



Economics Discussion Papers

Macroeconomic Impacts of the Transition to Net Zero in Small Open Economies: A Case Study for Canada

Tatjana Dahlhaus, Madan Ghosh, Yena Joo, Stephen Murchison, Genevieve Nelson, Rachit Lumb, Jonathan Swarbrick, Alexander Ueberfeldt, Raven Wheesk, Yinxu Xie, and Yang Zhang

Economics Discussion Paper No. 2604

Published: 29 September 2026

JEL classification: E27; E52; Q43; Q58

Keywords: macroeconomic simulations; transition to net-zero; climate policies; scenario analysis

Department of Economics, Business School, University of St Andrews

Discussion Papers Series

ISSN 2978-4026

<https://ideas.repec.org/s/san/econdp.html>

bschoolecondor@st-andrews.ac.uk

Macroeconomic Impacts of the Transition to Net Zero in Small Open Economies: A Case Study for Canada*

Tatjana Dahlhaus, Madan Ghosh, Yena Joo, Stephen Murchison,
Genevieve Nelson, Rachit Lumb, Jonathan Swarbrick, Alexander Ueberfeldt,
Raven Wheesk, Yinxi Xie, Yang Zhang

September 29, 2026

Abstract

Climate change presents significant macroeconomic challenges, particularly for small open economies deeply integrated into global trade and energy markets. Focusing on Canada, we analyze the macroeconomic implications of the transition to a low-carbon economy, paying attention to global and domestic spillovers. On the domestic side, we introduce Energy-ToTEM (E-ToTEM), an extension of the Bank of Canada's Terms-of-Trade Economic Model (ToTEM), which captures energy sector dynamics, substitution effects, and policy interactions. To account for international forces, we use a global, multi-sector, multi-region general equilibrium model, allowing us to assess international climate policy transmission and global demand implications for Canada. Our results indicate that, under the net-zero scenario, global carbon prices rise persistently through 2050. By 2050, world gross domestic product (GDP) is about 8% lower and Canadian GDP about 7% lower relative to a no-policy benchmark, while inflation rises modestly under the historical monetary policy rule. Monetary policy faces a clear trade-off: strict inflation targeting would deepen the Canadian output loss to about 7.5%, whereas a more accommodative stance would limit it to around 5.5%, at the cost of inflation about 1 percentage point above target. Overall, our findings highlight the importance of accounting for both global spillovers and monetary policy when evaluating the macroeconomic consequences of the transition to net zero.

JEL: E27, E52, Q43, Q58 **Keywords:** Macroeconomic simulations; Transition to net-zero; climate policies; scenario analysis

*Dahlhaus (corresponding author): Bank of Canada (tdahlhaus@bank-banque-canada.ca); Ghosh: Carleton University (MadanmohanGhosh3@cunet.carleton.ca); Joo: Bank of Canada (yenajoo@bank-banque-canada.ca); Murchison: Bank of Canada (smurchison@bank-banque-canada.ca); Nelson: Bank of England (genevieve.nelson@bankofengland.co.uk); Lumb: (rachit_l@yahoo.com); Swarbrick: University of St Andrews (jms48@st-andrews.ac.uk); Ueberfeldt: Bank of Canada (aueberfeldt@bank-banque-canada.ca); Wheesk: Bank of Canada (rwheesk@bank-banque-canada.ca); Xie: Indiana University, Bloomington (yinxxie@iu.edu); Zhang: Bank of Canada (yangzhang@bank-banque-canada.ca).
The views expressed here do not necessarily reflect those of the Bank of Canada, the Bank of Canada's Governing Council or the Bank of England.

1 Introduction

Climate change poses significant macroeconomic challenges arising from the frequency and severity of climate-related events (e.g., wildfires, floods) and the policy-driven transition to a low-carbon economy. Climate policies aimed at supporting the transition to a low-carbon economy influence macroeconomic variables such as inflation, output, and relative prices. For example, carbon taxes and green investment subsidies may raise energy costs, alter production structures, and shift sectoral demand, permanently reshaping the economy's structure.

While elected governments are responsible for policies designed to smooth the path to net-zero carbon emissions, the economic implications are of interest to all economic entities. In Canada, the commitment to achieve net-zero emissions by 2050 is legislated through the Canadian Net-Zero Emissions Accountability Act, which became law in June 2021.¹ Understanding the economic implications—particularly for inflation and output—of a global and domestic transition to net zero is crucial for monetary policymakers as they navigate the transition while seeking to achieve their policy objectives.

A key question is how this transition will impact small open economies, given their deep integration in global trade and energy markets, and what this means for maintaining low and stable inflation. These economies face particular challenges, including exposure to shifts in global demand for fossil fuels, the need for sectoral reallocation, and the macroeconomic consequences of climate policies implemented by larger economies.

This paper focuses on Canada as a representative case with characteristics that make it especially relevant for examining the macroeconomic implications of the net-zero transition. First, Canada is a small-open economy with a high trade-to-GDP ratio (above 60%), reflecting its deep integration into global markets. The country relies on international trade, particularly with the United States (its largest trading partner), as well as with Europe and Asia. Second, as a net exporter of oil and gas, Canada faces the prospect of a shrinking major sector during the net-zero transition, while simultaneously serving as a supplier of non-energy commodities essential for that very transition.² Third, Canada is already relatively green: Over 80% of its electricity production is non-emitting. Starting from a greener electricity sector suggests that abatement could become more costly on the path to net zero emissions.

We ask two questions. First, how large are the output and inflation costs of a globally consistent transition to net zero for a small open economy that is a net exporter of brown energy? Second, since the transition is stagflationary, should monetary policy approach the resulting trade-off with greater flexibility, accommodating additional inflation in order to limit output losses? Answering the second question requires a framework in which nominal rigidities and an explicit monetary policy rule sit alongside the structural energy transition

¹See <https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html>.

²Canada's oil and gas extraction sector represents roughly 3% of GDP. Moreover, Canada produces non-energy commodities such as copper, lithium, nickel, and cobalt. Canada is a net exporter of copper, nickel, and cobalt and holds just over 3% of global reserves of lithium, along with reserves of other critical minerals for the green transition.

itself.

A growing body of work develops net-zero pathways for Canada. In its long-term strategy submitted under the Paris Agreement, the Government of Canada sets out a range of possible approaches to reaching net-zero emissions by 2050 without committing to any single pathway ([Environment and Climate Change Canada 2022](#)). Canada’s energy regulator has published long-term outlooks built around net-zero scenarios covering all energy commodities and all provinces and territories ([Canada Energy Regulator 2023](#)), and [Canadian Institute for Climate Choices \(2021\)](#) reviews more than sixty Canadian net-zero pathways.³ This body of work is far richer than ours in energy, regional, and sectoral detail. Its focus, however, is largely on real-side outcomes, so it speaks less directly to inflation, to the policy rate, or to the trade-off between stabilizing output and stabilizing inflation along the transition. Our exercise is intended as a complement and asks what the net-zero transition could imply for a central bank and monetary policy.

To assess the implications of both a global and domestic transition to net zero, this paper relies on a suite-of-models approach. Our methodology provides a rich representation of a small open economy by capturing the key characteristics of the Canadian economy relevant for the transition and modeling the interactions between global climate policies and domestic macroeconomic outcomes. This approach allows for a comprehensive assessment of monetary policy trade-offs over the course of the net-zero transition.

Our approach relies on two main complementary models. On the domestic side, we extend one of the Bank of Canada’s projection models, the Terms-of-Trade Economic Model (ToTEM), incorporating features to analyze the transition to a low-carbon economy within Canada (see [Dorich et al. 2013](#), [Corrigan et al. 2021](#), for details of ToTEM). The enhanced version, Energy-ToTEM (E-ToTEM), introduces a richer production setup with both energy and non-energy sectors, distinguishing between greenhouse gas (GHG) neutral (green) energy and CO₂-emitting (brown) energy. This allows us to study substitution effects, whereby firms and households adjust energy consumption in response to global and domestic climate policies. Additionally, the model captures spillover effects to non-energy sectors, illustrating how structural shifts in the energy sector propagate throughout the broader economy.

As a small open economy model, E-ToTEM does not directly model international macroeconomic dynamics. It also does not endogenously capture CO₂ emissions. Thus, to implement a net-zero transition scenario in E-ToTEM, we rely on externally generated inputs that reflect global and domestic climate policy trajectories, such as carbon prices, energy demand, and global activity. These exogenous paths are derived from a global, multi-sector, multi-region dynamic general equilibrium model that incorporates sectoral and fuel-specific emissions, with an extended Canadian block (see [McKibbin & Wilcoxon 2013](#), [McKibbin et al. 2021](#)). This combined approach allows us to model global, sectoral, and emission linkages necessary to assess how international climate policies interact with domestic economic conditions. In addition to these two

³These references are illustrative rather than exhaustive; [Canadian Institute for Climate Choices \(2021\)](#) provides a summary of Canadian studies in the Annex.

models, we draw two further series—global inflation and the global policy rate—from the Bank of Canada’s Global Economy Model (BoC-GEM), since E-ToTEM requires these at quarterly frequency to determine the exchange rate.

Our contribution to the literature is therefore twofold. First, we develop a global and domestic climate transition scenario analysis by incorporating a suite-of-models approach with a rich representation of both global and domestic dynamics. We design a global and domestic net-zero scenario that is consistent with net-zero emissions by 2050.⁴ In particular, until 2030, we model climate policies announced as of 2022 and assume they remain in place until 2050.⁵ Any additional policy actions that may be necessary to reach net-zero emissions are captured via so-called shadow carbon taxes in our scenario exercise—which is one possible policy instrument commonly used in net-zero scenario modeling. We recover the associated impacts on global demand and prices for both energy and non-energy exports that we show to be important for Canada. At the same time, we assess the macroeconomic implications of domestic carbon-reducing policies to reach net zero. Compared to other scenario-based net-zero transition analyses, our integrated approach contributes to the existing literature (see, e.g., [Chen et al. 2022](#), [Black et al. 2022](#), and [Bertram et al. 2022](#)) by integrating forward-looking investment decisions, sectoral reallocation, global and domestic climate policy spillovers, as well as monetary policy into a dynamic stochastic general equilibrium (DSGE) framework.⁶

Second, we contribute to the emerging research using DSGE models to examine the macroeconomic impact of the net-zero transition and climate policies. Like studies by [Del Negro et al. \(2023\)](#), [Coenen et al. \(2024\)](#), [Airaud et al. \(2023\)](#), [Olovsson & Vestin \(2023\)](#), and [Ferrari & Nispi Landi \(2024\)](#), we explore monetary policy’s role in this transition. Our focus is on the macroeconomic spillovers of global and domestic net-zero policies in small, open economies that are net exporters of brown energy. Moreover, in contrast to [Del Negro et al. \(2023\)](#), [Coenen et al. \(2024\)](#), [Airaud et al. \(2023\)](#), and [Olovsson & Vestin \(2023\)](#), who focus on a limited, more short-term transition that fails to attain net-zero emissions, our analysis is consistent with a transition to net-zero emissions (both globally and domestically). Unlike these studies, we examine how the trade-off between short-run stabilization and long-run climate objectives shapes the design of monetary policy over the transition horizon.

Our results are as follows. Under the net-zero scenario, global carbon prices continuously increase until 2050. Higher energy costs drive a shift away from fossil fuels, but clean energy supply cannot expand quickly enough to fully offset this decline. Given the global economy’s heavy reliance on fossil fuels, this transition creates cross-sectoral spillovers, leading to an estimated 8% reduction in world GDP by 2050. For small open economies like Canada, weaker global demand and lower pre-tax commodity prices, especially for fossil

⁴We assume a reduction in CO₂ emissions consistent with net zero by 2050 for advanced economies, 2060 for China, OPEC, and Russia, and 2070 for India.

⁵For Canada, we also consider policies that were announced in 2023, such as the oil and gas sector emissions cap or the green investment tax credits. Note that our analysis includes the scheduled increases in Canadian carbon taxes until 2030. However, in April 2025, Canada’s carbon tax (Federal fuel surcharge) was set to zero.

⁶Some of the widely known quantitative macroeconomic scenarios for climate risks are provided by the [International Energy Agency \(IEA\)](#), [Intergovernmental Panel on Climate Change](#), and the [Network for Greening the Financial System](#).

fuels, place additional downward pressure on GDP.

Under the announced policies modeled, Canada’s emissions are projected to decline by around 28% by 2030 relative to 2005. Achieving net zero in 2050 is modeled via higher carbon prices beyond 2030. This implies higher brown energy prices, providing an incentive for Canadian businesses and households to shift towards more green energy consumption. Similarly, the higher relative price of brown energy to green energy reduces brown energy demand, leading energy producers to cut production. This shift in demand towards green energy leads to a 180% increase in green investment by 2050 under the net-zero scenario. However, total business investment remains lower throughout the transition due to the contraction of fossil-fuel-intensive industries, which are more capital intensive than most other sectors. Overall, Canadian GDP is projected to be 7% lower by 2050 under the net-zero scenario. The associated rise in carbon prices creates a modest increase in inflationary pressures. As with any long-term scenario analysis, these estimates are subject to considerable uncertainty. For instance, stronger technological growth in green sectors could lessen the reliance on higher carbon taxes and reduce the upward pressure on inflation.

Our main specification used in the scenario exercise relies on a historical monetary policy rule. To better understand the implications of alternative policy responses, we explore a stylized monetary policy framework in which the central bank chooses between stabilizing output and stabilizing inflation. This simple rule-based approach allows us to trace out the short- and long-run inflation–output trade-off implied by the transition and quantify the effects of different policy stances. The resulting range of possible outcomes suggests that the macroeconomic impacts of net-zero climate policy will depend not only on the design of carbon pricing, but also on the objectives and flexibility of monetary policy frameworks.

The remainder of the paper is structured as follows. Section 2 introduces and discusses the key features of E-ToTEM and how the net-zero scenario is implemented. Section 3 details our net-zero scenario design and how we model the global net-zero transition. Section 4 shows the net-zero simulation results, highlighting both the global spillovers and effects on the domestic economy. We also present an exercise to showcase the output–inflation trade-off for monetary policy. Section 5 concludes.

2 E-ToTEM: A Small Open Economy Model for the Net-Zero Transition

To better understand how the transition to a low-carbon economy influences Canada’s economic performance and inflation dynamics, we rely on a large-scale DSGE model. Specifically, we use an augmented version of ToTEM—the Bank of Canada’s workhorse model for macroeconomic projections and policy evaluation—as the primary tool to assess the domestic macroeconomic implications of the transition. ToTEM has been central to major policy assessments, including the evaluation of alternative monetary policy frameworks

during Canada’s 2021 Monetary Policy Framework Renewal (Bank of Canada 2021).⁷ To capture the structural features of the Canadian economy relevant for the net-zero transition, E-ToTEM extends ToTEM to include elastic global demand for energy and non-energy commodities, and a disaggregated energy sector in which production occurs through either greenhouse gas (GHG) neutral (green) or CO₂-emitting (brown) technologies. To implement a globally consistent net-zero scenario within E-ToTEM, we incorporate net-zero emissions trajectories and paths for key global and domestic variables obtained from a multi-sector global model.

2.1 E-ToTEM

E-ToTEM is a large-scale open economy DSGE model built on top of the third generation of ToTEM (ToTEM III). ToTEM III’s multi-sector structure, the treatment of commodity exports, and the central role of the terms of trade make it an ideal modelling environment for analysing the economic consequences of decarbonization in Canada.⁸ The multi-sector structure allows for differentiated sectoral responses to policy changes, capturing the reallocation effects of the transition. Additionally, terms-of-trade dynamics are central to assessing how climate policies affect Canada’s macroeconomic conditions through shifts in energy prices and global fossil fuel demand.

An important feature of ToTEM III is its ability to capture sectoral spillovers. The model features input–output linkages between commodity sectors, reflecting that commodities are used as intermediate inputs across all firm sectors, including within the commodity sector itself. In each sub-sector within the commodity sector, we introduce roundabout production: firms use the final commodity composite as an intermediate input in production, which is not the case in ToTEM III.

Furthermore, energy and non-energy commodities are modelled as highly complementary, namely aggregated via a Leontief technology, recognizing that both are used jointly in household consumption and firm production. For example, household demand for both food and fuel, and the use of both raw materials and energy in production. This complementarity ensures that structural changes in the energy sector driven by the transition to net zero spill over to the non-energy commodity sector.

