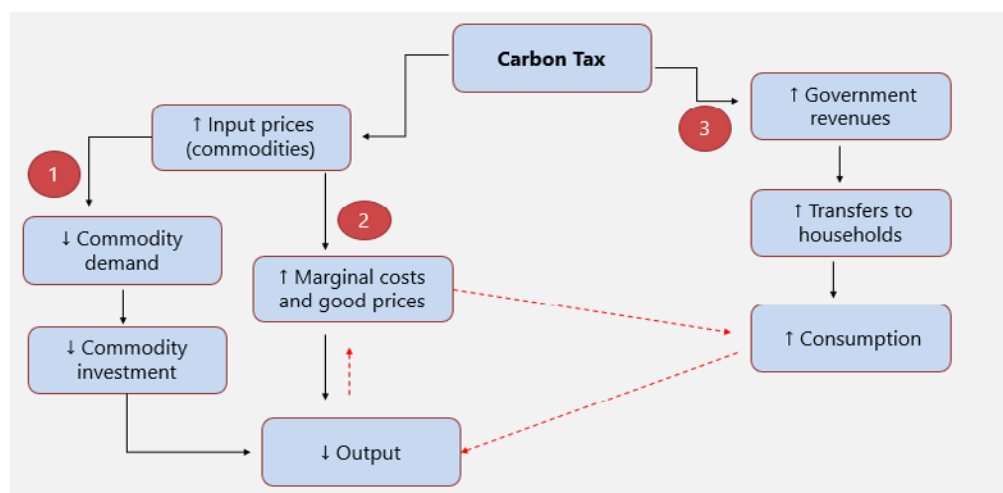


Figure 3. Stylized transmissions channels of a domestic carbon tax

¹⁶ As a result, the scenarios' carbon price paths may differ from those stated by the government.

¹⁷ Our scenarios assume carbon tax revenue is returned to households in the same period as lump-sum transfers, and this may differ from federal carbon tax schemes.

1. The increase in the carbon tax pushes up the price of commodities paid by firms in all sectors. This leads to lower commodity demand that has a heavy impact on the commodity-producing sector, lowering investment and labour demand.
2. Higher input prices push up marginal costs for firms in all sectors. A portion of this increase is passed on to consumers, leading to higher goods and services prices.
3. The carbon tax paid by firms boosts government revenues. Since we assume that all revenues are transferred back to households, this higher income dominates the fall in demand from higher prices and leads to higher consumption in Canada.

Channel 2: Lower foreign demand for Canadian goods.

At the same time that Canada applies the carbon tax and other policies, other countries implement their own measures. In these scenarios, the rise in the carbon tax leads to lower global demand for Canadian goods and services, which weighs on Canadian exports, GDP and inflation.

Channel 3: Lower demand for commodities and lower prices.

Commodity prices, particularly oil prices, decline as a result of lower global demand triggered by policy shifts in other countries. These lower commodity prices transmit through the Canadian economy, weighing heavily on high-cost and high-emission oil production, lowering the terms of trade and thus putting downward pressure on output and inflation.

3.2.2 Global implications of the emissions mitigation scenarios: Insights from BoC-GEM-Fin

We evaluate the global implications of the emissions mitigation scenarios using a large-scale global macroeconomic model, BoC-GEM-Fin (De Resende and Lalonde 2011; Lalonde and Muir 2007). The model is a dynamic stochastic general equilibrium model and thus is in the same class of models as ToTEM III. Unlike ToTEM III, which focuses on a single small open economy, BoC-GEM-Fin comprises five regions that together cover the entire world economy: Canada, the United States, commodity exporters, Asia, and the remaining countries (mainly Europe).¹⁸ The model aims to capture bilateral trade flows and exchange rates between these regions, along with financial frictions on the demand and supply sides of credit markets (De Resende, Dib and Peravalov 2010; Dib 2010).

¹⁸ The model's predictions for Canada play no direct role in our analysis, since ToTEM III provides a significantly more detailed description of the Canadian economy relative to BoC-GEM-Fin. The results emerging from the Canadian block of BoC-GEM-Fin are broadly in line with the ToTEM III results described in the previous section.

The model assumes two types of households in each region: liquidity-constrained and unconstrained. The production side of the model is quite rich, with a dedicated raw materials sector responsible for producing oil and other commodities, and a variety of tradable and non-tradable intermediate goods feeding into the production of final goods ultimately used for consumption and investment purposes. Gasoline is also modelled as a separate intermediate good and represents an input into final consumption of households.

Domestic oil and imported oil represent key inputs in the production of intermediate goods. This model feature makes BoC-GEM-Fin a useful laboratory to study the macroeconomic effects of carbon taxes, which we introduce by allowing the governments in each region to impose a tax on firms' oil inputs. This leads firms to shift their input mix away from oil and consumers to substitute their gasoline consumption with other goods. These taxes are assumed to be paid whether oil inputs are purchased domestically or externally, and the proceeds are distributed to households on a lump-sum basis. As a result, the taxes have no direct effects on overall fiscal balances.

Much as in ToTEM, the specific tax-rate profiles that we impose on the model are chosen to match EPPA-generated carbon tax revenue paths for each region. We also use supply shocks in oil markets to fine-tune oil production volumes and the global price of oil, bringing these in line with EPPA predictions while capturing the impacts of other, non-tax-related green policies in reduced form.

4 Results

4.1 Key sectoral results

Meeting emissions targets requires a rise in the shadow price of carbon, reflecting the increased intensity of government climate policy consistent with the scenario (**Chart 6**). Delayed action leads to a sharper transition. The below 2°C *delayed* scenario maintains the same target of limiting warming to below 2°C as that of the below 2°C *immediate* scenario, but it assumes that policy actions do not intensify until 2030. Because of delayed action, emissions must fall rapidly to make up for lost time, implying a sharper transition through mid-century. In addition, the net-zero 2050 (1.5°C) scenario shows a front-loading of impacts in order to be consistent with the more ambitious target than in the below 2°C *immediate* scenario. However, as advanced technologies in the form of BECCS become available in the net-zero 2050 (1.5°C) scenario, less pressure is placed on the shadow carbon price to reduce emissions in line with the ambition of the scenario.

The transition to a low-carbon economy leads to significant structural change across all industries (**Chart 7**). We see that it is not just fossil-fuel sectors like coal, oil, natural gas, and refined oil reducing their respective emissions levels

