Energy and Climate Change 5 (2024) 100147

Contents lists available at ScienceDirect

Energy and Climate Change

journal homepage: www.sciencedirect.com/journal/energy-and-climate-change

Similarities and contrasts: Comparing U.S. and Canadian paths to net-zero☆

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ARTICLE INFO

Keywords:
Net zero emissions
Canadian climate policy
United States climate policy
Economic outcomes
Energy economy emissions modelling

ABSTRACT

Canada and the United States (US) have both committed to reaching net zero emissions by 2050 but neither have implemented policy sufficient to reach this target. Knowledge of the technical steps to deep decarbonization is needed alongside an understanding of how each country might be similarly and uniquely impacted by a transition to net zero emissions, contingent on specific technology advancements or policy decisions. We use the computable general equilibrium model, gTech, to simulate sixteen net zero scenarios for Canada and the US varying by technology and policy assumptions as part of the energy modelling forum 37 (EMF37) study. We find that both economies similarly continue to grow in all scenarios out to 2050 with the rate of growth largely determined by assumptions on negative emissions technology. Sectoral impacts differ between countries as a result of current emissions and GDP profiles in combination with assumed net zero scenario policy and technology advancements. In the US, we find that efficient use of electricity is a slightly more important predictor of economic outcomes, while Canada's economy is marginally more responsive to cost and performance improvements in carbon capture technologies.

Abbreviations

EEE	energy economy emissions
NZ	net zero emissions by 2050
ROW	rest of world
BECSS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
DAC	direct air capture
H2	hydrogen gas
AFW	agriculture, forestry and waste
EMF37	energy modelling forum 37

1. Introduction

In this paper we add to a growing body of research examining pathways to net zero greenhouse gas (GHG) emissions targets. As energy economists and climate policy experts have argued for decades, jurisdictions serious about climate change mitigation must implement policies to reduce GHG emissions from energy supply and consumption, industrial processes, and land-use practices. To withstand political and economic pressures, policies should be flexible, introduced with predictably increasing stringency, and should aim to equate marginal costs between emissions abating firms or consumers [1]. Further, climate measures should minimize emission leakage, loss of competitiveness, and unequitable impacts, and should incentivize technology advancement. The pathway to net zero emissions is a critical topic not only for academics but for industry stakeholders, consumers, and policymakers looking ahead to a net zero future: warranting complex and highly adaptable analysis. We focus here on exploring alternative net zero pathways for the United States and Canada.

The rationale for developing and analyzing alternative net zero trajectories is multi-faceted. First, international success in addressing the negative externality of greenhouse gas emissions has largely yet to transpire [2], while the impacts of climate change become increasingly critical [3]. Better understanding of how to deploy measures that rapidly and efficiently reduce emissions is needed by decisionmakers in countries with net zero commitments. The implications of a net zero target add further complexity to much-needed analyses of system-wide transitions: multidecade timeframes require interim targets and milestones, "net" implies some residual or gross emissions, and the unique circumstances of individual countries and jurisdictions dictates policy and technology feasibility [4]. Lastly, (though not exhaustively), the

☆ Re-submitted to *Energy and Climate Change* on July 8th, 2024
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https://doi.org/10.1016/j.egycc.2024.100147

Available online 25 July 2024
2666-2787/© 2024 Published by Elsevier Ltd.

potential for emerging and future technologies to alter emissions trajectories is highly uncertain but potentially critical to the success prospects of various net zero pathways, necessitating adaptable analytical tools and methods. Net zero scenario analysis through energy economy emissions (EEE) modelling helps to identify policy options that are robust to future uncertainties and to highlight areas where improved policy and technological options for abatement might be needed (as in this special issue [5]).

Several recent studies are particularly useful for understanding how US energy use and technology adoption should evolve on a net zero trajectory and highlight the interdependencies of potential abatement strategies with key uncertainties [6–10]. Similarly, global analyses have demonstrated how decarbonization pathways identified at the international level might transpire within a Canadian context and have estimated how far current climate policies will take Canada towards its emissions targets [11–15]. Elements of deep decarbonization pathways identified in all these studies include widespread electrification, increased low-emitting electricity supply, reduction in unabated fossil fuel combustion, modified land-use practices, and some residual contribution from carbon dioxide removal technology. While important to understand what these aspects mean for policy design and sectoral efforts to reduce emissions, a technical understanding of the steps a country *should* take to reach net zero is only part of the picture for decision-making.