To provide a structural underpinning of the economic adjustments required for a transition to net zero, E-ToTEM introduces five key enhancements to the commodity sector in ToTEM III. Appendix B describes the changes in detail. First, energy is explicitly disaggregated into green (non-carbon-emitting) and brown (carbon-emitting) energy (see Figure 1).⁹ This distinction is essential to capture substitution effects required for the transition to net zero. It also allows us to model Canadian-specific dynamics, including the likely

⁷Canada’s monetary policy framework is reviewed every five years, and in this context, critical aspects of the framework are analyzed and reviewed. The outcome of the review is a formal agreement with the Department of Finance and the Bank of Canada. The use of ToTEM in this context reflects its credibility and suitability when analyzing Canada’s key policy issues.

⁸For details of the model outside of the commodity sector, see Corrigan et al. (2021). The model features the following distinct production sectors: private consumption goods, residential structures, public consumption goods, capital investment goods, non-commodity exports, and commodities.

⁹A mapping between the energy sector and the Canadian input-output tables can be found in Table B.2.

contraction of the oil and gas sector and the related fall in exports, as well as the already low carbon intensity of Canada’s electricity generation sector, which implies that further abatement is likely to be very costly. Second, climate policy interventions are modeled explicitly, incorporating: i) a per-unit tax on brown energy levied on households and firms, and ii) an investment tax credit for capital investment in green energy production. The brown energy tax captures Canada’s carbon tax introduced in 2019 and updated in 2021, as well as other incentives aimed at shifting energy use toward green sources. A fraction of the brown energy tax revenue is rebated to households, reflecting Canada’s carbon tax rebate policy.¹⁰ The variety of instruments allows for a rich mix of policies and distinct interactions between fiscal and monetary policy.

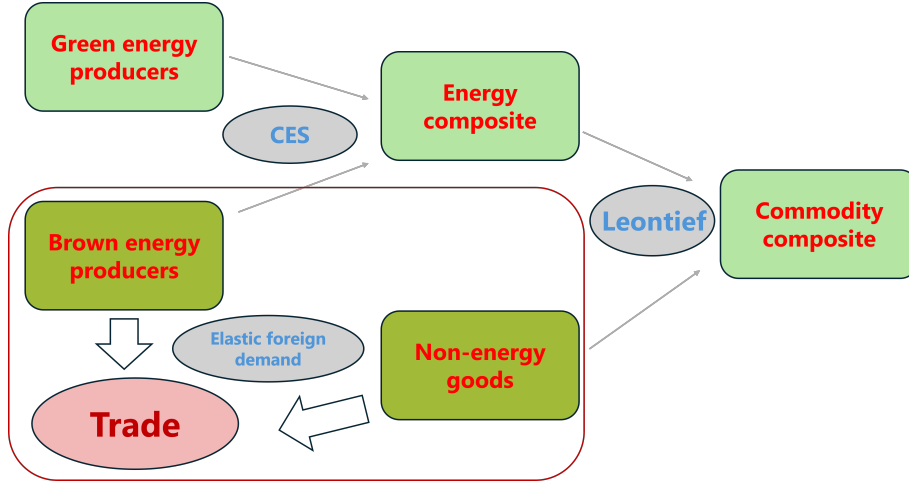


Figure 1: Production Structure in the Commodity Block

Sectoral heterogeneity in commodity use is another key feature of E-ToTEM. Different sectors use varying proportions of brown energy, green energy, and non-energy commodities. This means exposure to carbon taxes and energy price shifts differs across sectors. These differences reflect empirical evidence that certain sectors are more reliant on brown energy and hence more vulnerable, at least in the short run, to carbon taxation (see, e.g., [Canada Energy Regulator 2023](#), [Daraji & Li 2025](#)).¹¹

We can define the total real domestic product as:

$$Y_t = C_t + RS_t + I_t + G_t + X_t - M_t + \text{inventories}_t \quad (2.1)$$

which sums over private consumption (C_t), investment in residential structures (i.e., the housing stock, RS_t), business (capital) investment (I_t), public consumption (G_t), and net exports ($X_t - M_t$). A small portion

¹⁰More details are discussed in Appendix B.3. We assume that 63% of tax revenues are transferred back to households. This number is determined as follows: first, in Canada about 90% of the actual carbon tax that was in place till April 2025 was transferred to households; second, we scale this percentage by the proportion of the actual carbon tax in the overall carbon tax (which includes the shadow carbon price) in 2030. Note that the aggregate response of the economy is robust to this choice.

¹¹See Appendix B.1.3 for further detail on commodity demand in E-ToTEM.

of output from the consumption-good sector also accumulates toward inventories. In addition to the energy input use in each of the production sectors, private consumption C_t includes both final goods from the consumption-goods sector and the direct consumption of commodities. This structure allows us to capture shifts in household energy demand from fossil fuels toward green energy. This setup therefore reflects the changing energy mix in the production of durable and non-durable goods, as well as the increasing share of households' green energy consumption. By modeling changes in households' direct demand for brown and green energy, we capture the transition of households to new technologies, for example, from gas boilers to electric heat pumps, and from internal combustion engine (ICE) vehicles to electric vehicles. Both of these shifts permit a move from fossil fuel consumption to renewably sourced electricity consumption.

Finally, E-ToTEM improves the treatment of international trade by allowing for elastic world demand for Canadian commodity exports (Appendix B.2.1). Unlike ToTEM III, which assumes perfect pass-through of world prices to Canadian commodity exporters, E-ToTEM allows the export prices to deviate from world prices to reflect the imperfect substitutability of Canadian commodities with those produced abroad. This is particularly relevant for Canadian crude oil (brown energy) and non-energy commodities. For example, Canadian crude oil is generally heavier and more carbon-intensive than global benchmarks such as Brent or WTI, and often trades at a discount due to quality differences and transportation constraints. This limits its substitutability in global markets. Only brown energy and non-energy commodities are traded internationally, while green energy is exclusively produced and consumed domestically.

2.2 The Net-zero Transition in E-ToTEM

As a small open economy model, E-ToTEM does not directly model international macroeconomic dynamics. Moreover, it also does not endogenously capture CO₂ emissions. Thus, to implement transition scenario analysis, we require external inputs, which are computed using a complementary model, described in Section 3.2. This adapts the 'G-Cubed' model developed by McKibbin & Wilcoxon (2013) to Canada. The primary role of G-Cubed in this exercise is to simulate trajectories for key variables consistent with a global and domestic transition to net zero. As a multi-sector, multi-region dynamic general equilibrium (DGE) model, G-Cubed is well-suited to support this analysis. Available external projections, such as those from the International Energy Agency, do not explicitly incorporate current global actions; instead, they present possible pathways toward achieving global net zero emissions by 2050. In contrast, our approach begins with a baseline that incorporates announced and implemented policies, allowing us to assess the effects of additional climate action required to meet net-zero targets.

Figure 2 sets out how the framework fits together. Simulation results from G-Cubed are used to construct profiles that serve as exogenous inputs to E-ToTEM. For Canada, these include carbon prices, implemented as unit taxes on domestic brown energy consumption, projected levels of domestic brown energy use, and emissions per unit brown energy. Given that countries are assumed to maintain current policies through

2030 before intensifying efforts to reach net zero by 2050, E-ToTEM follows the carbon price path from G-Cubed until 2030, consistent with the policy framework described in Section 3. Beyond 2030, under the net-zero scenario, carbon taxes in E-ToTEM are adjusted to target the trajectory of domestic brown energy consumption implied by the required emissions reductions.

To capture global transmission channels most relevant for Canada, E-ToTEM incorporates additional profiles from G-Cubed. These cover the global price index of brown energy commodities, a foreign activity measure for brown energy commodities, the global price index of non-energy commodities, a foreign activity measure for non-energy commodities, and a foreign activity measure for non-commodity exports, the latter being represented as a trade-weighted measure of rest-of-world GDP. Non-energy commodities include agriculture, forestry, fishing and hunting, and mining (excluding oil and gas extraction). In a small open economy like Canada, foreign climate actions are critical for determining external demand, particularly under a globally coordinated transition to net zero.

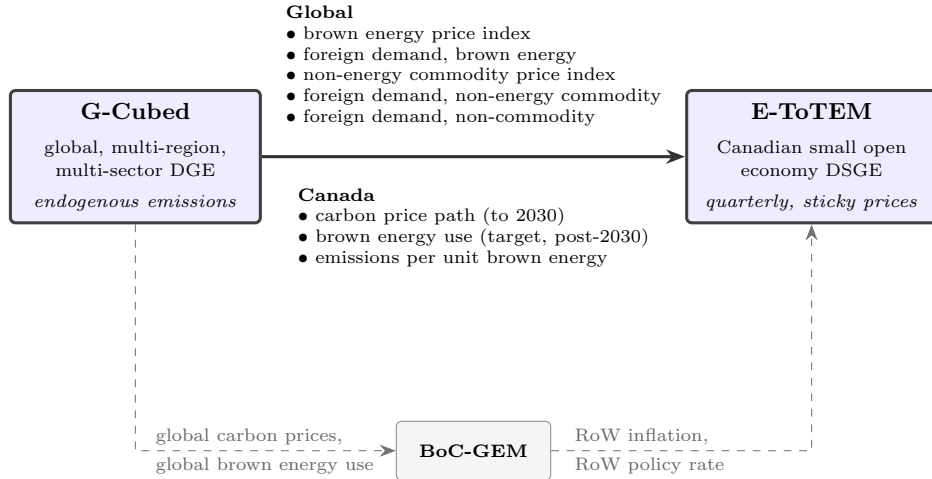


Figure 2: Overview of the modelling framework. G-Cubed and E-ToTEM are the two substantive models: G-Cubed generates globally consistent net-zero trajectories, which E-ToTEM takes as exogenous inputs in order to deliver Canadian macroeconomic outcomes. BoC-GEM enters only to supply rest-of-world (RoW) inflation and interest rates, whose quarterly frequency and treatment of nominal rigidities are comparable to E-ToTEM's.

Two further series are needed to complete the set of external inputs: rest-of-world (RoW) inflation and the rest-of-world policy rate. E-ToTEM determines the exchange rate through an uncovered interest parity (UIP) condition, in which both of these enter. In principle, they could be taken from G-Cubed along with the profiles above. We do not do so because G-Cubed is an annual model in which output prices are flexible and nominal rigidity is confined to wages, whereas E-ToTEM is a quarterly New Keynesian model with sticky prices and wages. Inflation and interest rates are precisely the variables most sensitive to this difference. We therefore take these two series from the Bank of Canada's Global Economy Model (BoC-GEM), a multi-region New Keynesian model whose frequency and treatment of nominal rigidities are comparable to E-ToTEM's.¹²

¹²For an overview of BoC-GEM, see Lalonde & Muir (2007)

BoC-GEM is simulated using the global carbon price and brown energy consumption paths obtained from G-Cubed, so that the rest-of-world profiles remain consistent with the same underlying scenario. BoC-GEM is used for these two series only; all other external inputs to E-ToTEM come from G-Cubed.

3 Transition Scenario Design and Modeling

In this section, we first describe our net-zero scenario design and outline the key global and domestic climate policies considered. Second, we introduce G-Cubed and describe how we model the domestic and global transition to net zero, and the resulting variable paths that are used as inputs into E-ToTEM.

3.1 Net-zero Transition Scenario Design

To assess the economic implications of a transition to a low-carbon economy, we conduct a scenario analysis over a 27-year horizon from 2023 to 2050 (see Figure 3). Between 2019 and 2030, we assume that the global and domestic policies that were announced and implemented as of 2022 remain in place and that no further policy actions are introduced.¹³

We consider both domestic and global climate policies (see Appendix C for a detailed list). For Canada, we incorporate announced and implemented policies as of 2022 that impact emissions reductions, energy production, and investment incentives, such as carbon taxes, green investment tax credits, and other policies implemented up to November 2022, such as the Clean Fuel Regulation.¹⁴ We also include policies announced or legislated in 2023: the zero-emission vehicle sales mandate and the oil and gas sector emissions cap.

Beyond Canada, we incorporate major global climate policies. In particular, we account for policy developments in the United States, the European Union, and other regions. Specifically, we account for the U.S. Tax Credits from the Inflation Reduction Act, the European Union Emissions Trading System (EU ETS), and other climate policies implemented globally as of the end of 2022. In Section 3.2.2, we explain in detail how these policies are captured in our modeling approach.

Starting in 2031, these policies are assumed to remain, but the intensity of climate policies—captured by a rising (shadow) carbon tax—is assumed to increase further, consistent with pledged net-zero emission targets. Our net-zero scenario is benchmarked against a hypothetical no-policy counterfactual, in which emissions are projected to increase until 2050, driven by underlying economic growth and demographic trends.

Achieving net zero does not imply eliminating all emissions, but rather offsetting them through various carbon dioxide removal (CDR) measures, including nature-based solutions (e.g., tree planting), technological solutions such as direct air carbon capture and storage (DACCS) (Fuss et al. 2018), and other approaches

¹³Since G-Cubed simulations begin in 2019, we assume that the difference between historical emissions and the no-policy counterfactual reflects the effects of policies over the period 2019–2022.

¹⁴As of April 2025, the carbon tax has been set to \$0/tonne. These recent policy changes are not reflected in our analysis, since our simulations were carried out beforehand.

such as enhanced weathering and ocean alkalization (Bach et al. 2019).

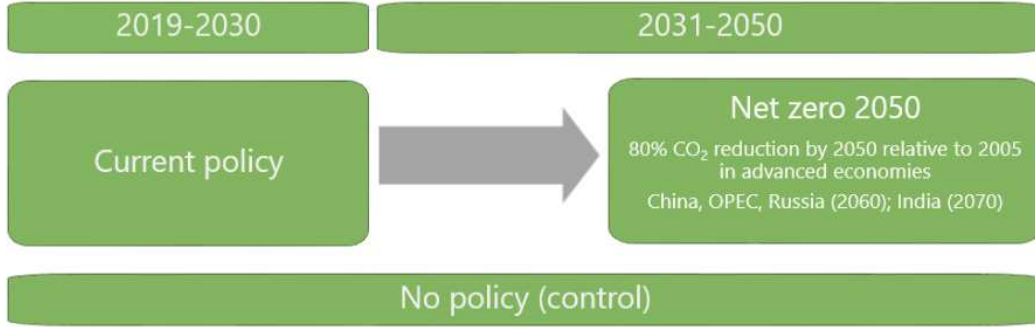


Figure 3: Climate Transition Scenario

In our net-zero scenario, we assume that emissions in advanced economies are reduced by 80% relative to 2005 levels by 2050. In contrast, China and the Organization of the Petroleum Exporting Countries (OPEC) are assumed to reach an 80% reduction by 2060, while India achieves this by 2070, in line with their declarations. This implies that the remaining emissions are offset by nature-based solutions, decarbonization or abatement technologies directly. These removal channels are not modeled explicitly in either G-Cubed or E-ToTEM, where emissions are tied to fossil fuel and brown energy use; the residual 20% is assumed to be offset outside the models.

This assumption is consistent with the existing literature and can be considered relatively conservative. Studies have shown that CDR solutions alone could achieve at least 20% of the required emissions reductions in our net-zero scenarios (Bertram et al. 2022, Sylvan 2024, IPCC 2018b,a). Furthermore, the carbon prices needed to reach net zero in our analysis are well above the thresholds at which abatement technologies become economically viable, supporting the plausibility of this scenario.

Since we assume no additional climate policy action before 2030, our net-zero 2050 scenario is most comparable to a delayed transition scenario, as for example in Chen et al. (2022).

3.2 Modeling the Net-zero Transition

3.2.1 The G-Cubed Model

As outlined earlier, to implement net-zero scenario analysis in E-ToTEM, we rely on inputs from G-Cubed. G-Cubed is a global, multi-sector, multi-region dynamic general equilibrium (DGE) model developed by McKibbin & Wilcoxon (2013). G-Cubed has been used to explore a wide range of issues where international and sectoral dimensions play central roles, including trade integration, financial crises, and climate change.

In the version used in this paper, the global economy is disaggregated into eleven regions, including Canada.¹⁵

¹⁵Regions modeled in G-Cubed include: United States, Japan, Australia, Europe, Canada, Rest of Advanced Economies, China, India, Russian Federation, Oil-exporting and the Middle East, Rest of World.