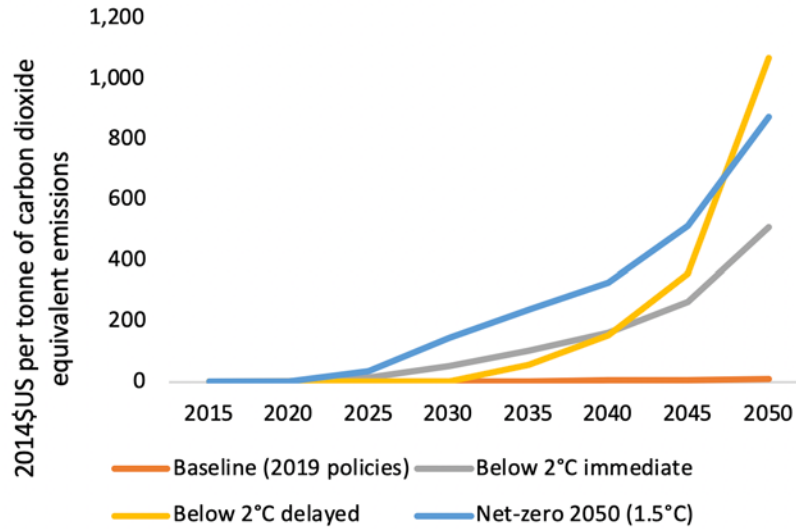


Chart 6. Global GDP-weighted shadow carbon price across scenarios

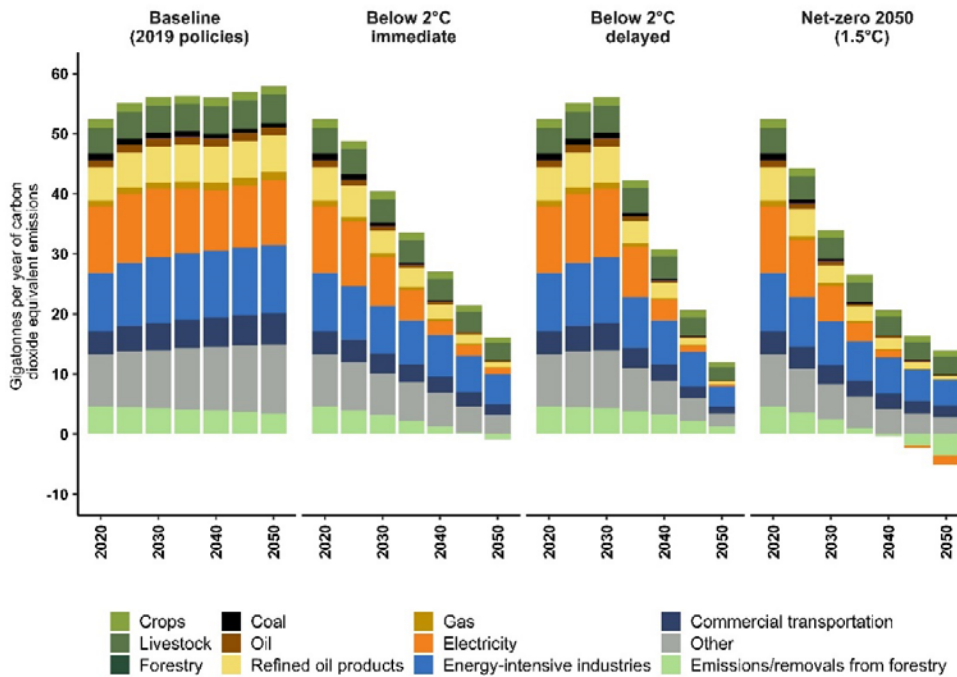


Chart 7. Global greenhouse gas emissions by sector across scenarios

through to mid-century, but all sectors contribute. The fact that the fossil-fuel sectors contribution to global greenhouse gas emissions goes down is largely driven through reduced demand for their products. Some sectors, such as electricity generation and commercial transportation, reduce emissions by relying on advanced technologies and other cost-effective low-carbon solutions. For example, the electricity sector has low- or even zero-emissions technologies at its disposal to help facilitate the decarbonization of the sector (e.g., wind, solar). Many sectors electrify by substituting away from fossil-fuel inputs toward electric-

ity. The transportation sector is a prime example, where large reductions in greenhouse gas emissions are achieved through transitioning from internal combustion engines to electric vehicles.¹⁹

Yet, despite these strategies, other sectors reduce their emissions by less. Energy-intensive industries and livestock are two prime examples. In energy-intensive industries,

19 Some segments of the transportation sector might be harder to decarbonize, and it is not immediately clear whether electrification is an option (e.g., water and air transportation).

concrete, chemical and steel manufacturing, for example, are emissions-intensive. The scenarios rely on electrification and improved energy efficiency to help facilitate the transition. Methane, the principal emission in the livestock sector, is difficult to decarbonize through the channels embedded in the model, such as energy efficiency improvements and electrification.

Global primary energy is presented in **Chart 8**. First, fossil fuels are currently the dominant form of energy. With little additional climate policy assumed in the baseline (2019 policies) scenario, this trend continues through mid-century. In addition, global demand for primary energy rises steadily through time in line with recent trends, indicating no material change in the energy intensity of economic growth in the baseline (2019 policies) scenario. The mitigation scenarios, in contrast, see two distinct changes to these patterns. First, industry invests in becoming more energy efficient, helping to lower the overall demand for energy through mid-century. Second, the composition of energy demand changes. Carbon prices make fossil fuels relatively more costly to consume and encourage a substitution toward lower- or zero-emissions alternatives, such as bioenergy, wind and solar.

Electrification supports decarbonization in many sectors, as described, and is facilitated first through a transition in the electricity sector. Traditional fossil-fuel technologies are decommissioned, and large investments are made in renewable sources of energy to lower the emissions-intensity of electricity generation in all transition scenarios (**Chart 9**). This encourages other sectors to substitute inputs in production toward electricity and away from fossil fuels when climate

policies are introduced. Because of this substitution, we see a material increase in the amount of electricity generation required to support the electrification of the economy.

The net-zero 2050 (1.5°C) scenario allows for BECCS to emerge, beginning in 2035 (**Chart 9**) to bring emissions in global electricity sectors negative (as was shown in **Chart 7**). BECCS plays a key role in reducing emissions in line with the ambition of the net-zero 2050 (1.5°C) scenario, and in some cases puts less pressure on other industries to transition. The amount of BECCS in the Bank's net-zero 2050 (1.5°C) scenario falls within the range of other estimates (**Chart 10**). Although, it should be noted that considerable uncertainty exists around the role BECCS will play by mid-century, due in part to societal acceptance of relying on forests and agriculture for energy and to costs around feedstock and competition for natural resources.

The sectoral restructurings in Canada and the United States along the scenarios are presented **Chart 11** and **Chart 12**, respectively. Similar to what was observed at the global level, the scenarios see all sectors in Canada and the United States contributing to reducing emissions. Yet, some differences between the relative contributions of some sectors are worth noting:

- The electricity sector contributes a greater share of total emissions in the United States than in Canada because of compositional differences in electricity generation (the primary source of electricity in the United States is fossil fuels, while most electricity in Canada comes from renewables). This means the US electricity sector has more opportunity than Canada's to decarbonize by substituting from fossil fuels to renewables like wind

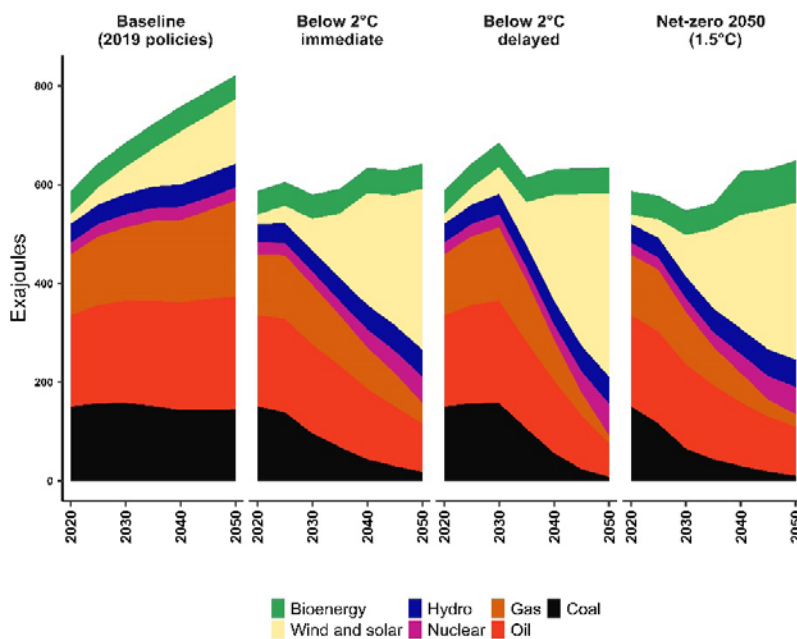


Chart 8. Global primary energy, across scenarios

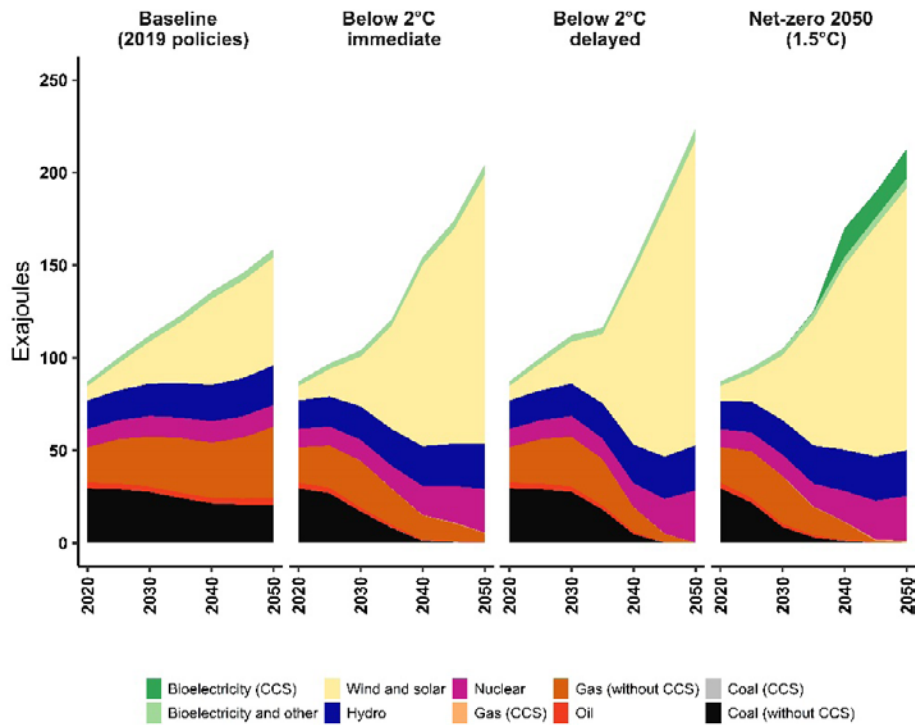


Chart 9. Global electricity generation, across scenarios

Note: CCS stands for carbon capture and storage

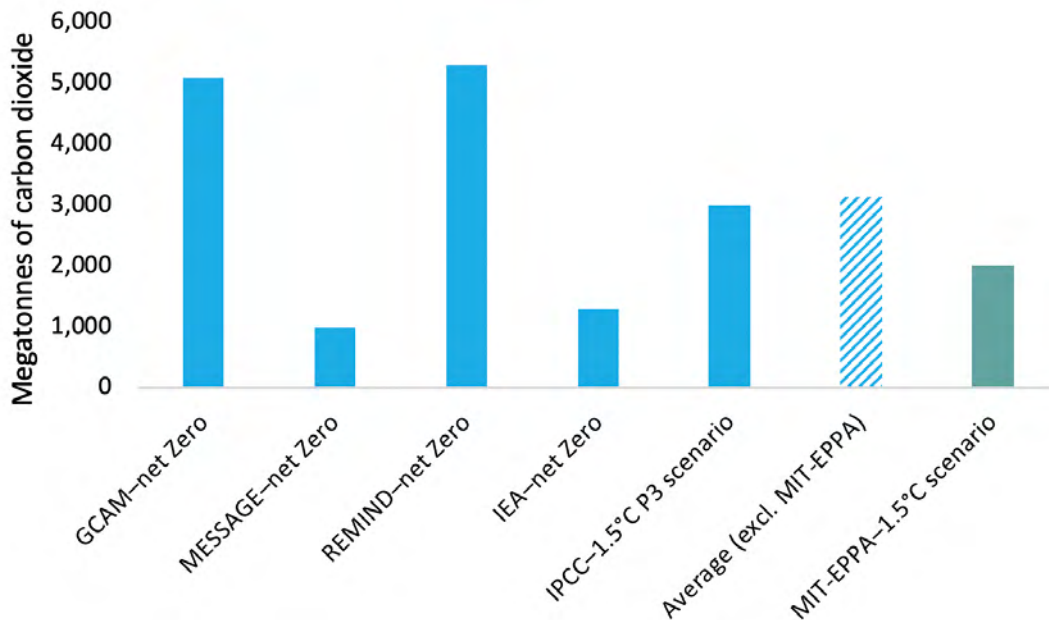


Chart 10. Comparison of bioenergy with carbon capture and storage across various net-zero pathways, 2050

Note: GCAM refers to the Global Change Analysis Model, MESSAGE is the Model of Energy Supply Systems and their General Environment Impact, REMIND is the Regional Model of Investment and Development, IEA is the International Energy Agency, MIT-EPPA is the Economic Projection and Policy Analysis model from MIT.

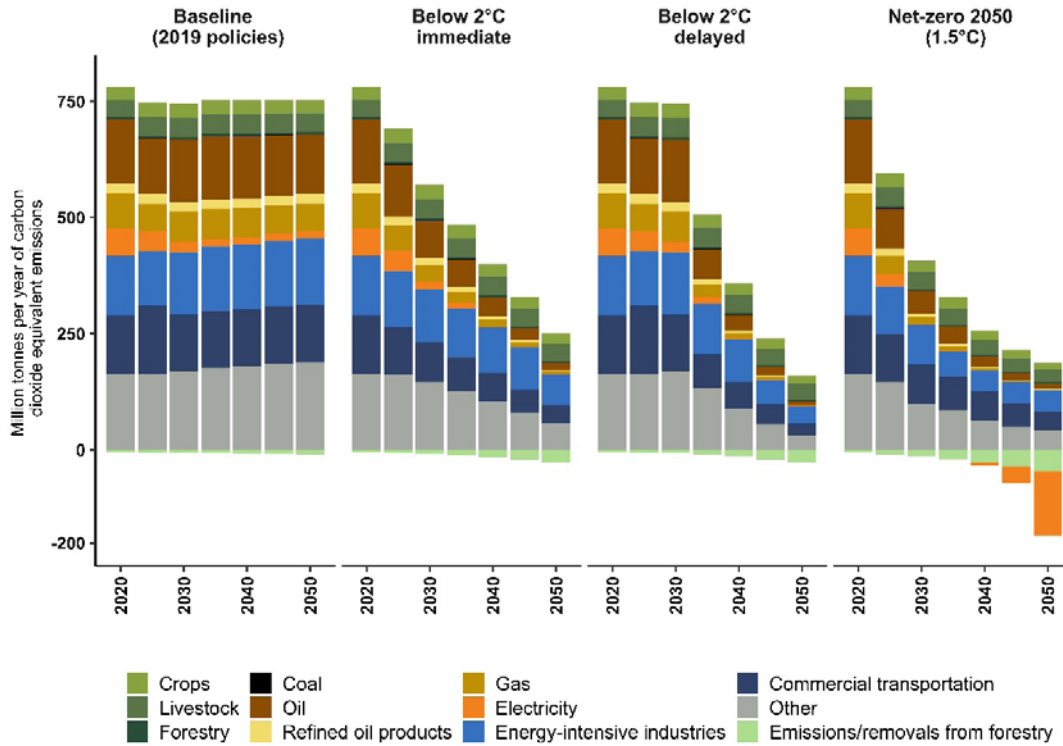


Chart 11. Canada greenhouse gas emissions by sector, across scenarios

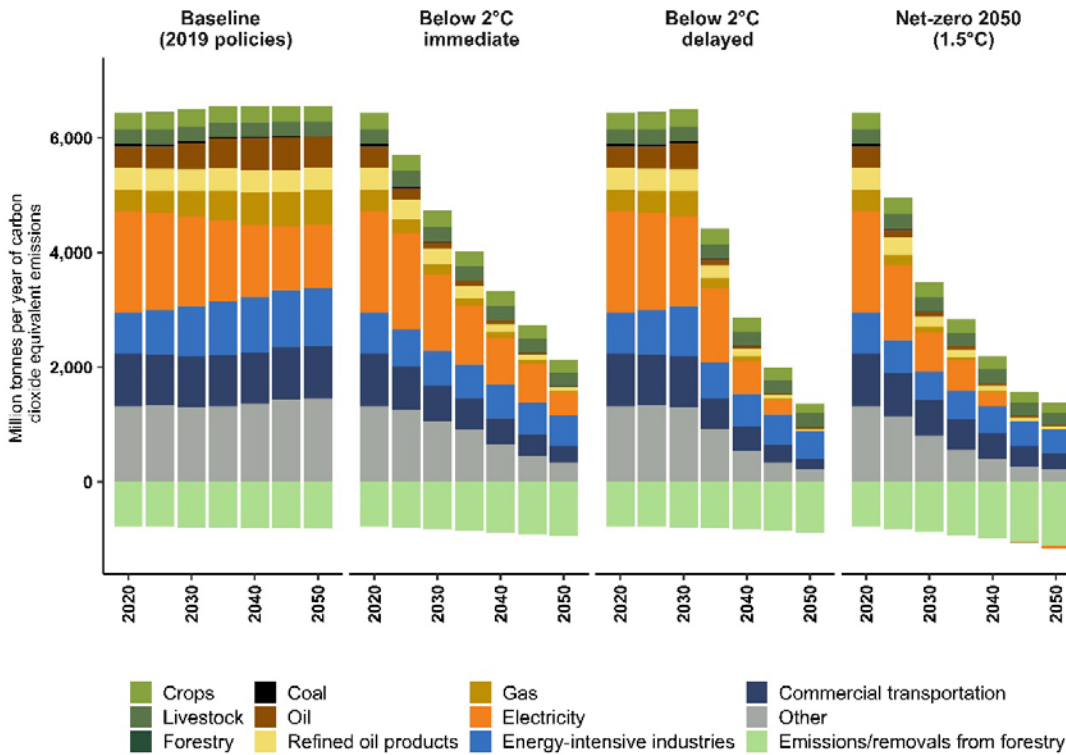


Chart 12. US greenhouse gas emissions by sector, across scenarios

and solar. This contributes to significant reductions in emissions through the transition.

- Proportionally fewer reductions in emissions can be achieved in the electricity sector in Canada by substituting away from fossil fuels. As a result, negative emissions technologies like BECCS appear to play a key role in having the sector contribute to Canada’s net-zero commitments by mid-century.
- Forest carbon sequestration plays a larger role in the US carbon budget than in Canada’s—a trend that is assumed to continue in all scenarios.