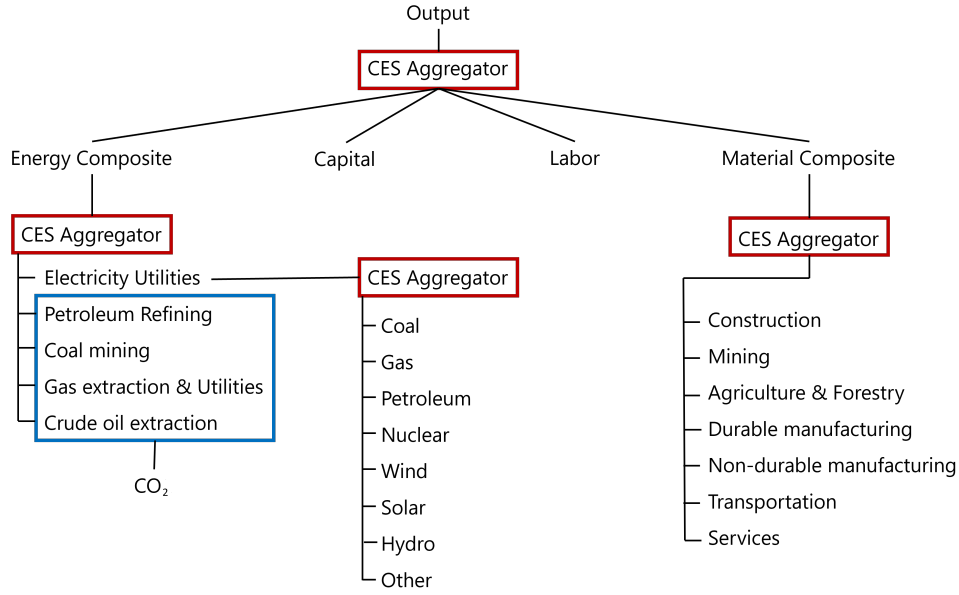


Figure 4: Schematic presentation of production function in G-Cubed

Production in G-Cubed follows multi-level nested constant elasticity of substitution (CES) functions, a widely used specification in computable general equilibrium (CGE) models (Figure 4). This nested CES structure provides a flexible framework to represent how firms and industries combine different types of inputs to produce output.

The production structure in G-Cubed allows the model to incorporate the effects of technological change (e.g., shifts towards renewables), changing relative prices, and policy interventions (such as carbon pricing) on the mix of inputs used in production. At the top level, sectoral output is produced using a composite of capital, labour, energy, and materials. Each of these inputs is itself constructed through lower-tier CES aggregations. The energy composite, for example, is formed by combining an electricity composite with fossil energy inputs. The electricity composite is, in turn, a CES aggregate of electricity from different generation technologies: coal, gas, nuclear, wind, solar, hydro, and other sources. Fossil energy inputs consist of crude oil, coal, gas, and refined petroleum products.

Each region is divided into twelve sectors, with electricity generation further disaggregated into eight sub-sectors based on generation type.¹⁶ A key feature of the model for transition scenario analysis is that fossil fuel consumption by firms and households generates CO₂ emissions, which can be subject to carbon pricing policies.¹⁷

On the macroeconomic and financial side, the model includes a rich set of variables for each region and

¹⁶Electricity delivery, gas extraction and utilities, petroleum refining, coal mining, crude oil extraction, construction, other mining, agriculture and forestry, durable goods, non-durable goods, transportation, services. The electricity sector is disaggregated into coal, natural gas, petroleum, nuclear, wind, solar, hydroelectric, and other generation.

¹⁷Only energy-related CO₂ emissions are modeled in this version of G-Cubed. Other greenhouse gases such as methane and nitrous oxides, and emissions from fugitive sources or land-use, land-use change, and forestry (LULUCF), are excluded.

country, including real and nominal GDP, interest rates, bond yields, and consumer and producer price inflation. G-Cubed is an annual model with flexible prices and sticky wages, making the labour market the primary source of nominal rigidity.

To better reflect short-run macroeconomic dynamics, the model incorporates several real frictions, including quadratic adjustment costs in investment, immobile physical capital, and two types of households and firms. On the household side, one group maximizes an intertemporal utility function, while another follows a rule-of-thumb and consumes current income. On the firm side, some firms are forward looking and optimize investment decisions, while others follow a backward-looking rule. Rule-of-thumb households maximize current utility, while rule-of-thumb firms set investment using a backward-looking Tobin’s Q rule. These features allow G-Cubed to assess how firms and households adjust investment, consumption, and labour supply in response to announced climate policies, such as carbon tax schedules.

G-Cubed has been widely used in recent climate policy research, including: modeling the implementation of Paris Agreement commitments; exploring the role of monetary policy regimes during the transition to a low-carbon economy; and evaluating growth-friendly approaches to net-zero emissions by 2050 (Liu et al. 2020, Dollman et al. 2020, Jaumotte et al. 2021).

As per standard practice, the G-Cubed model is calibrated to real economic flows, using input–output tables from the Global Trade Analysis Project Database (GTAP 11; Aguiar et al. 2022) for each country or region represented in the model. For Canada, we complement the GTAP input–output data with updated tables from Statistics Canada (2020). Sectoral shares of material and energy inputs, labour, and capital—as well as commodity allocations in final consumption—are drawn from these detailed input–output tables. We ensure that the mapping from granular sectors to model sectors is consistent across G-Cubed and E-ToTEM. CO₂ emissions from fossil-fuel use at both the sectoral and household levels are likewise sourced from GTAP 11, and sectoral and total demand emission factors per unit of energy use are calibrated accordingly. The elasticities of substitution in production and consumption in G-Cubed are estimated rather than calibrated. The value of the elasticity of substitution varies across sectors—at the first level it is between 0.2 and 1.28; in the energy nest it lies between 0.2 and 1.15; in the material nest it ranges between 0.2 and 2.76; and in the electricity nest it is 3.0.

The baseline projection in G-Cubed is driven by sector-specific assumptions about labor-augmenting technical change (LATC) in the United States, which is treated as the technology frontier, with other regions catching up to the frontier, see, e.g., McKibbin et al. (2007) and Liu et al. (2025). For other regions, sectoral productivity gaps relative to corresponding U.S. sectors are estimated using the Groningen Growth and Development Centre (GGDC) Productivity Level Database, 2023 Edition (Inklaar et al. 2023). This baseline across sectors and regions is then augmented with information on current climate policies and projected emissions pathways.

3.2.2 Climate Policies in the G-Cubed Model

Our approach explicitly models key climate policies, including carbon taxes and investment tax credits. However, certain policies such as regulations, mandates, or direct spending on green initiatives cannot be directly incorporated into the model. To capture the effects of these policies, we rely on shadow carbon prices (SCPs) at an economy-wide level or sectoral level (for Canada). The SCPs can be thought of as an implicit emissions price, serving as a proxy for the intensity of government climate policies. Table 1 summarizes how climate policies are modeled across different regions.

Region	Carbon taxes	Clean investment tax credit	Economy-wide SCP	Sectoral SCP
Canada	✓	✓	✓	✓
USA		✓	✓	
Europe	✓		✓	
Other Regions			✓	

Table 1: Climate policies modelled in G-Cubed.

For Canada, the model includes the planned carbon price schedule as initially announced in December 2020, which reaches \$170/tonne of CO₂ by 2030, and a 15% investment tax credit for green energy projects. Additionally, we model the oil and gas cap-and-trade program, and the ZEV sales mandate. These sectoral policies are implemented through sectoral carbon taxes, affecting oil and gas producers and household oil consumption, respectively. All non-tax policies in Canada are captured via economy-wide SCPs, which are consistent with emissions under the “with measures” projections of Environment and Climate Change Canada (ECCC), as presented in Canada’s Fifth Biennial Report on Climate Change ([Government of Canada 2022](#)). This projection reflects all implemented and announced policies as of November 2022.¹⁸

Internationally, we explicitly model the European carbon price under the ETS and the U.S. investment tax credits from the IRA. To supplement these explicitly modelled policies, we impose economy-wide shadow carbon prices in each region, consistent with regional (external) projections of emissions under announced policies until 2030. Specifically, as in [Chen et al. \(2022\)](#), we use the “Policies and Action” emission projections from the Climate Action Tracker (CAT) to obtain CO₂ reductions between 2005 and 2030.¹⁹ Figure A.1 in the Appendix presents the projected emissions reductions under current policies for each region, which are used to obtain the economy-wide shadow carbon prices for all regions, including Canada.

Beyond 2030, we assume increasing climate policy stringency, captured by rising economy-wide shadow carbon prices within each region, consistent with achieving net-zero emissions by 2050. These SCPs follow a linear reduction path in emissions, ensuring consistency with the net-zero transition described in Section

¹⁸The emissions reductions obtained from the oil and gas cap-and-trade program and the ZEV sales mandate are in addition to those projected by ECCC’s “with measures” scenario, reflecting the fact that these policies were not included in ECCC’s official projections as of late 2022.

¹⁹This scenario incorporates existing and announced country-specific policies. CAT primarily uses official government or international projections but will integrate bottom-up quantifications of policies announced in cases where they are not included in the latest official projections. More details on CAT methodology can be found [here](#).

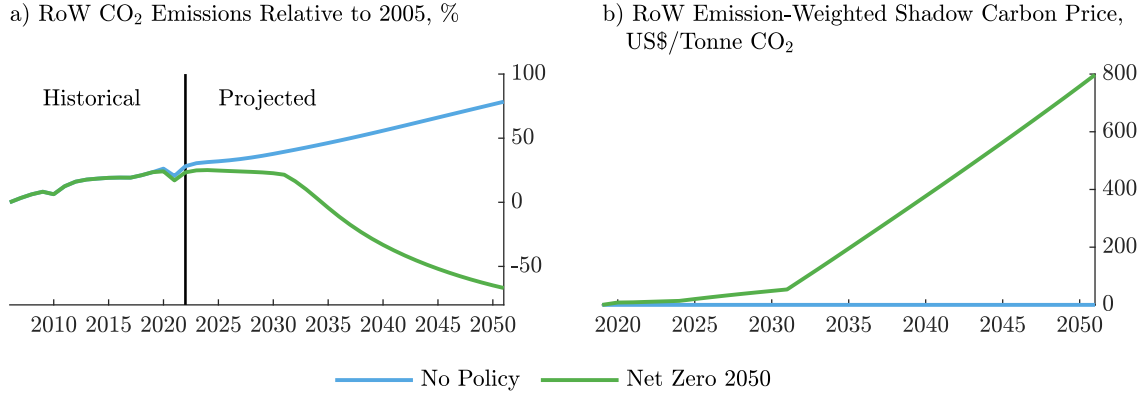


Figure 5: Emission reductions relative to 2005 (%) and emission-weighted shadow carbon price (US\$ per tonne of CO₂) under the no-policy (blue) and net-zero (green) scenarios for the Rest of the World. Source: G-Cubed simulations.

3.1. All other climate policies are assumed to remain at their 2022 levels throughout the transition.

4 Net-Zero Simulation Results

4.1 Global Effects of the Transition

Under the net-zero scenario, shadow carbon prices rise steadily to achieve net-zero emissions (Figure 5). In the hypothetical no-policy counterfactual, emissions are projected to continue rising through 2050, driven by underlying economic growth and demographic trends.

With the policy commitments outlined in Section 3.2, global shadow carbon prices increase only modestly until 2030, leading to limited reductions in emissions. Under the net-zero scenario, however, substantial increases in shadow carbon prices are necessary beyond 2030 to meet net-zero emission reduction targets across regions. Figure 5 (b) shows that by 2050, the average price of CO₂ reaches close to US\$800 per tonne of CO₂. The estimated carbon price for the net-zero scenario is in line with those obtained from the MIT Emissions Prediction and Policy Analysis model (EPPA) in previous scenario analysis exercises by the Bank of Canada (Chen et al. 2022, Ens & Johnston 2020). It is also consistent with the range of shadow carbon prices obtained by the Network for Greening the Financial System (NGFS) from three integrated assessment models, between US\$600–1300/tonne of CO₂ (NGFS 2023).

Global climate policy action drives higher shadow carbon prices across all regions, inducing a transition away from fossil fuels over the subsequent decades. This generates serious macroeconomic spillovers for Canada, operating through three primary transmission channels:

1. Declining global demand and lower prices for fossil fuel exports
2. Weaker global demand and falling prices for non-energy commodity exports

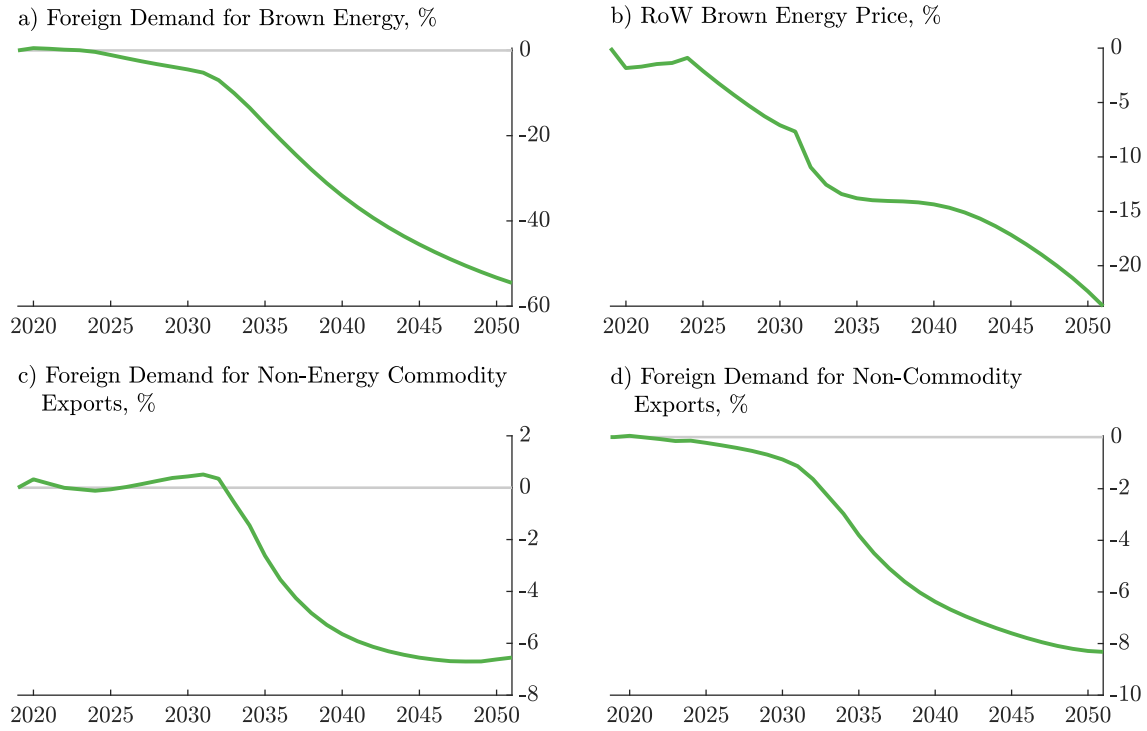


Figure 6: Trajectories for RoW variables under the net-zero scenario. Responses are in percent deviation relative to the no policy control. Source: G-Cubed simulations.

3. Reduced demand for non-commodity exports

These structural shifts in the world's energy system have direct consequences for Canada's brown energy exports, with spillover effects on non-energy commodity and non-commodity exports. The development of E-ToTEM allows for a more granular analysis of these transmission channels, as each export sector is explicitly modeled. Notably, the separation of brown energy from non-energy commodities captures the fact that global trade in fossil fuels may be disproportionately affected relative to other goods and services.

Global climate action increases the cost of fossil fuel use through the necessary increases in carbon prices, leading to a decline in global brown energy demand. As a result, world demand for Canadian brown energy falls by just over 5% by 2030 under current policies (Figure 6, a). Under the net-zero pathway, this decline accelerates sharply after 2030, with brown energy demand 55% lower than the no-policy counterfactual by 2050. This occurs alongside a fall in global brown energy prices, as brown energy supply adjusts more slowly than demand (Figure 6, b). Under current climate policies as of 2022, the global benchmark price against which Canadian exporters compete is 8% lower by 2030, and 24% lower by 2050 under the net-zero scenario.

Significant structural change is required for a global transition to a low-carbon economy. Climate policy aims to reduce the consumption of fossil fuels, but firms and households still need energy. As a result, investment shifts towards green energy, increasing demand for a different mix of commodities in the supply chain, such

as critical minerals. However, this adjustment is costly; the global economy’s present reliance on fossil fuels makes it difficult for firms and households to substitute towards alternative energy sources and production methods.

Since the supply of green energy and non-energy commodities cannot be scaled instantly, global climate policy action has spillover effects from brown to non-brown activities, creating a drag on RoW GDP that reduces overall demand for Canadian exports. However, these negative impacts are much less severe than for brown energy demand, as they are offset by increased demand for some goods and services that are less carbon-intensive. This is most apparent for non-energy commodities pre-2030, before carbon prices start to increase substantially (Figure 6, c). Even in the long run, prices of non-energy commodities are only 7.9% lower in 2050, roughly one-third of the impact on brown energy prices (see Figure A.1 in the Appendix).