4.2 Mapping climate scenario data into sectoral financial impacts

We mapped selected outputs from the scenarios developed in this pilot into components of net income to reflect changes in direct emissions costs, indirect costs, capital expenditures and revenues along the transition path relative to the baseline scenario. These components were calculated for every country/region and sector in the analysis using the following generalized equations:

$$\begin{aligned} \text{Revenues} &= \text{output price} * \text{production} & (1) \\ \text{Direct emissions costs} &= \text{carbon price} * \text{scope 1 emissions} & (2) \\ \text{Indirect costs}^{20} &= \text{input price} * \text{inputs in production} & (3) \\ \text{Capital expenditures} &= \text{capital price} * \text{new capital added} & (4) \end{aligned}$$

An increase in a sector’s costs associated with the release of greenhouse gases from burning fossil fuels is measured

20 This reflects all inputs in production, excluding capital and labour.

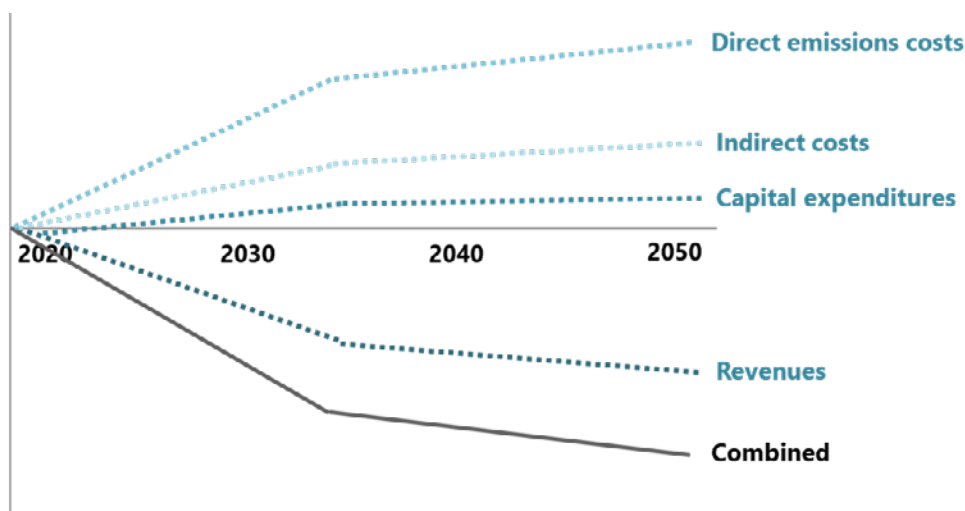
as direct emissions costs. Upstream sectors may pass on their direct emissions costs to other sectors, measured as indirect costs for those sectors. A sector may require investments in new technologies in order to become more efficient, increasing capital expenditures. Finally, revenues may fall because of reduced demand for the sector’s output if it remains emissions-intensive.

The combined effect on the components of net income illustrates how the sector as a whole is affected through the transition and helps us evaluate the financial impacts on a given sector. A stylized chart of the evolution of the components of net income is presented in **Chart 13**, while an in-depth example illustrating the evolution of these components for the electricity sectors in Canada and the United States is presented in **Box 1**. Data for the components of net income across all sectors and geographies included in the scenarios are provided in the accompanying database.

Assessing the financial impacts across sectors shows diverse impacts from the transition to a low-carbon economy (**Chart 14**). We can group the sector impacts into three broad buckets:

- those that experience a decline in demand as economies decarbonize
- those that experience a rise in demand through the transition
- others that experience challenges associated with increases in emissions costs or increases in capital costs to mitigate their exposure to the transition

The financial impacts may also vary across geographies, even for the same sector (**Chart 15**). For illustrative pur-



$$\text{Net income} = \text{revenues} - \text{direct emissions costs} - \text{indirect costs} - \text{capital expenditures}$$

Chart 13. Illustrative evolution of the components of net income, percent change from baseline

poses, recall the evolution of the electricity generation sector between Canada and the United States (Box 1). In Canada, a majority of electricity is already generated from renewable sources. This means it is a relatively lower emissions-intensive source of energy (compared with fossil fuels), supporting early electrification of the Canadian economy. In contrast, the United States currently produces the majority of its electricity from

fossil fuel sources, implying a longer path to decarbonization. Therefore, large investments are made to lower the emissions-intensity of electricity generation in the United States, adversely affecting the sectors' net income in the short run. After this costly transition period is complete, the benefits of broad electrification in the United States can materialize.

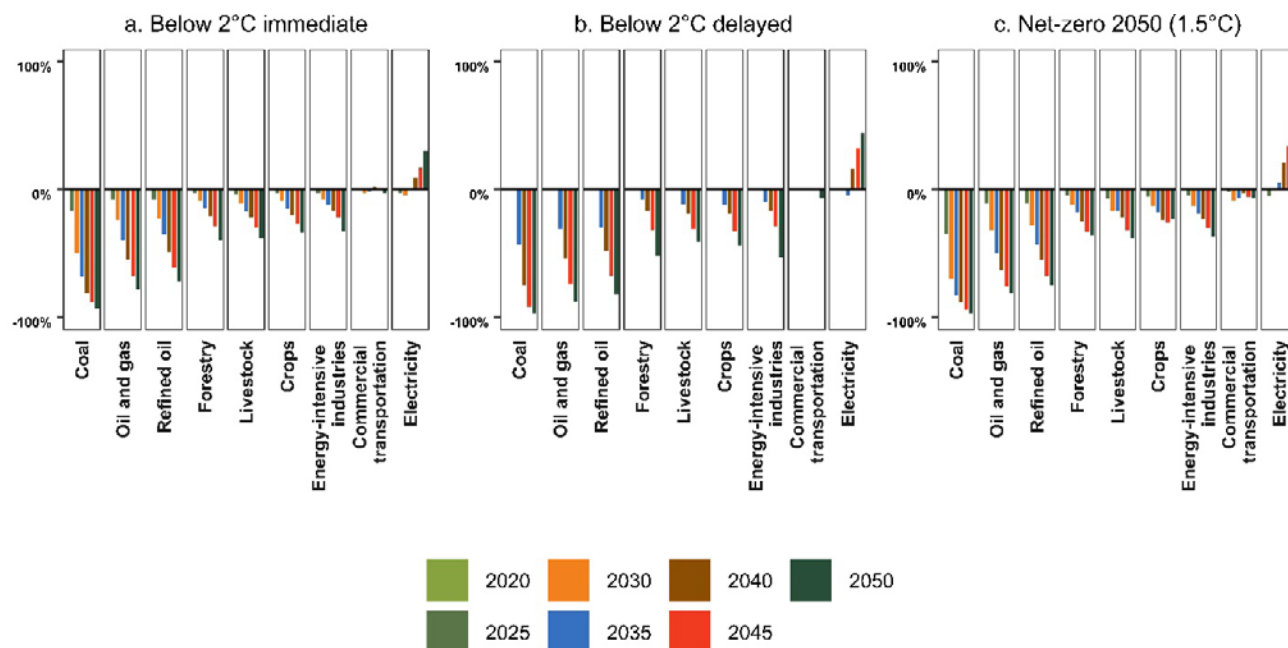


Chart 14. Change in global sectoral net income relative to baseline (2019 policies) across scenarios

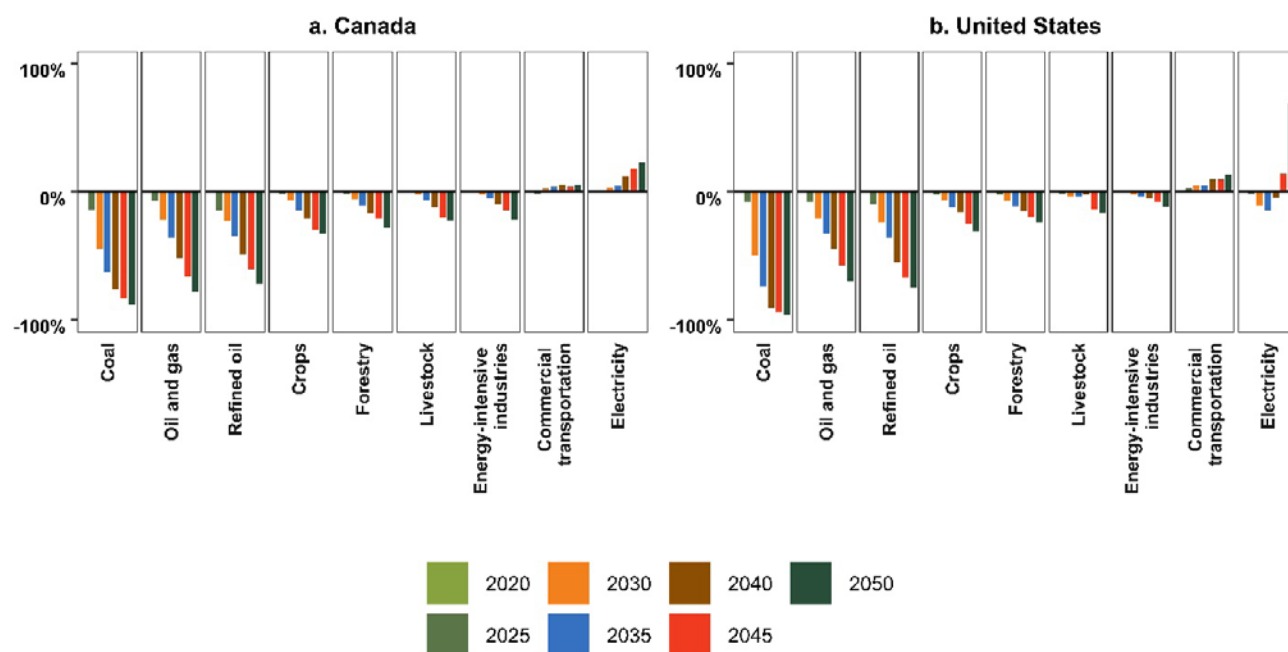


Chart 15. Change in sectoral net income under below 2°C immediate scenario relative to baseline (2019 policies) for Canada and the United States

Box 1: Electricity pathways for Canada and the United States

The electricity sectors in Canada and the United States both invest in renewable sources of electricity and shift away from traditional fossil fuels. As the sectors reduce the emissions-intensity of electricity, it becomes a more desirable input in production for downstream producers. As a result, the transition scenarios see an increased demand for electricity—known as electrification.

While both countries share this broad storyline, the dynamics differ:

- Canada’s electricity grid is already relatively green, and the introduction of fossil-fuel-penalizing carbon taxes makes the lower emissions-intensive electricity a more desirable substitute almost immediately. Transition scenarios see a rapid electrification in Canada, with the below 2 °C delayed and net-zero 2050 (1.5 °C) scenarios having a sharper transition and a larger amount of electricity demanded through mid-century (Chart 1-A, panel a).
- Conversely, widespread electrification of the US economy does not take place until the electricity sector moves sufficiently away from traditional fossil-fuel sources of energy (Chart 1-A, panel b). This happens late in the below 2 °C immediate scenario, which encourages sharp investments in renewables like wind and solar. This adjustment occurs earlier in the below 2 °C delayed and net-zero 2050 (1.5 °C) scenarios because restructuring of the economy is sharper and relies more on electrification to meet climate targets.

The transition scenarios for Canada see a short-term rise in the direct emissions costs as carbon prices rise,

penalizing the small amounts of remaining fossil-fuel generation (Chart 1-B). As the sector removes these utilities, the direct emissions costs fall to nearly zero. Since these costs under the baseline (2019 policies) scenario are nearly zero in 2050, the below 2 °C delayed scenario shows a large percentage increase in direct emissions costs in 2050—this is a negligible change in true costs. The costs in the United States are more material because of the continued reliance on fossil fuels through the transition. Under the net-zero 2050 (1.5 °C) scenario, the direct emissions costs become negative after 2040 for Canada and after 2045 for the United States due to carbon dioxide removal technologies, including bioenergy with carbon capture and storage. Direct emissions costs in the net-zero 2050 (1.5 °C) scenario may become negative due to electricity being produced from negative emissions technologies. Since these costs under the baseline (2019 policies) scenario are nearly zero, the percentage change in direct emissions costs in the net-zero 2050 (1.5 °C) scenario versus the baseline (2019 policies) scenario may be a large negative number.

Changes in capital expenditures in the two countries are largely driven by investments in lower-emitting sources of electricity, as well as by the removal and decommissioning of fossil-fuel utilities. Revenue changes in both countries are mostly positive: Canada experiences an earlier benefit through an earlier move to electrification brought about through its greener starting point. The United States takes longer to adjust, and thus the benefits accrue as we move closer to mid-century.

Box 1 (continued)

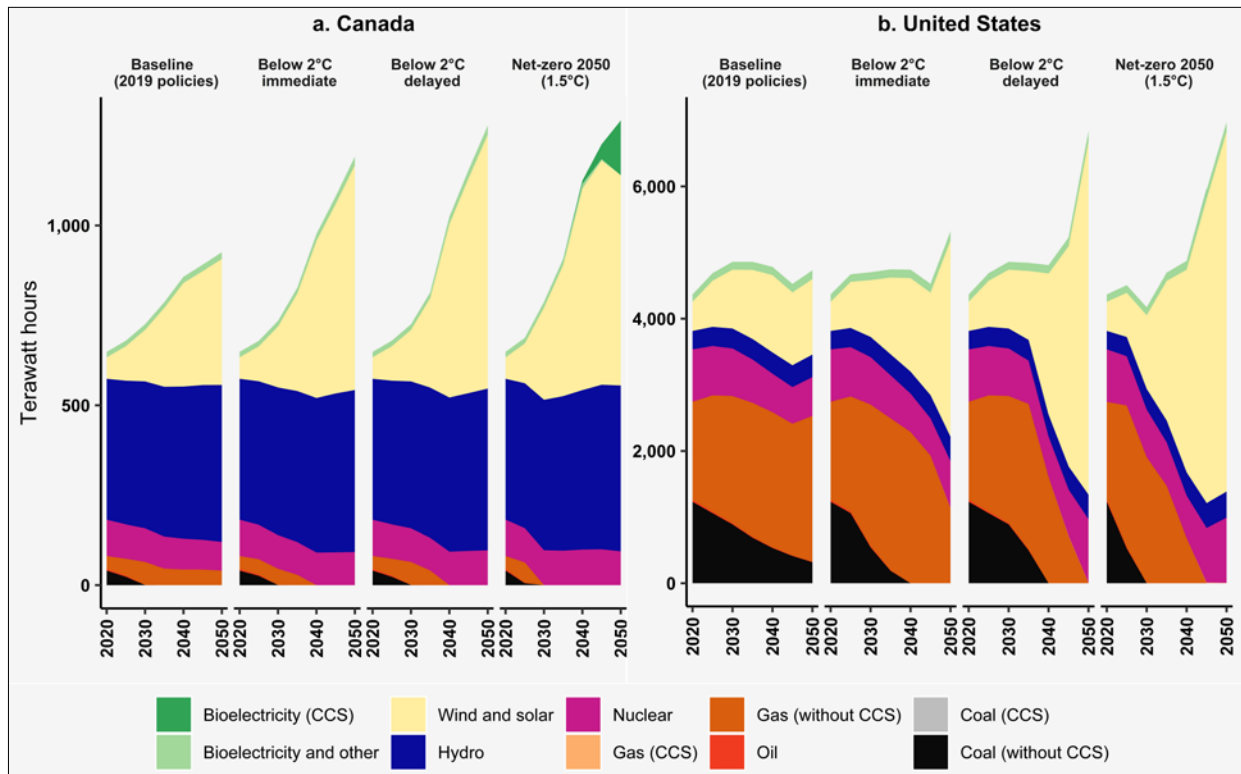


Chart 1-A. Projected electricity generation in Canada and the United States across the scenarios

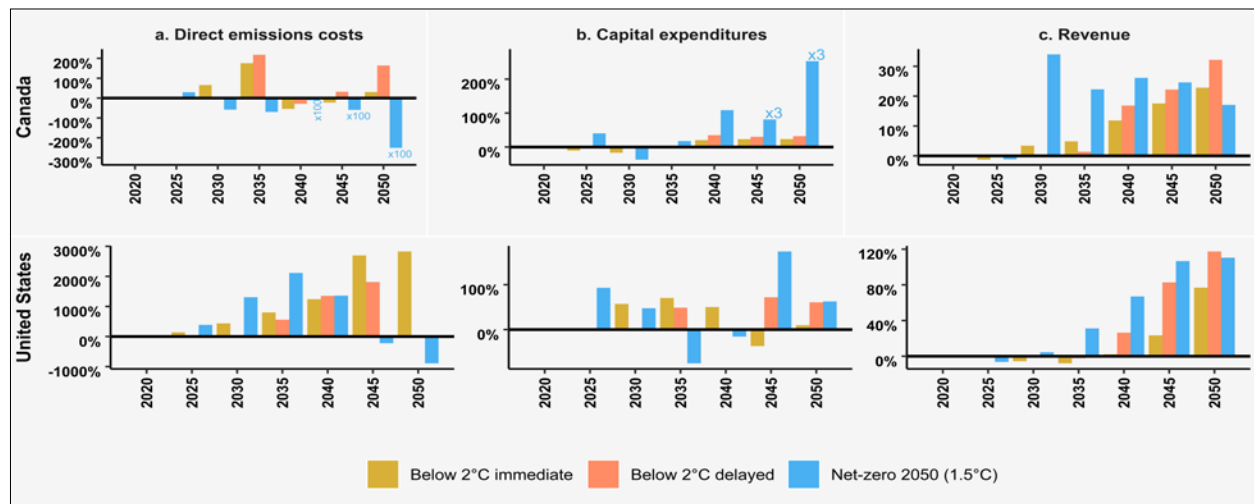


Chart 1-B. Projected changes in the components of net income for the Canadian and US electricity sectors relative to the baseline (2019 policies)

4.3 Macroeconomic results

The impacts of the transition scenarios to the level of Canadian GDP are material by mid-century, driven largely by global factors (Chart 16).²¹ The increase in the domestic carbon price pushes up the prices firms pay for fossil fuels, leading to lower demand for these products and heavily impacting commodity-producing sectors. In addition, a portion of the costs are passed through to consumers, leading to higher prices for goods and services.