Altogether, global efforts to achieve net zero cause a severe and persistent terms-of-trade shock that is particularly costly for Canada due to its position as a major commodity exporter. These dynamics have far-reaching macroeconomic implications, which we analyze using E-ToTEM. The model is designed to capture the structure of the Canadian economy, allowing us to assess how Canada adjusts to the powerful structural forces driving the net-zero transition.

4.2 Effects on the Domestic Economy

In Canada, historical emissions have remained relatively stable since 2005, but are projected to rise under the hypothetical no-policy counterfactual due to GDP growth and demographic trends (Figure 7). Under the policies described in Section 3.2, Canadian emissions are projected to decline by around 28% relative to 2005 levels by 2030. In the net-zero scenario described in Section 3.1, emissions in Canada fall by 80% relative to 2005 levels by 2050.

Net zero can be achieved through adjustments along several dimensions, which can be described by an extension of the Kaya identity:²⁰

$$Emissions = GDP * \frac{Energy}{GDP} * \frac{BrownEnergy}{Energy} * \frac{Emissions}{BrownEnergy}.$$

In our no-policy scenario, the absence of climate action sees emissions increase with GDP. With continued economic growth, achieving net zero therefore requires a reduction in emissions per unit of GDP. Figure 6 (b) decomposes this adjustment into three key components of the Kaya identity. First, Canada needs to reduce emissions per unit of brown energy consumption (green area). This reflects within-sector substitution towards lower-emission fossil fuels, and a shift away from industries that are highly reliant on emissions-intensive fossil fuels. This is facilitated by policies such as the Clean Fuel Regulation. Second, the largest decline in emissions per unit of GDP stems from shifting away from brown energy toward alternative sources of energy (blue area).

²⁰This identity was the subject of Kaya & Yokobori’s (1997) book.

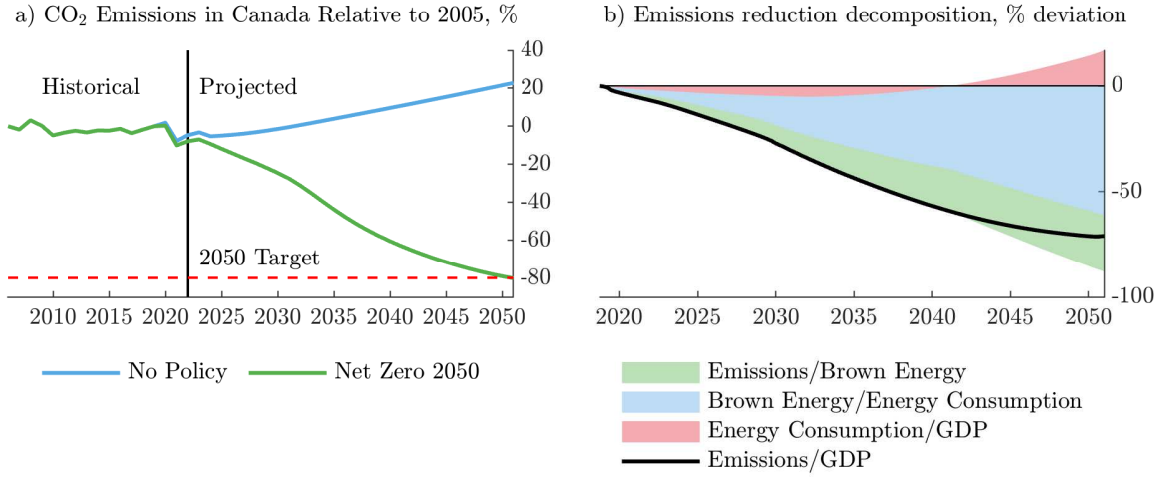


Figure 7: a) Historical and projected percentage change in CO₂ emissions relative to 2005 in Canada under the no-policy (blue) and net-zero scenario (green); b) transition of the emissions/GDP ratio for Canada with the reduction decomposed into the falling rate of emissions per unit of brown energy (green area), falling total energy share of brown energy (blue), and changing energy consumption–GDP ratio (red). Responses are in percentage deviation relative to the no-policy control. Source: historical data for chart (a) from Environment and Climate Change Canada (2023); projections for chart (a) and emissions per unit of brown energy (chart b) are obtained from G-Cubed simulations. The paths for brown energy, total energy consumption, and real GDP are obtained from E-ToTEM simulations.

Climate policies such as the carbon tax and ITCs incentivize and support, respectively, the substitution of green for brown energy. Finally, the policy-induced transition from brown to green energy drives the steady expansion of green energy production. Combined with a decline in capital investment, production becomes relatively less capital-intensive and more energy-intensive, eventually resulting in a modest increase in energy consumption per unit of GDP (red area).

As discussed earlier, in the net-zero scenario, the shadow carbon tax profile follows the announced government policies as of 2022/2023 until 2030. Beyond 2030, we use E-ToTEM to determine the shadow carbon price required to achieve the net-zero target. In addition to the Canadian Carbon Fuel Charge, which was set to reach \$170 CAD/tonne by 2030, the remaining policies already announced in Canada are equivalent to an additional shadow carbon price of approximately \$100 CAD by 2030 (Figure 8, a). The scenario suggests that more aggressive climate action is required to meet net-zero by 2050 because carbon prices would have to continue rising beyond 2030, reaching approximately \$1400 CAD/tonne by 2050. Consequently, the real (after-tax) price of brown energy rises by approximately 70% by 2030 and about 300% by 2050 under the net zero scenario (Figure 8, b). These higher brown energy prices introduce a strong incentive for households to reduce brown energy consumption and shift towards green energy alternatives.

Canadian firms are similarly affected under the net-zero scenario. On the supply side, energy producers reduce output in response to declining domestic brown energy demand, leading to a sharp contraction in business investment, due to the capital intensity of the energy sector. At the same time, firms face rising

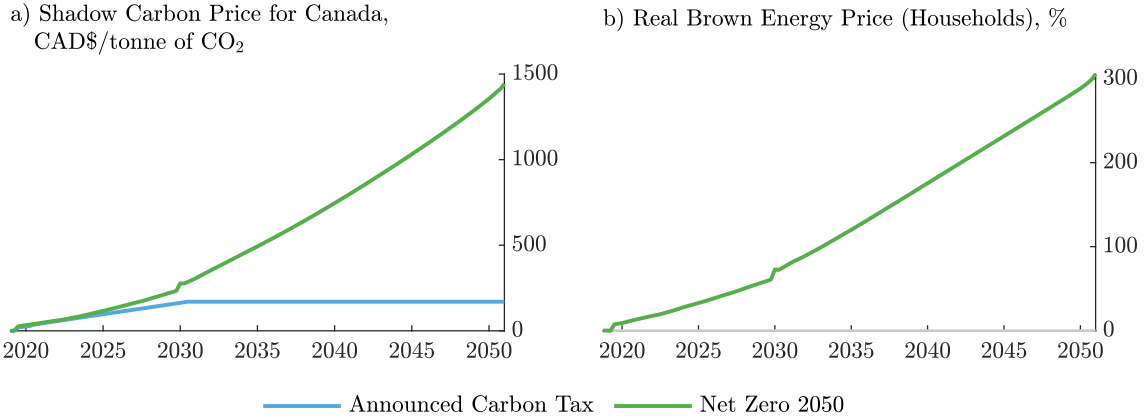


Figure 8: Shadow carbon price (CAD\$ per Tonne of CO₂) in Canada and real brown energy price (after tax) for Canadian households (% deviation relative to no-policy) under the net-zero scenario. Source: Simulations from E-ToTEM, with pre-2030 shadow carbon prices exogenously following the path obtained from G-Cubed simulations.

brown energy prices due to the higher carbon price, increasing the costs of production. In contrast, green energy prices rise more gradually, making green energy an increasingly attractive alternative (Figure 9, a). As a result, firms adjust their energy input mix, and the ratio of brown-to-green energy consumption declines sharply relative to the no-policy counterfactual (Figure 9, b).

These changes have a significant impact on business investment across energy sectors. Capital investment in the green energy sector rises by around 180% relative to the no-policy scenario (Figure 9, c), while brown energy investment declines by about 30%, contributing to the broader slowdown in aggregate capital investment. Total capital investment contracts despite the increased investment in the green sector, but begins to recover towards 2050 (Figure 9, d). This reflects the relatively large size of the capital stock in Canada's brown energy sector, which is initially more than ten times as large as that of the green energy sector.²¹ The decline in business investment is broad-based across sectors in Canada and creates a persistent drag on GDP.

Another channel through which climate policies affect GDP and inflation is the trade balance and the exchange rate. Following the global increase in carbon prices, world demand for brown energy goods falls significantly. Brown energy exports fall as a result (Figure 10, b). Because manufacturing exporters produce using brown energy as inputs, when faced with an increase in production costs from higher energy prices, non-commodity exporters also raise their prices. This leads to a decline in non-commodity exports when global activity contracts. The combined decline in brown energy and non-commodity exports implies a deterioration in Canada's terms of trade, and a depreciation of the CAD (Figure 10, a).

The impacts of the progressive increase in carbon prices to reach the net-zero target are comparable to those of a negative supply shock to the economy. Under the net-zero scenario, GDP falls by about 7% relative to

²¹Note that the investment measure shown includes capital expenditure by firms across sectors but excludes household purchases such as residential renovations or durable goods like electric vehicles, which are classified as private consumption in the model.

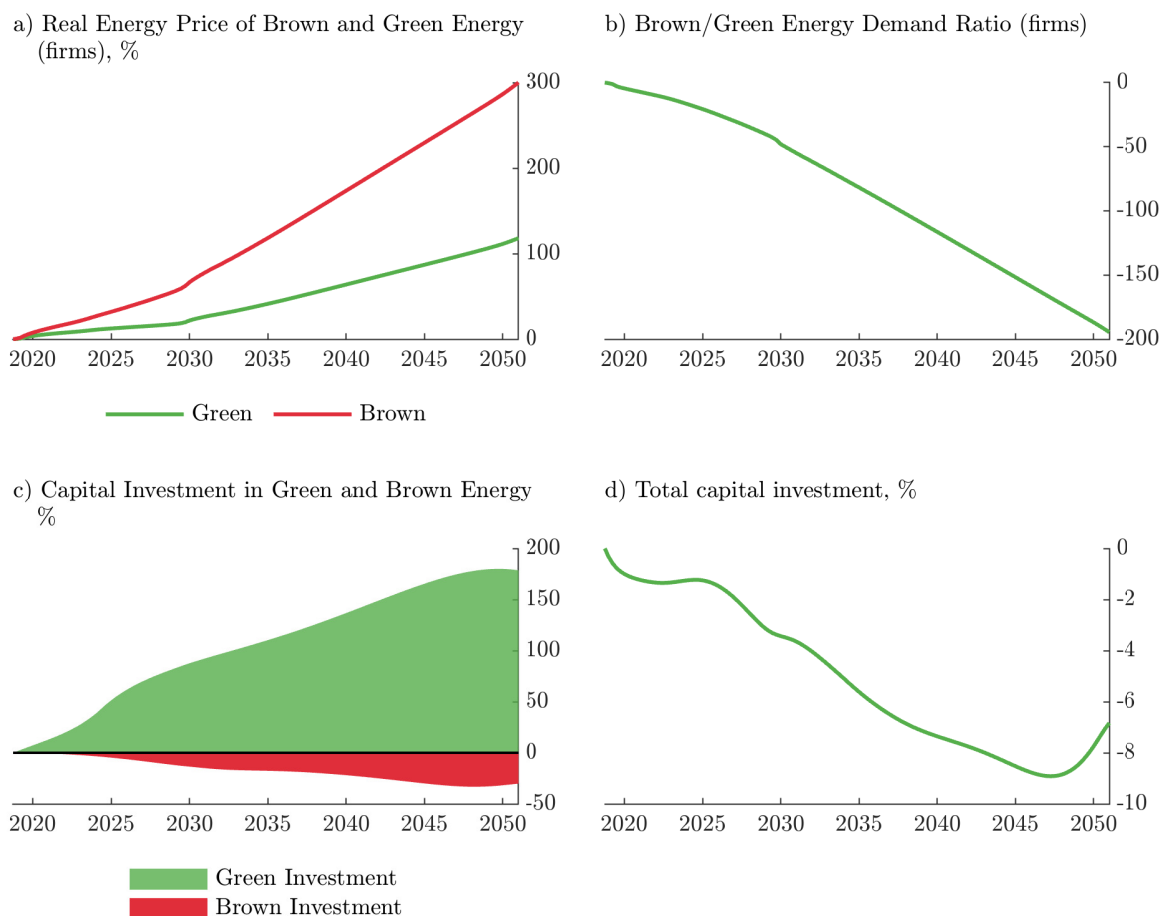


Figure 9: Transition of Canadian variables under the net-zero scenario in percent deviation relative to no-policy scenario. Chart c) shows capital investment in green and brown energy sectors in Canada. Chart d) shows total business investment in Canada. Total investment includes capital investment across all production sectors in the economy, including those producing public and private consumption goods, residential structures, investment goods, commodity goods and export goods. Source: E-ToTEM simulations.

the no-policy scenario (Figure 10, c). Most of the decline in GDP comes about from a reduction in energy production, business investment in the energy sector and weaker net exports. At the same time, Canadian inflation increases due to higher consumer fuel prices and higher prices of other consumption goods. Since brown energy is an important input into firms' production, higher brown energy prices put upward pressure on the cost of production, raising inflation. The weaker Canadian dollar also reinforces inflationary pressures. However, the effect on CPI inflation is not large; at its peak, inflation increases by about 0.3 percentage points (Figure 10, d).²²

The magnitude of these effects depends on how readily energy users can substitute away from fossil fuels and

²²An inflationary spike is observed close to 2050 in anticipation of the changes in climate policy once net-zero is reached and dissipates shortly afterward. After this point, brown energy consumption remains at a level consistent with net-zero, and carbon prices do not increase further. This change in trajectory of the carbon price influences agents' behaviour as 2050 approaches, as seen with investment in Figure 9, d.

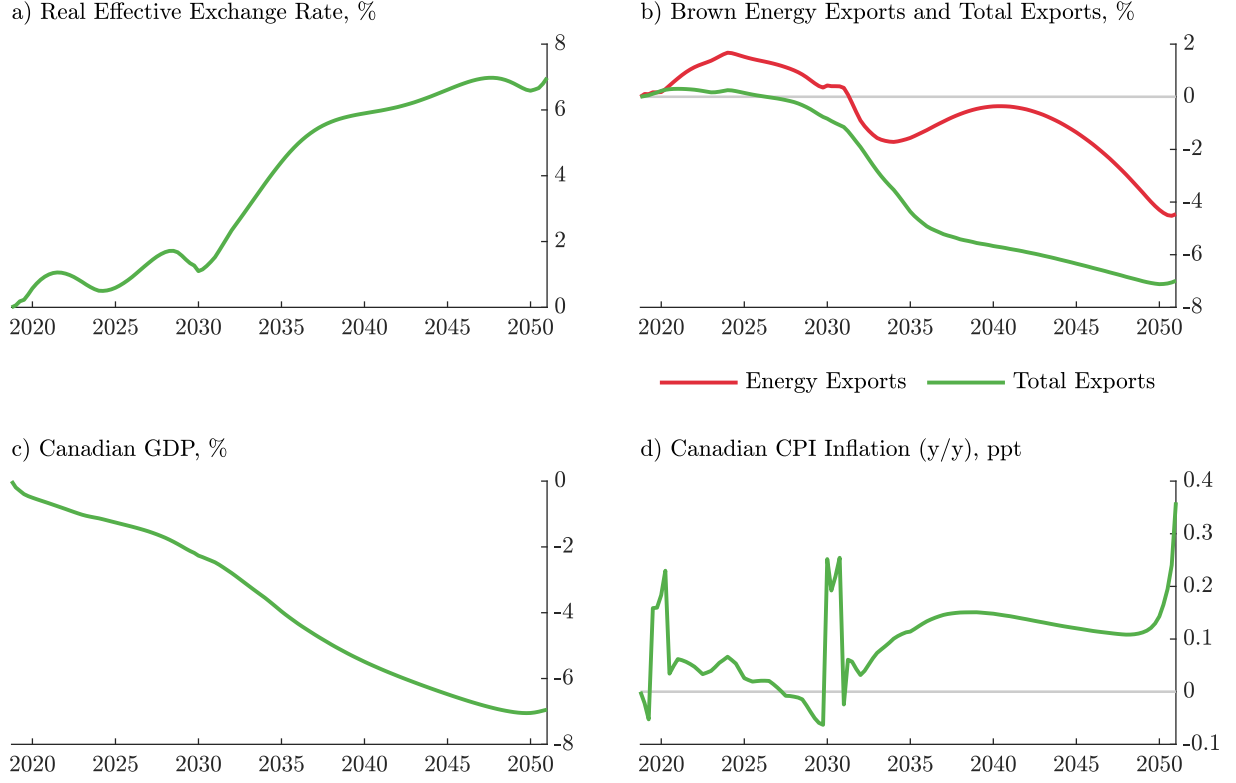


Figure 10: Transition of Canadian variables under the net-zero scenario in percent deviation relative to no-policy scenario. Note, an increases in the exchange rate indicates depreciation. Source: E-ToTEM simulations.

on how quickly green energy supply can expand. A higher elasticity of substitution between green and brown energy delivers faster growth in green investment, a smaller decline in total exports and a smaller GDP loss, while permanently higher TFP growth in the green energy sector moderates both the GDP and inflation impacts; in neither case are the qualitative results affected, and we report these exercises in Appendix D.