Taken together, these effects weigh on GDP. However, as assumed in the scenarios, revenues from the carbon pricing scheme are transferred back to households, and this higher income offsets most of the adverse impacts. At the same time that climate policies are introduced domestically, other countries implement their own measures. This has two main effects:

- The rise in global efforts to combat climate change leads to lower foreign demand for goods and services, adding a further drag to domestic GDP.
- Global commodity prices decline as a result of lower global demand triggered by policy shifts around the world. This second effect weighs heavily on fossil-fuel-producing sectors and lowers the terms of trade of net energy-exporting regions.

The scenarios also highlight the importance of policy timing, with delayed action requiring a sharper transition and larger macroeconomic impacts. In contrast to the 2°C immediate scenario, climate policy action is delayed by 10 years in the 2°C delayed scenario, requiring a steeper increase in the shadow price of carbon to meet the same level of climate ambition. This exacerbates the channels by which climate policy affects the macroeconomy, leading to a sharper and more material decline of GDP by mid-century. While

not considered here, delayed climate action could trigger financial stress of the economy in the short-run, leading to sharper declines of GDP and business investment as well as a rise in cyclical unemployment. These issues are discussed further in Appendix B, but a more formal analysis is left for future work.

Comparing the below 2°C immediate scenario and net-zero 2050 (1.5°C) scenario, we see that the sharper increase in carbon prices required under the net-zero 2050 (1.5°C) scenario leads to a more front-loaded impact. Core inflation declines in all scenarios as lower foreign demand and commodity prices more than offset the cost-push effect of the tax increase. In reaction to disinflationary pressures, monetary policy adopts a more accommodative stance through a persistently lower policy rate.

Chart 17 presents headline results for the US economy along the transition scenarios. In the below 2°C immediate scenario, the impact on US GDP reaches about -4 percent in 2050 compared with its baseline level. In the below 2°C delayed scenario, the impact is larger and more abrupt, reaching -5 percent by 2050 relative to the baseline. Finally, the net-zero 2050 (1.5°C) scenario leads to a decline in US GDP close to that under the below 2°C immediate scenario. However, the time path is more abrupt, due to a need for more stringent policies in earlier parts of the simulation period.

Carbon taxes act like a negative supply shock in the scenarios, increasing both core and headline inflation in the United States. Faced with higher costs, firms invest less, lowering US output. Consumption also falls as a result of a decline in both incomes and wealth. However, since energy sectors do not account for as large a share of the economy in the United States as they do in Canada, the impact on investment and consumption is smaller than in Canada and other commodity-exporting countries.

21 It is important to note that while the GDP level changes relative to the baseline, GDP growth is still positive in the scenarios.

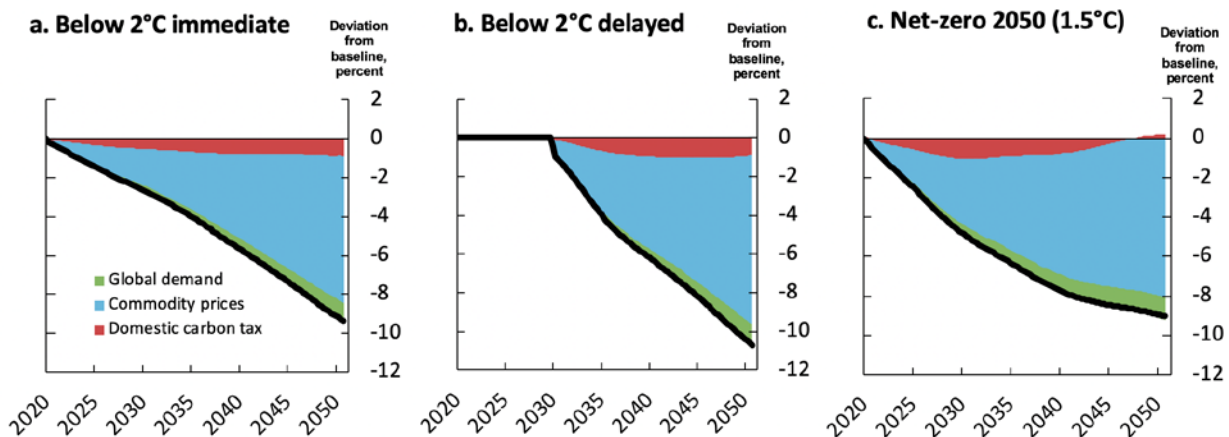


Chart 16. Decomposition of the level of Canadian GDP impacts across scenarios

Commodity-exporting regions are hit most severely in the transition scenarios as a result of a lower global demand for oil stemming from higher carbon taxes in all regions (**Chart 18**).²² In contrast, the Asian region, which is a net commodity importer, experiences a notably smaller decline in GDP relative to the baseline. Results for the United States and Europe fall between these polar cases. These findings suggest that the transition to a lower carbon economy should be more costly for commodity exporters, like Canada, relative to other economies.

22 Relative to baseline, pre-tax oil prices fall in world markets 33 percent by 2050 in the below 2°C *immediate* scenario, 38 percent in the below 2°C *delayed* scenario and 34 percent in the net-zero 2050 (1.5°C) scenario.

Non-energy commodity prices also fall along the scenarios as a result of lower levels of overall economic activity, though this effect is partially offset by the fact that firms respond to carbon taxes by substituting from oil to non-oil commodities in their input mixes. In the below 2°C *immediate* scenario, the net effect is a 6.7 percent drop in non-energy commodity prices by 2050 relative to baseline, while the corresponding figures in the net-zero 2050 (1.5°C) and below 2°C *delayed* scenario are 6.2 and 7.9 percent, respectively.

5 Discussion and conclusions

The assessment of the macroeconomic and financial risks associated with transitioning to a low-carbon economy is still in its early stages. This paper focused on the develop-

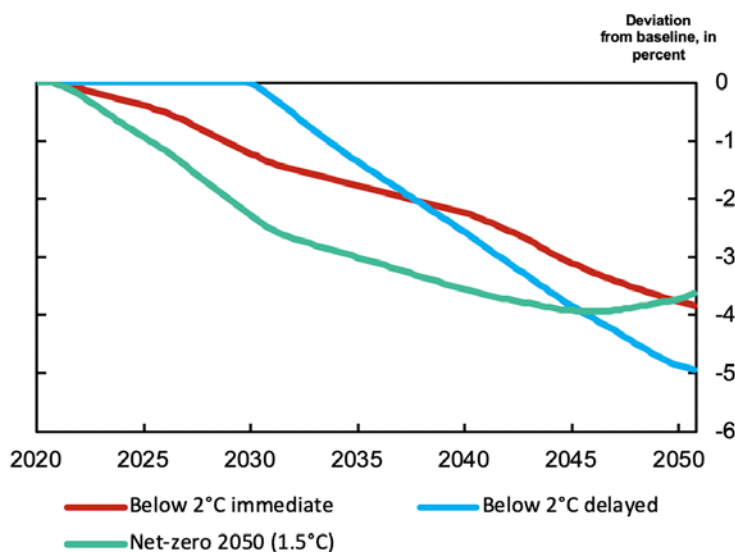


Chart 17. GDP-level impact for the US economy in the emissions mitigation scenario

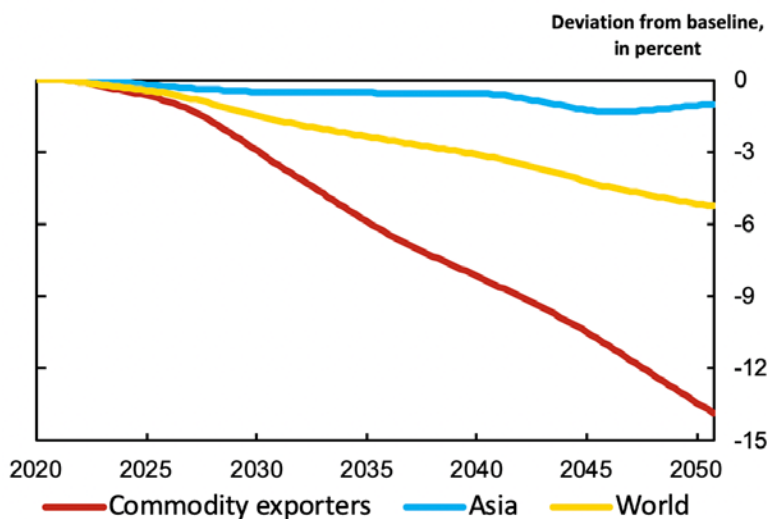


Chart 18. GDP-level impact for the world in the below 2°C *immediate* scenario

ment of Canadian-centric transition scenarios intended to shed light on the risks to the macroeconomy and financial system of a transition to a low-carbon economy. As previously discussed, the scenarios presented in this report do not aim to predict the most likely outcome, rather they explore plausible but intentionally adverse transition pathways that put pressure on industry to decarbonize.