4.3 The Inflation-Output Trade-off Over the Net-zero Transition

Under the net-zero scenario, carbon prices rise gradually through 2050, leading to persistently higher inflation and lower GDP. This stagflationary environment presents monetary policy-makers with a trade-off between stabilizing inflation at its target and output close to its potential. The simulations described above rely on the following monetary policy rule:

$$r_t = \rho r_{t-1} + (1 - \rho) \left[\bar{r} + \gamma_\pi \mathbb{E}_t (\pi_{t+4}^{yy} - \pi^*) + \gamma_y (y_t - y_t^*) \right]. \quad (4.1)$$

The estimated rule prioritizes inflation stabilization, assigning relative weights of approximately 90% and 10% to inflation and the output gap, respectively.²³ As a result, the inflationary effects of the transition are

²³As seen in equation (4.1), the monetary policy rule in E-ToTEM is an inertial Taylor rule with coefficients estimated by Corrigan et al. (2021), including 4.65 for the inflation gap and 0.4 for the output gap. The inflation gap is defined as the deviation of one-year-ahead expected year-over-year CPI inflation from target.

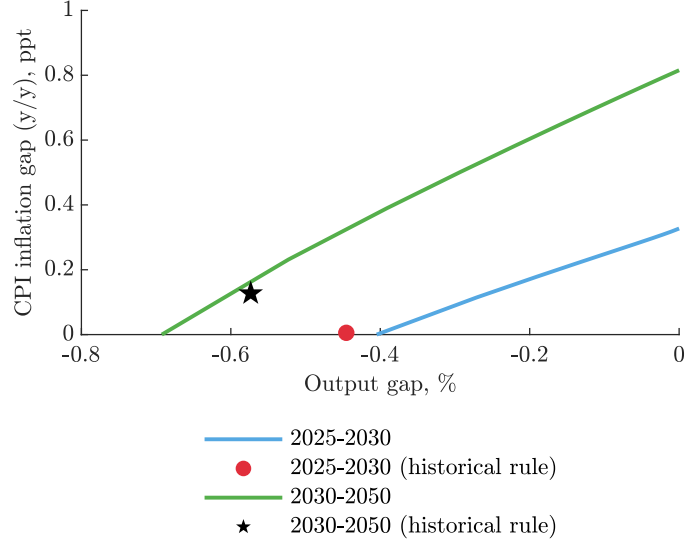


Figure 11: CPI inflation-output trade off under the historical (estimated) rule and for a simple rule varying the relative weight on CPI inflation. Figures show average output and inflation gaps for 2025Q1-2029Q4 and 2030-2050. Source: E-ToTEM simulations.

modest, but come at the expense of real activity, with average output gaps of -0.45 and -0.57 percentage points across 2025–2030 and 2030–2050 respectively (Figure 11).

We now return to the second question raised in the introduction and explore this trade-off by experimenting with a class of simple monetary policy rules that balance inflation and output stabilization. Each rule targets a weighted average of inflation and output gaps:

$$\alpha (\pi_t - \pi^*) + (1 - \alpha) (y_t - y_t^*) = 0, \quad (4.2)$$

where $\alpha \in [0, 1]$ determines the central bank’s relative weight on inflation stabilization. $(\pi_t - \pi^*)$ is the deviation of contemporaneous annualized quarter-over-quarter (q/q) CPI inflation from the 2% target, and $(y_t - y_t^*)$ is the output gap. This approach is based on [Del Negro et al. \(2023\)](#) who focus on a more limited transition that does not necessarily attain net zero. The output gap is defined relative to a full-employment, full-capacity utilization potential level of output, consistent with the approach in [Corrigan et al. \(2021\)](#).²⁴

For each alternative rule specification, corresponding to $\alpha \in [0, 1]$, we replicate the scenario exercise and obtain the associated effects on the output gap and inflation. Figure 11 illustrates this trade off by plotting the average deviation of CPI inflation from target against the average output gap for each $\alpha \in [0, 1]$ over the periods 2025–2030 and 2030–2050. We also include the outcomes under the estimated historical rule.

This experiment provides a stylized feasibility set, that is, a menu of possible alternatives among which the central bank can choose, depending on its appetite for looking through inflationary pressures arising from

²⁴This is outlined in detail in [Murchison & Rennison \(2006\)](#).

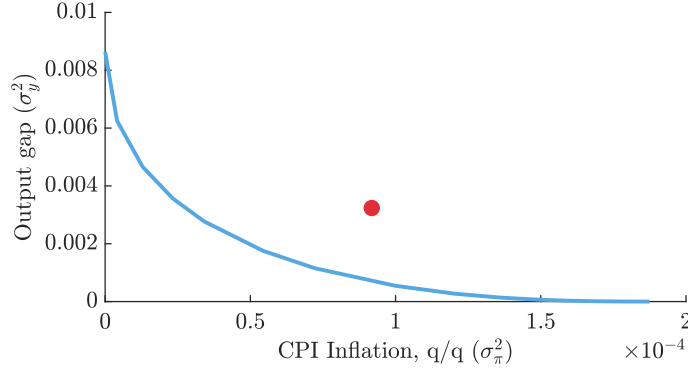


Figure 12: Stabilization trade-off for $\alpha \in [0, 1]$ with simple rule $\alpha(\pi - \pi^*) + (1 - \alpha)(y - y^*) = 0$. Simulated outcomes under the estimated historical rule shown with the red dot. Source: E-ToTEM simulations.

climate policy changes.²⁵ At one extreme ($\alpha = 1$), the central bank focuses entirely on stabilizing inflation, keeping CPI inflation at target, but at the cost of a significant output gap which averages -0.69% over 2030–2050 (Figure 11). At the other extreme ($\alpha = 0$), the central bank fully offsets the output gap by easing policy, but inflation exceeds target by about 0.82 percentage points on average over 2030–2050.

Decisions about whether to prioritize supporting real economic activity or achieving low and stable inflation during the transition must be weighed against central banks’ usual short-run stabilization objectives. Targeting one-year-ahead expected year-over-year CPI inflation, as in the historical rule, is effective at containing average inflation during the transition. However, once uncertainty is taken into account, this forward-looking approach proves less effective at stabilizing current inflation outcomes. This is shown in Figure 12, which presents the variance-based stabilization trade-off under the simple rules, alongside the outcome under the historical rule. The frontier shows that complete output gap stabilization can be achieved with an annualized quarter-over-quarter inflation standard deviation of around 5.5%, while full inflation stabilization entails output gap volatility of approximately 9.3%.²⁶ These results underscore that both price and output stability will remain central to monetary policy during the transition, but trade-offs with long-term priorities are unavoidable.

Two further considerations complicate the interpretation of output gaps during the net-zero transition. First, persistent negative output gaps and the disruptive structural transformation as documented in Section 4.2 could depress potential output itself, implying that actual GDP losses may be underestimated if measured solely by output gaps. More generally, structural change of this kind makes it more difficult for central banks to estimate potential output in real time, complicating the assessment of excess demand on which policy decisions rest. Second, the effects accumulate over time, so it is useful to consider the implications for the level of GDP relative to the no-policy benchmark. Figure 13 shows simulated outcomes for annualized quarter-

²⁵The rule specification is not fully optimal since a targeting rule of the form in equation (4.2) is likely to yield stabilization bias, as it does not take advantage of the expectation channel of monetary policy (see for example Galí 2008, chapter 5). A fully optimal rule would be a function of all state variables and shocks, making such an analysis unfeasible in a large model. Nevertheless, the simple rules are informative for characterizing the inflation–output trade-off in a tractable way.

²⁶These limiting values correspond to $\sigma_\pi^2 = 0.0002$ and $\sigma_y^2 = 0.0086$ respectively.

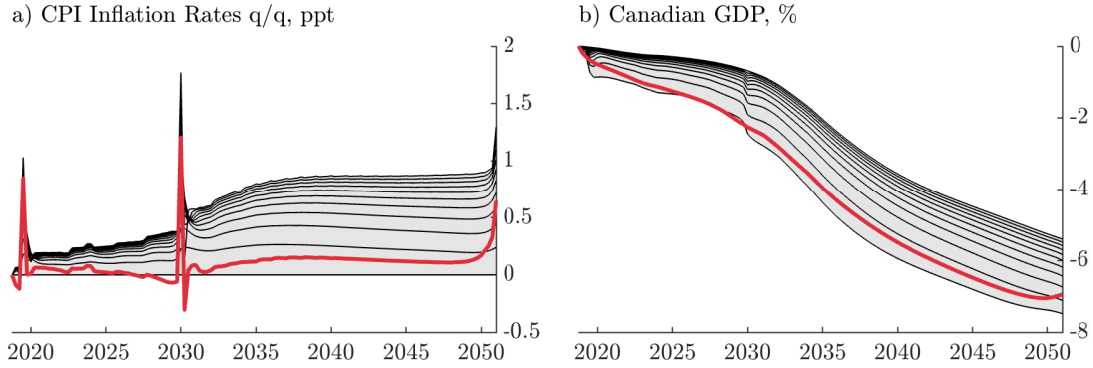


Figure 13: Range of possible outcomes over the net zero conditional on the simple rule (4.2) for $\alpha \in [0, 1]$. Figures show % deviation from the no-policy benchmark. Black lines show $\alpha = 0, 0.1, 0.2, \dots, 1$. Red line is the simulated outcome with the estimated historical rule (4.1). Source: E-ToTEM simulations.

over-quarter CPI inflation and GDP, both expressed as percent deviations from the no-policy scenario. A rule with $\alpha = 1$ maintains full price stability, but expected GDP is 7.5% lower than the benchmark by 2050, with a standard deviation of 9.3% (Figure 12). In contrast, a rule with $\alpha = 0$ limits GDP losses to around 5.5%, with lower volatility, but inflation rises to exceed target by around 1 percentage point up to 2050, with a standard deviation above 5.5 percentage points.

These outcomes indicate that the macroeconomic consequences of climate policy depend critically on the conduct of monetary policy. Managing the trade-off may require deviating from historically estimated rules to accommodate the structural pressures of the net-zero transition. In particular, the results suggest that some degree of inflation tolerance may be optimal if it allows for stronger output outcomes and public support for ambitious climate policy. Although a more accommodative monetary policy stance does imply that larger increases in carbon taxes are needed, it also makes those increases more manageable from a macroeconomic perspective. For example, the shadow carbon price under strict inflation targeting ($\alpha = 1$) reaches \$1,424 CAD/tonne and reaches \$1,503 CAD/tonne with the output target rule ($\alpha = 0$). Monetary policy can therefore complement the efforts of the government in achieving their net-zero objectives.

5 Conclusion

The transition to a low-carbon economy presents major challenges with implications for monetary policy. Using scenario analysis to examine the transition to net zero, we find that the net-zero transition puts modest but persistent upward pressure on CPI inflation.

Quantitatively, our scenario analysis points to substantial structural adjustment costs associated with a globally coordinated transition to net zero. Under the net-zero scenario, global carbon prices rise steadily through 2050, reaching levels close to US\$800 per tonne of CO₂, contributing to a decline in world GDP of roughly 8% relative to a no-policy benchmark. For Canada, weaker external demand, lower commodity

prices, and the contraction of fossil-fuel-intensive sectors reduce GDP by about 7% by 2050. At the same time, higher carbon prices raise energy costs and put upward pressure on inflation, although the effects remain modest, with CPI inflation increasing by at most around 0.3 percentage points. The transition also triggers a significant sectoral reallocation, with green-energy investment increasing by roughly 180% relative to the no-policy benchmark. These results highlight that the macroeconomic consequences of the transition stem not only from domestic climate policies, but also from powerful global spillovers operating through trade, commodity prices, and external demand.

Our analysis also highlights that the negative implications for GDP under the net-zero transition present significant challenges for central banks, not only in estimating potential output but also in managing the complex trade-offs between short-run stabilization and long-run transition objectives. The transition is likely to create persistent tensions between supporting economic activity and maintaining price stability. Monetary policy can play a complementary role by offsetting some of the adverse effects of climate policies on output, thereby enabling governments to pursue more ambitious carbon pricing without causing deeper declines in economic activity. In our simulations, a rule that fully stabilizes inflation leaves GDP about 7.5% below the no-policy benchmark by 2050, whereas a rule that fully stabilizes the output gap limits the loss to around 5.5%. However, this comes at the cost of higher inflation, rising to around 1 percentage point above target over the transition, highlighting the potential need for a careful evaluation of monetary policy priorities. Given the pressures associated with the transition to net zero, central banks may want to depart from historical policy rules and accept a greater degree of price instability to help manage the broader macroeconomic adjustments.

We highlight three areas for future research. First, our use of linearized models to solve transition dynamics, while standard, may miss important nonlinear effects given the scale of economic changes.²⁷ Second, we did not explicitly model carbon capture and storage technologies, which could alter transition trade-offs and warrant further investigation. Finally, our net-zero scenario does not incorporate climate change impacts or the benefits of mitigation, as we compare against a no-policy baseline assuming no economic costs from inaction. Including these interactions remains an important avenue for future work.

²⁷Given the size of E-ToTEM, a non-linear solution is outside the scope of this work.

References

- Aguiar, A., Chepeliev, M., Corong, E. & van der Mensbrugghe, D. (2022), ‘The GTAP data base: Version 11’, *Journal of Global Economic Analysis* **7**(2), 1–37.
- Airaudo, F., Pappa, E. & Seoane, H. D. (2023), The green metamorphosis of a small open economy, CEPR Discussion Papers 17863, C.E.P.R. Discussion Papers.
- Bach, L. T., Gill, S. J., Rickaby, R. E. M., Gore, S. & Renforth, P. (2019), ‘Co2 removal with enhanced weathering and ocean alkalinity enhancement: Potential risks and co-benefits for marine pelagic ecosystems’, *Frontiers in Climate* **1**.
- Bank of Canada (2021), Monetary Policy Framework Renewal, Report, Bank of Canada.
- Bertram, C., Boirard, A., Edmonds, J., Fernando, R., Gayle, D., Hurst, I., Liu, L. W., McKibbin, W., Payerols, C., Richters, O. & Schets, E. (2022), Running the ngfs scenarios in g-cubed: A tale of two modelling frameworks, Occasional paper, Network for Greening the Financial System.
- Black, S., Chateau, J., Jaumotte, F., Parry, I. W., Schwerhoff, G., Thube, S. D. & Zhunussova, K. (2022), ‘Getting on track to net zero: Accelerating a global just transition in this decade’, *Staff Climate Notes* **2022**(010), A001.
- Canada Energy Regulator (2023), Canada’s Energy Future 2023: Energy Supply and Demand Projections to 2050, CER Report, Canada Energy Regulator.
- Canadian Institute for Climate Choices (2021), Canada’s net zero future: Finding our way in the global transition, Technical report, Canadian Institute for Climate Choices.
- Chen, Y.-H. H., Ens, E., Gervais, O., Hosseini, H., Johnston, C., Kabaca, S., Molico, M., Paltsev, S., Proulx, A. & Toktamyssov, A. (2022), ‘Transition scenarios for analyzing climate-related financial risk’.
- Coenen, G., Lozej, M. & Priftis, R. (2024), ‘Macroeconomic effects of carbon transition policies: An assessment based on the ecb’s new area-wide model with a disaggregated energy sector’, *European Economic Review* **167**, 104798.
- Corrigan, P., Desgagnes, H., Dorich, J., Lepetyuk, V., Miyamoto, W. & Zhang, Y. (2021), ‘ToTEM III: The Bank of Canada’s main DSGE model for projection and policy analysis’.
- Daraji, E. & Li, G. (2025), Canada’s industrial energy use trends from 2009 to 2022, Environment Fact Sheets 16-508-X, Statistics Canada.
- Del Negro, M., di Giovanni, J. & Dogra, K. (2023), Is the Green Transition Inflationary?, Staff Reports 1053, Federal Reserve Bank of New York.