In our approach, we begin by identifying various scenarios that capture a distribution of potential risks across climate policy pathways through mid-century. We assess these pathways using a multi-country, multi-sectoral model capable of capturing the economic restructuring along the transition. Then we pair this model with two structural macroeconomic models to get a better sense of the macroeconomic impacts associated with the scenarios. Finally, we translate the scenarios into sector-specific financial information that describes the balance sheet impacts on select emissions-intensive sectors of the economy. The data behind the scenarios are provided in an accompanying database.²³

It is important to note that technological change, innovation and policy could play a key role in easing the transition. The transition scenarios presented in this paper rely conservatively on technology. That is, technologies that are not yet currently commercially available or that could face scalability issues in the future are assumed to be unavailable. However, several advanced technologies currently being developed show promise and could ease the transition. As pointed out in a recent report by the Canadian Institute for Climate Choices (CICC), these include geothermal energy, small modular nuclear reactors, hydrogen, second-generation biofuels and a wide range of clean technologies (CICC 2021).²⁴ In addition, the scenarios

do not fully capture all the benefits-associated opportunities for green growth, including innovation in new products and services or the creation of new industries and sectors. Those that are relevant to the Canadian context are outlined in that same recent report by the CICC. Innovation and investments in advanced technologies are essential to support the transition and mitigate its costs. Finally, policy could play a key role in easing the transition. The transition scenarios assumed carbon pricing schemes were revenue neutral, with proceeds returned entirely to households. Alternative uses of carbon pricing revenues could ease the transition, including public investments in green growth and innovation.

Some channels and relationships that emerged through the research warrant further investigation. The scenarios presented here focus exclusively on transition risks and do not consider the benefits associated with avoided physical risks or the interaction between transition and physical risks. In addition, we need to better understand the effects of disorderly transitions that could trigger the implementation of carbon border adjustments.

The scenario development described in this paper is the first step toward better understanding the economic and financial system impacts of a transition to a low-carbon economy. Further geographic and sectoral granularity in the scenarios is needed to provide a more refined picture of how the restructuring might unfold. In addition, further research is needed on how the macroeconomy and financial system will adjust through the transition: for example, a more detailed investigation of capital and labour mobility would allow us to better understand sectoral adjustments, stranded capital and unemployment effects. Finally, it is important to improve our understanding of how abrupt global policy changes could increase the risks of financial stress.

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23 The database is available on the Bank's website.

24 For example, blue hydrogen could be produced alongside natural gas with carbon capture and storage while providing a low-emissions source of energy for many downstream industries. Another promising technology is utility-scale battery storage as it continues to improve and become cheaper. These cost declines will make decarbonizing electricity systems easier.

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Appendix A. Charts and table

Table A-1. Emissions by country/region (million tonnes of carbon dioxide equivalent)

Country	Scenario	2020	2025	2030	2035	2040	2045	2050
Africa	Baseline (2019 policies)	4,413	4,764	4,868	5,102	5,290	5,671	6,112
Canada	Baseline (2019 policies)	776	741	739	746	745	744	743
China	Baseline (2019 policies)	12,709	13,287	13,233	12,517	11,626	11,646	11,793
Europe	Baseline (2019 policies)	4,694	4,331	3,770	3,315	3,020	2,889	2,793
Global	Baseline (2019 policies)	52,371	55,040	56,094	56,350	55,987	56,907	57,893
India	Baseline (2019 policies)	3,937	4,509	5,045	5,427	5,793	5,985	6,146
Japan	Baseline (2019 policies)	1,000	969	876	810	736	719	702
Rest of the world	Baseline (2019 policies)	19,179	20,776	21,858	22,667	23,018	23,501	23,858
United States	Baseline (2019 policies)	5,662	5,663	5,705	5,767	5,760	5,753	5,746
Africa	Below 2°C delayed	4,413	4,764	4,868	3,729	2,966	2,249	1,628
Canada	Below 2°C delayed	776	741	739	497	345	219	132
China	Below 2°C delayed	12,709	13,287	13,233	9,908	7,214	4,825	2,804
Europe	Below 2°C delayed	4,694	4,331	3,770	3,313	2,310	1,465	776
Global	Below 2°C delayed	52,371	55,040	56,094	42,133	30,802	20,579	11,917
India	Below 2°C delayed	3,937	4,509	5,045	4,054	3,075	1,861	737
Japan	Below 2°C delayed	1,000	969	876	567	328	191	99
Rest of the world	Below 2°C delayed	19,179	20,776	21,858	16,465	12,523	8,621	5,268
United States	Below 2°C delayed	5,662	5,663	5,705	3,601	2,041	1,149	474
Africa	Below 2°C immediate	4,413	4,082	3,403	2,847	2,287	1,794	1,260
Canada	Below 2°C immediate	776	660	562	472	383	308	225
China	Below 2°C immediate	12,709	12,172	10,148	8,253	6,732	5,460	3,999
Europe	Below 2°C immediate	4,694	4,250	3,484	2,918	2,342	1,856	1,316
Global	Below 2°C immediate	52,371	48,632	40,438	33,591	27,049	21,409	15,200
India	Below 2°C immediate	3,937	3,665	3,030	2,537	2,039	1,584	1,071
Japan	Below 2°C immediate	1,000	936	753	616	477	367	245
Rest of the world	Below 2°C immediate	19,179	18,125	15,162	12,771	10,338	8,206	5,886
United States	Below 2°C immediate	5,662	4,743	3,898	3,177	2,450	1,834	1,198
Africa	Net-zero 2050 (1.5°C)	4,413	3,656	2,860	2,084	1,403	1,132	830
Canada	Net-zero 2050 (1.5°C)	776	585	395	309	224	143	3
China	Net-zero 2050 (1.5°C)	12,709	10,997	8,729	6,721	5,734	4,086	2,732
Europe	Net-zero 2050 (1.5°C)	4,694	3,582	2,314	1,889	1,423	735	246
Global	Net-zero 2050 (1.5°C)	52,371	44,313	33,927	26,473	20,366	14,112	8,809
India	Net-zero 2050 (1.5°C)	3,937	3,937	3,166	2,584	2,016	1,424	863
Japan	Net-zero 2050 (1.5°C)	1,000	809	643	472	315	107	- 9
Rest of the world	Net-zero 2050 (1.5°C)	19,179	16,622	13,225	10,507	8,038	5,965	3,929
United States	Net-zero 2050 (1.5°C)	5,662	4,125	2,595	1,908	1,214	521	215