- Dollman, R., Arnal, P. A., Eis, J. & McKibbin, W. (2020), ‘The role of monetary policy during a low-carbon transition’. [Accessed 18-03-2024].
- Dorich, J., M. Johnston, R. Mendes, S. M. & Zhang, Y. (2013), ToTEM II: An Updated Version of the Bank of Canada’s Quarterly Projection Model, Technical Report No. 100, Bank of Canada.
- ECCC (2023), ‘New electric vehicle availability standard will give Canadians better access to more affordable cars and cleaner air’.
- Ens, E. & Johnston, C. (2020), Scenario analysis and the economic and financial risks from climate change, Staff Discussion Paper 2020-3, Bank of Canada.
- Environment and Climate Change Canada (2022), Exploring approaches for Canada’s transition to net-zero emissions: Canada’s long-term strategy submission to the United Nations Framework Convention on Climate Change, Technical report, Government of Canada, Gatineau, QC.
- European Commission (2024), ‘Scope of the EU ETS’.
- European Energy Exchange (n.d.), ‘Emissions products overview’.
- Ferrari, A. & Nispi Landi, V. (2024), ‘Will the green transition be inflationary? expectations matter’, *IMF Economic Review*.
- Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., del Mar Zamora Dominguez, M. & Minx, J. C. (2018), ‘Negative emissions—part 2: Costs, potentials and side effects’, *Environmental Research Letters* **13**(6), 063002.
- Galí, J. (2008), *Monetary Policy, Inflation, and the Business Cycle: An Introduction to the New Keynesian Framework*, Princeton University Press, Princeton, New Jersey.
- Gnocchi, S., McKellips, F., Sekkel, R., Simon, L., Xie, Y. & Zhang, Y. (2024), The output-inflation trade-off in Canada, Staff Discussion Paper 2024-7, Bank of Canada.
- Government of Canada (2022), ‘Canada’s fifth biennial report on climate change’.
- Government of Canada (2023), ‘Regulatory framework for an oil and gas sector greenhouse gas emissions cap’.
- Inklaar, R., Marapin, R. & Gräler, K. (2023), Tradability and sectoral productivity differences across countries, GGDC Research Memorandum 195, Groningen Growth and Development Centre. GGDC Productivity Level Database 2023 Edition.
- IPCC (2018a), ‘Chapter 4 in strengthening and implementing the global response. Geneva: Intergovernmental panel on climate change’.

- IPCC (2018*b*), ‘In global warming of 1.5°C. an ipcc special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty’. edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, and others.
- Jaumotte, M. F., Liu, W. & McKibbin, W. J. (2021), Mitigating climate change: Growth-friendly policies to achieve net zero emissions by 2050, IMF Working Papers 2021/195, International Monetary Fund.
- Kaya, Y. & Yokobori, K. (1997), *Environment, energy, and economy: Strategies for sustainability*, United Nations University Press, Tokyo.
- Lalonde, R. & Muir, D. (2007), The Bank of Canada’s Version of the Global Economy Model (BoC-GEM), Technical Report No. 98, Bank of Canada.
- Liu, W. L., McKibbin, W., Shuetrim, G. & Wilcoxon, P. (2025), ‘Modelling structural change in global macroeconomic models’, *Oxford Review of Economic Policy* **41**(2), 555–570.
- Liu, W., McKibbin, W., Morris, A. & Wilcoxon, P. J. (2020), Global economic and environmental outcomes of the Paris Agreement, CAMA Working Papers 2019-04, Centre for Applied Macroeconomic Analysis, Crawford School of Public Policy, The Australian National University.
- McKibbin, W. J., Pearce, D. & Stegman, A. (2007), ‘Long term projections of carbon emissions’, *International Journal of Forecasting* **23**(4), 637–653.
- McKibbin, W. J. & Wilcoxon, P. J. (2013), A Global Approach to Energy and the Environment, in P. B. Dixon & D. Jorgenson, eds, ‘Handbook of Computable General Equilibrium Modeling’, Vol. 1 of *Handbook of Computable General Equilibrium Modeling*, Elsevier, chapter 0, pp. 995–1068.
- McKibbin, W., Jaumotte, F. & Liu, W. (2021), Mitigating Climate Change: Growth-Friendly Policies to Achieve Net Zero Emissions by 2050, CEPR Discussion Papers 16553, C.E.P.R. Discussion Papers.
- Murchison, S. & Rennison, A. (2006), Totem: The bank of canada’s new quarterly projection model., ”technical report no. 97”, Bank of Canada.
- NGFS (2023), ‘NGFS Climate Scenarios for central banks and supervisors - Phase IV’.
- Olovsson, C. & Vestin, D. (2023), Greenflation?, Working Paper Series 420, Sveriges Riksbank (Central Bank of Sweden).
- Pahle, M., Sitarz, J., Osorio, S. & Görlach, B. (2022), *The EU-ETS price through 2030 and beyond: A closer look at drivers, models and assumptions*, Kopernikus-Projekt Ariadne.
- Statistics Canada (2020), ‘Symmetric input-output tables, 2016 and 2017’. Catalogue No. 15-207-X, Issue No. 2020001.

Sylvan, P. H. D. (2024), ‘Consensus on carbon dioxide removal: A large-sample expert elicitation on the future of cdr’.

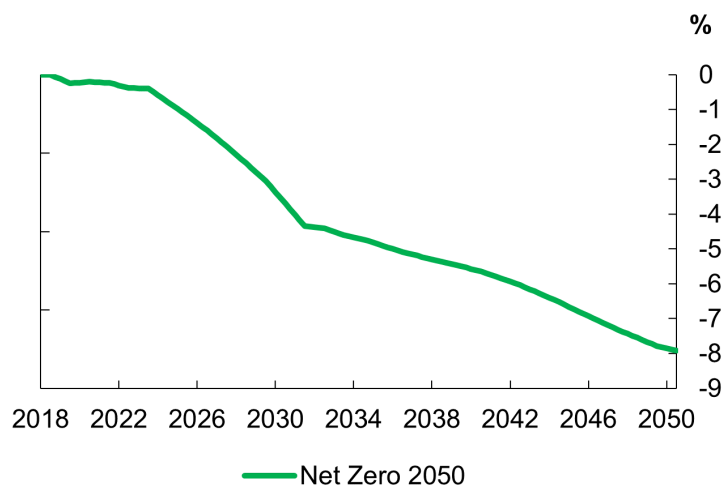
Appendices

A Tables and figures

Table A.1: Current policy 2030 CO₂ emissions reduction targets by region.

Region	Relative to 2005	2023-2030
Canada	-25.2%	-16.0%
USA	-21.0%	-6.9%
Japan	-32.5%	-17.3%
Australia	-15.4%	-11.0%
EU	-41.7%	-20.1%
Other advanced economies	-42.3%	-9.1%
China	+81.0%	-0.4%
India	+134.8%	+18.1%
Russia	+17.0%	+4.3%
Oil exporting emerging economies	+75.1%	+18.2%
Rest of world	+40.0%	+10.3%

Figure A.1: RoW Non-energy Commodity Prices



Notes: Response of non-energy commodity prices for Rest of the World under net-zero scenario. Responses are in percent deviation relative to no-policy control. Source: G-Cubed simulations.

B Energy-TOTEM: Model Description

E-ToTEM extends ToTEM III by breaking down the energy sector in ToTEM into *green* and *brown* energy, as well as introducing roundabout production in the commodity sector. As in ToTEM III there is a non-energy commodity sector. We model two climate transition policies: 1) a tax on brown energy (meant to capture the carbon tax in Canada introduced in 2018, and 2) a investment tax credit on investment into green energy. We also extend the model to capture the elastic world demand for Canadian commodity exports. Figure 1 produces an overview of E-ToTEM. For details of the model outside of the commodity sector, see the description of ToTEM III in [Corrigan et al. \(2021\)](#).

B.1 Commodities

B.1.1 Commodity Producing Firms - First Stage of Production

In each sub-sector within the commodity sector there is roundabout production: firms use the final commodity composite as an intermediate input in production (not the case in ToTEM III). The other components in the production function are the same as in ToTEM III, including labor (L_t^x), capital (K_t^x), and (fixed) land ($\mathcal{L}$).

We use index x to denote the subsectors, green energy/brown energy/non-energy commodities ($x \in \{eng, enb, ne\}$).

The firm in sector x maximizes:

$$\mathbb{E}_t \sum_{s=t}^{\infty} \mathcal{R}_{t,s} (P_s^{x,no} Y_s^{x,va} - W_s L_s^x - P_s^{COM} COM_s^x - P_s^I I_s^x) \quad (\text{B.1})$$

subject to the nested CES production technology (B.2-B.4), production after investment adjustment costs (B.5), evolution of capital (B.6), and capital utilization (B.7), and

$$\mathcal{G}_t^x = \left(\delta_x^{\frac{1}{\sigma_{kl}}} (A_t A_t^x L_t^x \xi_t^{L,x})^{\frac{\sigma_{kl}-1}{\sigma_{kl}}} + (1 - \delta_x)^{\frac{1}{\sigma_{kl}}} \left(u_t^x K_t^x \xi_t^{K,x} \right)^{\frac{\sigma_{kl}-1}{\sigma_{kl}}} \right)^{\frac{\sigma_{kl}}{\sigma_{kl}-1}} \quad (\text{B.2})$$

$$\mathcal{H}_t^x = \left(v_x^{\frac{1}{\sigma_{klc}}} (\mathcal{G}_t^x)^{\frac{\sigma_{klc}-1}{\sigma_{klc}}} + (1 - v_x)^{\frac{1}{\sigma_{klc}}} (COM_t^x \xi_t^{COM,x})^{\frac{\sigma_{klc}-1}{\sigma_{klc}}} \right)^{\frac{\sigma_{klc}}{\sigma_{klc}-1}} \quad (\text{B.3})$$

$$\mathcal{F}_t^x = \left(\gamma_x^{\frac{1}{\sigma_{klcm}}} (\mathcal{H}_t^x)^{\frac{\sigma_{klcm}-1}{\sigma_{klcm}}} + (1 - \gamma_x)^{\frac{1}{\sigma_{klcm}}} (A_t A_t^x \mathcal{L})^{\frac{\sigma_{klcm}-1}{\sigma_{klcm}}} \right)^{\frac{\sigma_{klcm}}{\sigma_{klcm}-1}} \quad (\text{B.4})$$

$$Y_t^{x,va} = \mathcal{F}_t^x - \frac{\chi^I}{2} \left(\frac{I_t^x}{I_{t-1}^x} - 1 \right)^2 I_t^x \quad (\text{B.5})$$

$$K_t^x = (1 - \omega_{t-1}^x) K_{t-1}^x + I_{t-1}^x \quad (\text{B.6})$$

$$\omega_t^x = u_x + \frac{u_x^{ss}}{u} \exp(u(\varepsilon_{u,t} u_{x,t} - 1)) \quad (\text{B.7})$$

$$(\text{B.8})$$

where u_t^x is the capital utilization, ω_t^x represents the depreciation rate, $Y_s^{x,g}$ represents the gross output, and $Y_s^{x,va}$ represents the output net of investment adjustment costs. A_t represents economy wide productivity and A_t^x represents sector-specific productivity. Here $\varepsilon_{u,t}$ represents an exogenous shock capital utilization and $\{\xi_t^{L,x}, \xi_t^{K,x}, \xi_t^{COM,x}\}$ are the adjustment costs following

$$\xi_t^{L,x} = 1 - \frac{\chi^L}{2} \left(\frac{L_t^x}{L_{t-1}^x} - 1 \right)^2, \quad (\text{B.9})$$

$$\xi_t^{K,x} = 1 - \frac{\chi^K}{2} \left(\frac{K_t^x/\mathcal{F}_t^x}{K_{t-1}^x/\mathcal{F}_{t-1}^x} - 1 \right)^2, \quad (\text{B.10})$$

$$\xi_t^{COM,x} = 1 - \frac{\chi^{COM}}{2} \left(\frac{COM_t^x/\mathcal{F}_t^x}{COM_{t-1}^x/\mathcal{F}_{t-1}^x} - 1 \right)^2. \quad (\text{B.11})$$

We define the net output in non-energy sector as equal to $Y_t^{x,va}$, that is, $EN_t^{eng} = Y_t^{eng,va}$, $EN_t^{enb} = Y_t^{enb,va}$, and $NE_t = Y_t^{ne,va}$ for green energy, brown energy and non-energy commodities respectively.

Green Energy: Investment Tax Credit The government imposes a subsidy (τITC_t) to investment in the green energy sector (I_t^{eng}). So the green energy firm maximizes profits as (B.1), with the following modification:

$$\mathbb{E}_t \sum_{s=t}^{\infty} \mathcal{R}_{t,s} (P_s^{eng,va} Y_s^{eng,va} - W_s H_s^{eng} - P_s^{eng} COM_s^{eng} - P_s^I (1 - \tau_s^{ITC}) I_s^{eng})$$

subject to same constraints as for objective function (B.1), where τ_s^{ITC} represents the investment subsidy in the green sector.

The first-order condition with respect to green-energy investment is

$$q_t^{K,eng} - (1 - \tau_s^{ITC}) p_t^I = \lambda_t^{eng,va} \left[\chi^{eng,I} \left(\frac{I_t^{eng} \varepsilon_t^I}{I_{t-1}^{eng}} - 1 \right) \frac{I_t^{eng} \varepsilon_t^I}{I_{t-1}^{eng}} + \frac{\chi^{eng,I}}{2} \left(\frac{I_t^{eng} \varepsilon_t^I}{I_{t-1}^{eng}} - 1 \right)^2 \right] \\ - \chi^{eng,I} \mathbb{E}_t \left[\mathcal{R}_{t,t+1} \lambda_{t+1}^{eng,va} \Pi_{t,t+1} \left(\frac{I_{t+1}^{eng}}{I_t^{eng} \varepsilon_t^I} - 1 \right) \left(\frac{I_{t+1}^{eng}}{I_t^{eng} \varepsilon_t^I} \right)^2 \right] \quad (\text{B.12})$$

$\chi^{eng,I}$ is the scaling parameter for the quadratic adjustment cost of green energy investment, similar to the definition of the economy-wide scaling parameter χ^I for investment adjustment costs. ε_t^I is an exogenous shock on investment inherited from ToTEM III.

B.1.2 Commodity Producing Firms - Second Stage of Production

Within each commodity sector x (green, brown and non-energy) a continuum of retailers purchase the raw sectoral production from the wholesale firms in Section B.1.1, repackage it into differentiated goods, and sell to downstream aggregators (described in the following section B.1.3). When retailers sell the brown and

green energy commodity to the energy aggregator for firms, they are subject to a nominal rigidity. This does not apply to the energy aggregator for households. The retailers selling the non-energy commodity are subject to nominal rigidity, regardless of whether they sell to the firm or household commodity aggregator. The price-setting regime follows the same setup in the ToTEM III. The nominal frictions are sector specific, as before x indexes the brown, green, and non-energy sectors: $x \in \{eng, enb, ne\}$.

As in ToTEM III, there are two different groups of price setters: rule of thumb (with a weight ω^x) and forward-looking (with a weight $1 - \omega^x$). With probability θ^x , both rule of thumb and forward-looking firms index their own price to the inflation target. With probability $1 - \theta^x$, rule of thumb firms index their price to partially lagged sectoral inflation. Their (linearized) rule is:

$$p_t^x = p_{t-1}^x + \gamma \pi_{t-1}^x + (1 - \gamma) \bar{\pi}_t,$$

where $\bar{\pi}_t$ denotes the inflation target in period t . With probability $1 - \theta^x$, forward-looking firms set prices following the Calvo pricing. See details in Section 1.1.3 of the ToTEM II technical report (Dorich et al. 2013) and the discussion in Gnocchi et al. (2024).

Note that the brown energy retailers pays the carbon tax on brown energy when they purchase brown energy from the wholesale brown energy firm. So their marginal cost is:

$$P_t^{enb,tax} = P_t^{enb,no} (1 + \tau_t^{itax}) \quad (\text{B.13})$$

The price that the firm energy aggregator pays for brown energy $P_t^{enb,f}$ is based on $P_t^{enb,tax}$ plus the markup. The price that the household energy aggregator pays for brown energy $P_t^{enb,c}$ is equal to $P_t^{enb,tax}$.