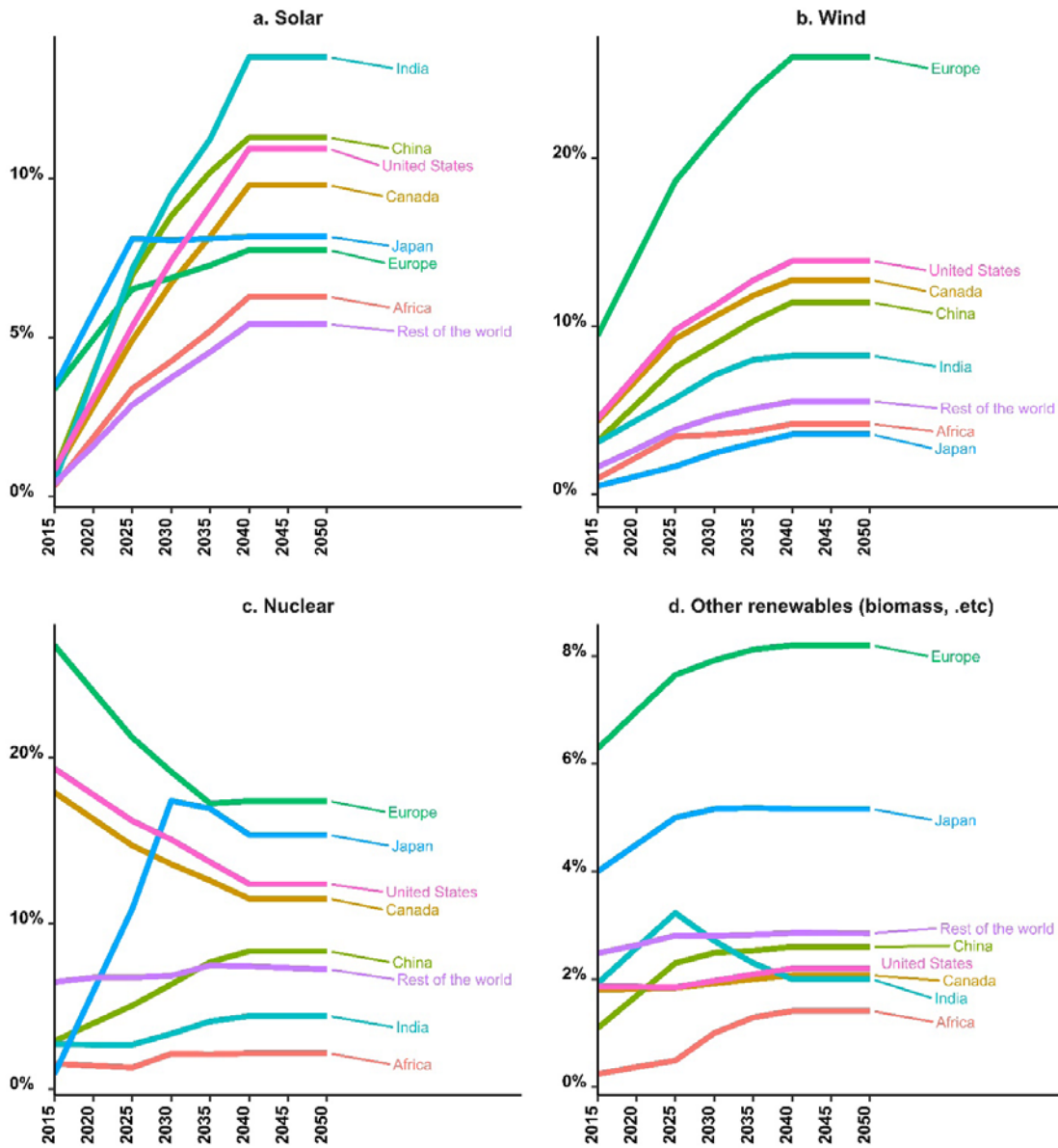


Chart A1. Renewable shares in total electricity generation, by type and region

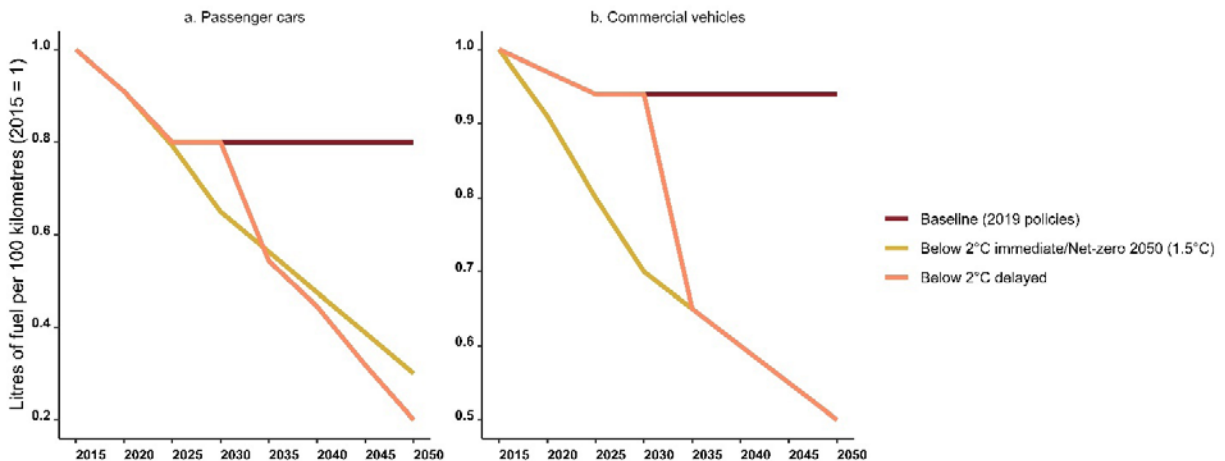


Chart A2. Corporate Average Fuel Economy standards on passenger and commercial vehicles

Appendix B. A financial stress channel and its macroeconomic implications

As described in section 2, the climate-transition scenarios developed for the pilot differ based on both the climate target and the speed of the transition to a low-carbon economy. Once announced, policies to curb emissions are increased steadily over time and are well understood by firms and households. As a result, the economy adapts smoothly, and resources have time to be reallocated across sectors. This approach is consistent with climate-transition modelling, which has traditionally been used to assess optimal policy paths for emissions reductions. However, the approach omits important frictions (e.g., search and matching frictions in the labour market) and systemic financial risk channels that could increase the economic short-run costs of the transition. We discuss how abrupt global policy changes could increase the risks of financial stress, particularly in countries with significant fossil-fuel exports, such as Canada.

The macroeconomic scenarios discussed in section 4.3 underscore how external changes in climate policy could have significant macroeconomic costs for Canada. Relative to the results presented in section 4.3, the abrupt shift in the global policy path in the below 2°C delayed scenario could have a much more acute impact in the short run if it triggered a disorderly reaction from financial markets.

To capture the potential impacts of such a disorderly reaction, we developed an alternative version of the below 2°C delayed scenario in which we capture the effects of financial stress by using shocks to risk spreads, household wealth and business and consumer confidence. In particular, the increase in risk spreads is intended to capture uncertainties surrounding the exposures of firms, households and financial institutions to climate transition risks. At the same time, we use shocks to household wealth to capture the effects of fire sales and other mechanisms that might move asset prices out of line with fundamentals during episodes of financial market disorder. Finally, business and consumer confidence shocks capture the impact that such episodes tend to have on consumption and investment behaviour. Shocks were calibrated based on experience during previous stress events, namely the 2008–09 economic and financial crisis and the 2014–15 oil price shock.

Chart B-1 illustrates the impact of such a scenario and shows how market repricing could pull forward transition costs, making for an earlier and more volatile adjustment.

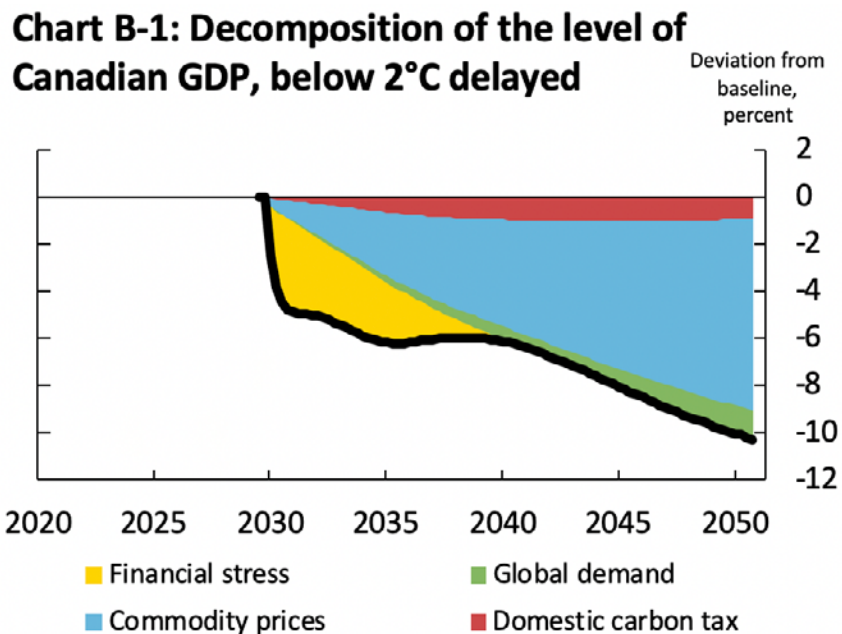


Chart B-1. Decomposition of the level of Canadian GDP, below 2°C delayed

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