B.1.3 Commodity Aggregation

This section describes the aggregation of green & brown energy into the energy aggregate, and energy & non-energy commodities into the commodity aggregate.

Green & Brown Energy Aggregator Green and brown energy is bundled into an energy aggregate using CES technology. There is a different energy aggregate for households (indexed by c) and firms (indexed by f):

$$EN_t^c = \left(\frac{1}{\delta_{eng,c}^{\frac{1}{\sigma_{en,c}}}} (EN_t^{eng,c})^{\frac{\sigma_{en,c}-1}{\sigma_{en,c}}} + (1 - \delta_{eng,c})^{\frac{1}{\sigma_{en,c}}} (EN_t^{enb,c})^{\frac{\sigma_{en,c}-1}{\sigma_{en,c}}} \right)^{\frac{\sigma_{en,c}}{\sigma_{en,c}-1}} \quad (\text{B.14})$$

$$EN_t^f = \left(\frac{1}{\delta_{eng,f}^{\frac{1}{\sigma_{en,f}}}} (EN_t^{eng,f})^{\frac{\sigma_{en,f}-1}{\sigma_{en,f}}} + (1 - \delta_{eng,f})^{\frac{1}{\sigma_{en,f}}} (EN_t^{enb,f})^{\frac{\sigma_{en,f}-1}{\sigma_{en,f}}} \right)^{\frac{\sigma_{en,f}}{\sigma_{en,f}-1}}, \quad (\text{B.15})$$

where superscript *eng* represents green-energy sector and *enb* represents brown-energy sector.

We include an adjustment cost to the green-brown energy mix such that the household (and analogously, the firm) solves:

$$\min_{EN_t^{eng,c}, EN_t^{enb,c}} \mathbb{E}_t \sum_{s=0}^{\infty} \left[\mathcal{R}_{t,s} \left(P_{t+s}^{eng,c} EN_{t+s}^{eng,c} + P_{t+s}^{enb,c} EN_{t+s}^{enb,c} + \frac{\phi^c}{2} \left(\frac{EN_{t+s}^{eng,c}/EN_{t+s}^{enb,c}}{EN_{t+s-1}^{eng,c}/EN_{t+s-1}^{enb,c}} - 1 \right)^2 EN_t^{eng,c} \right) \right]$$

subject to

$$EN_t^c = \left(\delta_{eng,c}^{\frac{1}{\sigma_{en,c}}} (EN_t^{eng,c})^{\frac{\sigma_{en,c}-1}{\sigma_{en,c}}} + (1 - \delta_{eng,c})^{\frac{1}{\sigma_{en,c}}} (EN_t^{enb,c})^{\frac{\sigma_{en,c}-1}{\sigma_{en,c}}} \right)^{\frac{\sigma_{en,c}}{\sigma_{en,c}-1}}.$$

Define $\theta_t^c \equiv EN_t^{eng,c}/EN_t^{enb,c}$ and denote the price wedges that arise from the adjustment costs as

$$q_t^{eng,c} \equiv \frac{\phi^c}{2} \left(\frac{\theta_t^c}{\theta_{t-1}^c} - 1 \right)^2 + \phi^c \left(\frac{\theta_t^c}{\theta_{t-1}^c} - 1 \right) \frac{\theta_t^c}{\theta_{t-1}^c} - \phi \mathbb{E}_t \left[\mathcal{R}_{t,t+1} \left(\frac{\theta_{t+1}^c}{\theta_t^c} - 1 \right) \frac{\theta_{t+1}^c}{\theta_t^c} \frac{EN_{t+1}^{eng,c}}{EN_t^{eng,c}} \right] \quad (\text{B.16})$$

$$q_t^{enb,c} \equiv -\phi^c \left(\frac{\theta_t^c}{\theta_{t-1}^c} - 1 \right) \frac{\theta_t^c}{\theta_{t-1}^c} \theta_t^c + \phi \mathbb{E}_t \left[\mathcal{R}_{t,t+1} \left(\frac{\theta_{t+1}^c}{\theta_t^c} - 1 \right) \frac{\theta_{t+1}^c}{\theta_t^c} \frac{EN_{t+1}^{eng,c}}{EN_t^{enb,c}} \right]. \quad (\text{B.17})$$

The first-order conditions can be written in

$$EN_t^{eng,c} = \delta_{eng,c} \left(\frac{P_t^{eng,c} + q_t^{eng,c}}{P_t^{en,c}} \right)^{-\sigma_{en,c}} EN_t^c \quad (\text{B.18})$$

$$EN_t^{enb,c} = (1 - \delta_{eng,c}) \left(\frac{P_t^{enb,c} + q_t^{enb,c}}{P_t^{en,c}} \right)^{-\sigma_{en,c}} EN_t^c, \quad (\text{B.19})$$

The corresponding price indices based on the CES aggregator are given as

$$P_t^{en,c} = \left[\delta_{eng,c} (P_t^{eng,c})^{1-\sigma_{en,c}} + (1 - \delta_{eng,c}) (P_t^{enb,c})^{1-\sigma_{en,c}} \right]^{\frac{1}{1-\sigma_{en,c}}} \quad (\text{B.20})$$

$$P_t^{en,f} = \left[\delta_{eng,f} (P_t^{eng,f})^{1-\sigma_{en,f}} + (1 - \delta_{eng,f}) (P_t^{enb,f})^{1-\sigma_{en,f}} \right]^{\frac{1}{1-\sigma_{en,f}}}. \quad (\text{B.21})$$

where $P_t^{eng,c}$ and $P_t^{eng,f}$ are green energy prices for households and firms, respectively, and $P_t^{enb,c}$ and $P_t^{enb,f}$ are brown energy prices for households and firms post carbon taxes. These are the prices that aggregators pay the retail firms, so for firms these prices are after the Calvo markup. See Section B.1.2 for the pricing problem of retail firms. For firms $P_t^{enb,f}$ is the price of brown after the carbon tax and markup from monopolistic competition.

Energy & Non-Energy Commodity Aggregator The energy composites are then aggregated into the final commodity composite with the non-energy commodity. It follows a Leontief production function, that

is,

$$COM_t^f = \min\left\{\frac{EN_t^f}{s_{en,f}}, \frac{NE_t^f}{1 - s_{en,f}}\right\}$$

$$COM_t^c = \min\left\{\frac{EN_t^c}{s_{en,c}}, \frac{NE_t^c}{1 - s_{en,c}}\right\},$$

which implies

$$\frac{EN_t^f}{s_{en,f}} = \frac{NE_t^f}{1 - s_{en,f}} \quad (\text{B.22})$$

$$\frac{EN_t^c}{s_{en,c}} = \frac{NE_t^c}{1 - s_{en,c}} \quad (\text{B.23})$$

and

$$COM_t^f = \frac{1}{1 - s_{en,f}} NE_t^f \quad (\text{B.24})$$

$$COM_t^c = \frac{1}{1 - s_{en,c}} NE_t^c. \quad (\text{B.25})$$

The price of commodities for households and firms are accordingly given by

$$P_t^{COM,f} = s_{en,f} P_t^{en,f} + (1 - s_{en,f}) P_t^{ne} \quad (\text{B.26})$$

$$P_t^{COM,c} = s_{en,c} P_t^{en,c} + (1 - s_{en,c}) P_t^{ne}, \quad (\text{B.27})$$

where P_t^{ne} is the non-energy commodity price subject to nominal rigidity (both household and firm aggregators pay the same price when purchasing the non-energy from the retailer firm). See details in Section [B.1.2](#). Note, we have $P_t^{com,f} = P_t^{com}$, where P_t^{com} is the factor input price of commodity in Section [B.1.1](#).

B.2 Export & Import of Commodities

B.2.1 Commodity Exports

Brown energy and non-energy commodities are exported, green energy is not exported. World demand for Canadian brown energy and non-energy commodity exports is elastic, i.e. we allow for there to be spread between the domestic and world price (adjusted for the real exchange rate). When firms export brown energy commodities, they are not subject to any carbon taxes, whereas when they sell to domestic purchasers, they are subject to carbon tax.

The foreign demand functions for brown energy and non-energy commodity is as follows:

$$\frac{P_t^{enb,no}}{P_t^C} = \frac{P_t}{P_t^C} e_t \frac{P_t^*}{P_t} \frac{P_t^{enb,*}}{P_t^*} \left[\frac{1}{\eta_{row,eng}} \frac{EN_t^{enb,X}}{Y_t^{enb,*}} \right]^{-1/\varepsilon_{row,enb}} \xi_t \quad (B.28)$$

$$\frac{P_t^{ne,no}}{P_t^C} = \frac{P_t}{P_t^C} e_t \frac{P_t^*}{P_t} \frac{P_t^{ne,*}}{P_t^*} \left[\frac{1}{\eta_{row,eng}} \frac{NE_t^X}{Y_t^{ne,*}} \right]^{-1/\varepsilon_{row,ne}} \xi_t \quad (B.29)$$

$P_t^{enb,no}$, and $P_t^{ne,no}$ are the brown and non-energy commodity prices before monopolistic markups and (in the case of brown) before the carbon tax. P_t is the GDP deflator and P_t^C is the core CPI price level. e_t is the nominal exchange rate. $EN_t^{enb,X}$ represents the exported quantity of brown energy commodity. NE_t^X represents the exported quantity of the non-energy commodity. Starred variables are the variables for the rest of the world. $\eta_{row,enb}$ and $\eta_{row,ne}$ are constant scaling parameters, which are the steady state ratio of export quantities to world demand. ξ_t is an exogenous shock, representing a global shock on row prices. In E-ToTEM scenario analysis.

B.2.2 Brown Energy Absorption

The brown energy absorption is defined as the total brown energy commodity consumed in the domestic country, which equals the total domestic demand of brown energy plus the imported brown energy. Since E-ToTEM does not model imported brown energy directly but incorporates the imported commodity as intermediate inputs, we assume the imported commodity includes a fixed share of brown energy commodity:

$$COM_t^{enb,abs} \equiv EN_t^{enb,f} + EN_t^{enb,c} + (1 - \delta_{eng,f}) s_{en,f} M_t^{com}, \quad (B.30)$$

where $COM_t^{enb,abs}$ represents the domestic brown energy absorption and M_t^{com} is the imported commodity. Brown energy is assumed to make up the same fraction of commodity imports as its fraction in the domestic commodity aggregate.

B.3 Fiscal Policy

The government collects revenue from carbon tax (and the expense of investment tax credit introduced in Section B.1.1) as the general government surplus. A fixed fraction (63%) of the carbon revenue is uniformly redistributed to the households as lump-sum transfers. All else is the same as in ToTEM III on the fiscal side.

Specifically, on the fiscal side, we make two changes relative to ToTEM III on the government deficit and the total lumps-sum transfer to households. The new term in the government deficit becomes

$$D_t^{new} = D_t^{ToTEM} + T_t^{tf} + T_t^{ITC} - T_t^{itax}, \quad (B.31)$$

where D_t^{ToTEM} denotes the government deficit in the ToTEM III, T_t^{tf} denotes the government total lump-sum transfer to households. T_t^{ITC} denotes the expense of investment tax credit and T_t^{itax} denotes carbon tax revenue. Where:

$$T_t^{itax} = \tau_t^{itax} P_t^{enb,no} (EN_t^{enb,f} + EN_t^{enb,c}), \quad (B.32)$$

$$T_t^{ITC} = \tau_t^{ITC} P_t^I I_t^{eng}, \quad (B.33)$$

where τ_t^{ITC} is the exogenous rate of investment tax credit and I_t^{eng} is the quantity of investment in the green energy sector. See details in Section B.1.1.

B.4 Market Clearing Conditions

Goods market of final commodity composite, brown energy commodity, and non-energy commodity clear. Labor market and factor input markets clear, same as in ToTEM III, so we do not lay out them here.

Specifically, for the commodity composite, the market clearing condition follows:

$$\begin{aligned} \text{For firms: } & COM_t^f = COM_t^{f,d} \\ \text{For households: } & COM_t^c = COM_t^{c,d}, \end{aligned}$$

where

$$\begin{aligned} COM_t^{f,d} = & COM_t^{c,ind} + COM_t^{irs,ind} + COM_t^{inv,ind} + COM_t^{g,ind} + COM_t^{x,ind} \\ & + COM_t^{enb} + COM_t^{eng} + COM_t^{ne}. \end{aligned} \quad (B.34)$$

The superscript “ind” represents the demand from industry sectors such as consumption and residential property. To have a similar notation as in ToTEM III for total commodity composite, we also define it as

$$COM_t^{tot} \equiv EN_t^{enb,c} + EN_t^{eng,c} + NE_t^c + EN_t^{enb,f} + EN_t^{eng,f} + NE_t^f + EN_t^{enb,X} + NE_t^X. \quad (B.35)$$

This is simply for notation similarity and is not part of the market equilibrium condition.

The brown energy commodity market clearing condition yields

$$EN_t^{enb} = EN_t^{enb,X} + EN_t^{enb,f} + EN_t^{enb,c}, \quad (B.36)$$

where $EN_t^{enb,X}$ is the exported quantity of brown energy.

The green energy commodity market clearing condition yields

$$EN_t^{eng} = EN_t^{eng,f} + EN_t^{eng,c}. \quad (\text{B.37})$$

Non-energy commodity market clearing condition yields

$$NE_t = NE_t^X + NE_t^f + NE_t^c, \quad (\text{B.38})$$

where NE_t^X is the exported quantity of non-energy.

B.4.1 Imports in the Production of Other Sectors

Imports, which are used as intermediate inputs in the production in sectors other than the commodity sector, are decomposed into energy and non-energy imported goods.

Firms in other sectors such as the consumption sector and export sector are still subject to the same production function and optimization problem as in ToTEM III. The only difference is that the import, as factor input in production, is now a composite of commodity and non-commodity import goods, following a CES aggregation. It follows

$$M_t^x = \left(\delta_{com}^{\frac{1}{\sigma_M}} (M_t^{x,com})^{\frac{\sigma_M-1}{\sigma_M}} + (1 - \delta_{com})^{\frac{1}{\sigma_M}} (M_t^{x,ncom})^{\frac{\sigma_M-1}{\sigma_M}} \right)^{\frac{\sigma_M}{\sigma_M-1}}, \quad (\text{B.39})$$

where x represents sectors other than the commodity sector, i.e., $x \in \{c, irs, g, inv, X\}$, including consumption/residential property/government/investment/export sectors.

The total imported commodity and non-commodity goods are given by

$$M_t^{com} = M_t^{c,com} + M_t^{irs,com} + M_t^{g,com} + M_t^{inv,com} + M_t^{X,com}, \quad (\text{B.40})$$

$$M_t^{ncom} = M_t^{c,ncom} + M_t^{irs,ncom} + M_t^{g,ncom} + M_t^{inv,ncom} + M_t^{X,ncom}. \quad (\text{B.41})$$

The CES aggregation (B.39) implies the corresponding price indices satisfying

$$P_t^M = \left[\delta_{com} (P_t^{com})^{1-\sigma_M} + (1 - \delta_{com}) (P_t^{ncom})^{1-\sigma_M} \right]^{\frac{1}{1-\sigma_M}}, \quad (\text{B.42})$$

and the elastic demand function:

$$M_t^{x,com} = \delta_{com} \left(\frac{P_t^{com}}{P_t^M} \right)^{-\sigma_M} M_t^x, \quad (\text{B.43})$$

$$M_t^{x,ncom} = (1 - \delta_{com}) \left(\frac{P_t^{ncom}}{P_t^M} \right)^{-\sigma_M} M_t^x. \quad (\text{B.44})$$

Here it has been assumed that the price of imported commodity goods is the same as the domestic price of commodity faced by firms in the commodity sector, P_t^{com} .

B.5 Exogenous Shock Processes

$$\tau_t^{itax} = \tau_{t-1}^{itax} + \delta_t^{itax}, \quad (\text{B.45})$$

$$\tau_t^{ITC} = \tau_{t-1}^{ITC} + \delta_t^{ITC}, \quad (\text{B.46})$$

$$\ln Y_t^{enb,*} = \rho_{enb,*} \ln Y_{t-1}^{enb,*} + \delta_t^{enb,*}, \quad (\text{B.47})$$

$$\ln Y_t^{ne,*} = \rho_{ne,*} \ln Y_{t-1}^{ne,*} + \delta_t^{ne,*}, \quad (\text{B.48})$$

$$\ln A_t^{enb} = \rho_{enb} \ln A_{t-1}^{enb} + \delta_t^{enb,a}, \quad (\text{B.49})$$

$$\ln A_t^{eng} = \rho_{eng} \ln A_{t-1}^{eng} + \delta_t^{eng,a}, \quad (\text{B.50})$$

$$\ln A_t^{ne} = \rho_{ne} \ln A_{t-1}^{ne} + \delta_t^{ne,a}, \quad (\text{B.51})$$

$$\ln A_t = \rho_a \ln A_{t-1} + \delta_t^a, \quad (\text{B.52})$$

where $\{\delta_t^{itax}, \delta_t^{ITC}, \delta_t^{enb,*}, \delta_t^{ne,*}, \delta_t^{enb,a}, \delta_t^{eng,a}, \delta_t^{ne,a}, \delta_t^a\}$ are iid shocks with mean zero.

B.6 Calibration within the Commodity Sector

The calibration of E-ToTEM follows ToTEM III in most cases. This section describes the calibration of parameters that are new to E-ToTEM. Table B.1 lists the parameters.

Table B.1: Calibration of Parameters New to E-ToTEM

Symbol	Description	Value
$s_{en,c}$	share of energy in the households' commodity aggregate	0.711
$s_{en,f}$	share of energy in the firms' commodity aggregate	0.413
$\delta_{eng,c}$	share of green energy in the households' energy aggregate	0.323
$\delta_{eng,f}$	share of green energy in the firms' energy aggregate	0.066
$\sigma_{en,c}$	elasticity of substitution between green and brown energy in the households' energy aggregate	1.01
$\sigma_{en,f}$	elasticity of substitution between green and brown energy in the firms' energy aggregate	1.01
$\chi^{eng,I}$	green energy investment adjustment cost	20.189
$\varepsilon_{row,enb}$	degree of elastic demand for brown energy exports	10
$\varepsilon_{row,ne}$	degree of elastic demand for non-energy commodity exports	10
ϕ^c	adjustment cost weight between green & brown energy in the households' energy aggregate	0.7
ϕ^f	adjustment cost weight between green & brown energy in the firms' energy aggregate	0.7

The share of energy in the commodity aggregates ($s_{en,f}$, $s_{en,c}$) and the share of green energy in the energy aggregates ($\delta_{eng,c}$, $\delta_{eng,f}$) are calibrated using the Canadian symmetric input-output tables (Statistics Canada

Table: 36-10-0001-01). Shares are computed by aggregating the granular sectors of the input-output tables into the commodity sectors of the model with Leontief input-output matrices. This methodology accounts for both the direct, and indirect, usage of energy and non-energy commodities by firms and households. The green energy sector corresponds to electric power generation, transmission and distribution, while the brown energy sector is comprised of sectors related to the extraction, processing, and distribution of fossil fuels, as seen in B.2. Mining, agriculture, fishing and forestry are classified as non-energy commodities.

Table B.2: Input-Output Industry Classification of Model Sectors

Sector	Code	Title
Green energy	BS221100	Electric power generation, transmission and distribution
Brown energy	BS211110	Oil and gas extraction (except oil sands)
	BS211140	Oil sands extraction
	BS211113*	Conventional oil and gas extraction
	BS211114*	Non-conventional oil extraction
	BS212100	Coal mining
	BS21311A	Support activities for oil and gas extraction
	BS221200	Natural gas distribution
	BS324110	Petroleum refineries
	BS3241A0	Petroleum and coal product manufacturing (except petroleum refineries)

Note: Conventional oil and gas extraction, and non-conventional oil extraction were terminated in the 2014 industry classification and replaced with oil and gas extraction (except oil sands) and oil sands extraction, respectively. They are retained in the model mapping for consistency with the 2013 input-output table.

The investment adjustment cost on green energy investment ($\chi^{eng,I}$) is assumed to be twice as high as the investment adjustment cost in other sectors. This is motivated by the longer time to build in green energy projects.

$\varepsilon_{row,emb}$ & $\varepsilon_{row,ne}$ govern the strength of the elastic world demand for brown energy exports and non-energy commodity exports specifically.

ϕ^c and ϕ^f are the weights on the adjustment cost between green and brown energy in the energy aggregator for households and firms respectively.

The parameters that govern the nominal frictions in the green energy and brown energy sectors are the same in E-ToTEM, and are the same calibration for the consolidated energy sector in ToTEM III. The calibration of non-energy is the same as that in ToTEM III.

C List of Canadian and Global Climate Policies Considered

Canadian Policies:

- Carbon pricing: In August 2021, the federal government announced an updated carbon pricing schedule, increasing the federal fuel charge to \$65/tonne of CO₂ in 2023, with planned annual increases of \$15/tonne until it reaches \$170/tonne in 2030.¹ As of April 2025, the fuel charge has been set to

¹Federal carbon pricing was introduced in 2019, initially starting at \$20/tonne of CO₂, and was set to increase to \$50/tonne in 2022, but no path beyond 2022 was outlined at the time.

\$0/tonne. These recent policy changes are not reflected in our analysis since our simulations were carried out beforehand.

- Green investment subsidies: The federal government has introduced refundable investment tax credits (ITCs) to support clean energy projects. Eligible investments span multiple 6-digit NAICS industries, primarily within the electricity, manufacturing, and mining sectors. The most relevant measure is the 15% tax credit on clean electricity investments.²
- Zero-Emission Vehicle (ZEV) Sales Mandate: As part of the 2022 Emissions Reduction Plan, the government introduced legally binding sales targets. Signed into law in December 2023, the New Electric Vehicle Availability Standard mandates that 100% of new light-duty vehicle (LDV) sales must be ZEVs by 2035, with interim targets of 20% by 2026, and 60% by 2030 (ECCC 2023)³.
- Oil and Gas Sector Emissions Cap: In December 2023, the government proposed a cap-and-trade system to limit emissions from upstream oil and gas facilities including oil sands production, natural gas processing, and LNG operations.⁴ The proposed 2030 emissions cap is 131–137 Mt CO₂e, representing a 20–23.4% reduction from 2019 levels.⁵
- Other Climate Policies: Additional policies implemented up to November 2022 include the Clean Fuel Regulations requiring gasoline and diesel suppliers to reduce carbon intensity by 15% by 2030; and Building Efficiency programs. The latter includes updated Building Codes and the Canada Green Homes Grant, supporting energy-efficiency improvements in residential and commercial buildings.

Global Policies:

- U.S. Tax Credits from the Inflation Reduction Act: The most significant policy development is the introduction of major energy and climate programs in the United States, particularly the Inflation Reduction Act (IRA) and the Bipartisan Infrastructure Law.⁶ We explicitly model key investment tax credits (ITC) and production tax credits (PTC) from the IRA that target energy producers and upstream manufacturers in the clean technology supply chain.⁷ To integrate these policies into G-Cubed, we use input-output data to calculate effective tax credit rates for firms in the electricity generation and manufacturing sectors. Tax credits are assumed to follow announced schedules, with

²Additional ITCs include a 30% Clean Technology ITC for clean technology adoption (e.g., heat pumps and heavy-duty EVs), a 30% Clean Technology Manufacturing Tax credit targeting upstream clean-tech production (including the extraction and processing of critical minerals, and the production of EVs and EV components), and sector specific credits for carbon capture and hydrogen projects, ranging from 15% to 60%.

³LDVs include passengers car, pickup trucks, SUVs/crossovers.

⁴See <https://www.canada.ca/en/environment-climate-change/news/2023/12/new-electric-vehicle-availability-standard-will-give-canadians-better-access-to-more-affordable-cars-and-cleaner-air.html> for details (Government of Canada 2023)

⁵These upstream facilities represented 85% of sector emissions in 2021. New LNG facilities are projected to be a growing emissions source. The cap aligns with the Canada Energy Regulator's Net-Zero emissions Forecast (Canada Energy Regulator 2023).

⁶These broad policy packages modernize the energy system through regulatory reforms and a variety of subsidies, including direct spending programs and tax credits.

⁷Tax credits considered include the Advanced Energy Project Credit and Clean Electricity ITC, Clean Electricity PTC, Zero-Emission Nuclear Power PTC, Advanced Manufacturing PTC, and Clean Hydrogen PTC. A full overview is provided here: <https://www.whitehouse.gov/cleanenergy/clean-energy-tax-provisions/>.

all currently expected to phase out by 2034.

- European Union Emission Trading System (ETS): The EU ETS, introduced in 2005, sets an emissions cap for energy producers, manufacturers, and domestic aviation, covering approximately 40% of total EU emissions.⁸ Allowances for each tonne of CO₂ equivalent under the cap are auctioned and can be traded in a secondary market.⁹ As part of the European Commission’s ‘Fit for 55’ package, the ETS is set to reduce emissions by at least 62% by 2030 compared to 2005 levels. Our assumptions on ETS price trajectories are based on modelling surveys that project carbon prices to reach €56-111 by 2025, and €140-160 by 2030 (Pahle et al. 2022). Using the midpoints of these ranges, we linearly interpolate prices between 2019-2025, and 2025-2030, resulting in a price path rising from €25 in 2019 to €145 in 2030.
- Other Climate Policies: We also account for additional policies across all regions enacted by the end of 2022. These are based on the Climate Action Tracker (CAT)¹⁰ which in a timely fashion documents global climate actions and evaluates their impact.

D Robustness

Decarbonization requires firms and households to substitute away from fossil fuels. It follows that the costs associated with the transition may vary according to the ability of energy users to switch between energy sources, and the pace at which the supply of green energy can be expanded to meet the shift in demand.

The ease of substitution between electricity and fossil fuels can vary widely across applications, and depends largely on the state of technology. Some activities may be relatively easy to electrify today, such as light-duty road transportation, while the electrification of other activities may be years away because of high costs or the limitations of current technology. To investigate how this dynamic could affect our results, we vary the elasticity of substitution between green and brown energy in E-ToTEM. A higher elasticity leads to a faster expansion of green energy investment, a smaller fall in total exports, and a smaller GDP loss from a transition to net zero. Simulation results are shown in Figure D.1.

The expansion of the green energy sector could also be assisted by increased total factor productivity (TFP) growth in the sector through learning-by-doing and technological innovation, particularly for newer technologies. Electricity generation methods such as wind and solar have experienced dramatic cost improvements in recent decades, but only represent a small share of Canada’s electricity mix today. As their uptake increases, wind and solar could become drivers of accelerated TFP growth in the green energy sector. To assess the potential macroeconomic implications of this, we assume that annual TFP growth in the green energy sector

⁸Further details are provided by the European Commission (2024).

⁹The European Energy Exchange provides a trading platform (see <https://www.eex.com/en/markets/environmental-markets/eu-ets-spot-futures-options> and European Energy Exchange n.d.) for spot and derivative transactions.

¹⁰A collaboration between Climate Analytics and the New Climate Institute, the CAT has provided independent policy analysis to policymakers since 2009.

is permanently 1.5% higher, compared to our original exercise with no TFP growth for all sectors. Figure D.2 shows the simulation results. We find that the higher TFP growth assumption in E-ToTEM leads to slightly lower impacts on inflation and GDP under the net-zero transition.

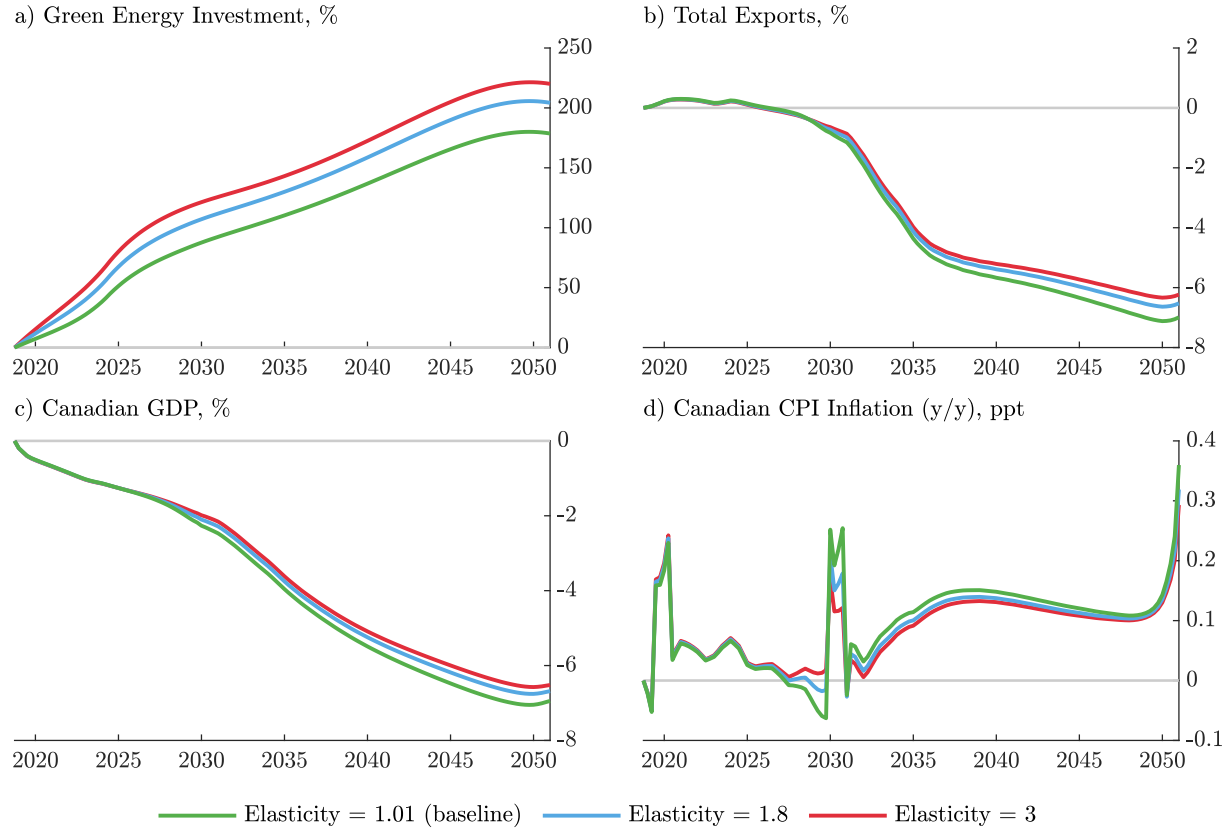


Figure D.1: Net-zero transition under alternative elasticities of substitution between green and brown energy for households and firms: 1.01 (baseline, green), 1.8 (blue) and 3 (red). Chart a) shows capital investment in the green energy sector, chart b) total exports, chart c) real GDP and chart d) year-over-year CPI inflation. Responses are in percent deviation relative to the no-policy control; chart d) is in percentage points. Source: E-ToTEM simulations.

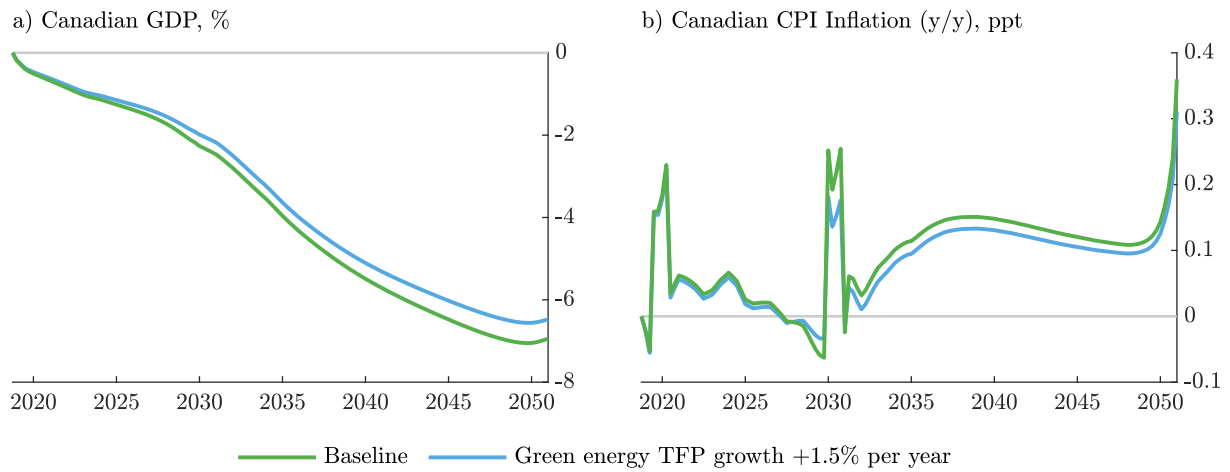


Figure D.2: Net-zero transition with annual TFP growth in the green energy sector permanently 1.5% higher (blue), compared with the baseline scenario with no TFP growth (green). Chart a) shows real GDP and chart b) year-over-year CPI inflation. Responses are in percent deviation relative to the no-policy control; chart b) is in percentage points. Source: E-ToTEM simulations.