Government, industry stakeholders, and households in countries with net zero targets also need to have a sense of the likely economic outcomes of a rapid and widespread energy system transition. Some of the work referenced above offers a flavour of this by comparing total GDP or energy system costs under alternative net zero scenarios to business-as-usual projections. Additional insights may be derived by exploring which sectors might be most adversely or positively impacted by a net zero transition, and by quantifying the degree to which these outcomes hinge on alternative assumptions about technology advancement and policy implementation. In this paper we thus evaluate how alternative net zero scenarios might impact the US and Canadian economies on an overall and sectoral scale and how these impacts differ between each North American economy.

We structure our paper as follows. Section 2 offers background information, Section 3 describes our methodology for simulation and analysis of Canadian and US net zero scenarios, Section 4 discusses results and key findings, and Section 5 concludes with key takeaways on the comparative economic effects of net zero trajectories in Canada and the US.

2. Background

As pledges to reach net zero emissions by 2050 continue to encompass more of the global economy, countries already committed to this target should be rapidly planning and implementing their decarbonization pathways. Canada and the United States are two countries with such net zero commitments for mid-century, along with quickly approaching interim targets to ensure their economies are progressing adequately towards deep decarbonization.

These North American countries are similar not only in their emissions targets, but have highly connected economies, physical geography, political landscapes, and abundant endowments of natural resources, including fossil fuels, minerals, and arable land. They trade intensely across their lengthy mutual border and compete to export many of the same goods. For major policy challenges, this means that each country may be influenced by actions taken by the other, adding complexity to the already arduous task of implementing ambitious policy changes. For Canada, as the much smaller economy, there is also considerable concern about the extent to which policies affecting its economy should differ from those in the US.

In 2022, bi-lateral trade with its southern neighbor represented two thirds of Canada's international trade, while Canada was the United States's largest trading partner, albeit at a much smaller percentage of the total [16]. Again, however, due to the dramatic differences in the size of their populations and economies, Canada will more likely need to respond and adjust to US policies affecting trade dynamics. This may be especially the case for climate policy given that Canada exports approximately 90 % of its energy product exports to the US, and energy product imports from the US make up about 70 % of Canada's total energy imports [16,17]. This energy trade dynamic is important as these countries endeavour to reduce energy system emissions while maintaining beneficial economic relationships and activity.

Further, and unlike many other countries serious about reducing GHGs, Canada and the US enjoy significant endowments of cheap fossil energy and raw natural resources. This has enabled emissions intensive industries to comprise significant portions of their economies and has put Canada and the US in a similar position of dependence on fossil-fuel supply and carbon-intensive industry. On the demand side, a global transition towards net zero will have widespread impacts on fossil fuel consumers regardless of a country's fossil fuel endowment. However, the effects are exacerbated when a country is relatively more dependant on fossil fuels and therefore more carbon intensive due to a legacy of plentiful domestic supply - and a political culture of resistance to taxation or regulatory polices. Canada and the US have among the lowest fuel taxes of the OECD countries [18], and this has historically guided consumers to rely more heavily on cheap and readily available fossil-derived energy sources. Combined with prominent fossil fuel supply and heavy industry sectors, domestic fossil fuel reliance creates challenges for each country to reduce emissions while maintaining economic prosperity and political acceptance of advancing climate goals.

Overall economic impacts of implementing net zero emissions policy depend on several characteristics, both at the sectoral and economy-wide levels. Consider an individual sector currently producing a large share of national emissions, generating a large share of total GDP, and with high-cost options to reduce emissions. In this case, feasible options to drastically reduce emissions are to reduce output from this sector or to implement expensive emissions abatement options and pass on costs to other parts of the economy. Either way, if climate policy heavily targets this sector, total economic growth is likely lower than in a counterfactual scenario. This effect depends on (1) the extent of sectoral output decline / output price increases caused by climate policy, (2) the importance of the sector or its outputs to rest of the economy, and (3) whether other parts of the economy benefit from climate policy to offset losses. When designing policy to reduce emissions it is therefore important to understand how sectoral emissions shares, GDP contributions, and abatement options intersect to determine both sectoral and economy-wide impacts.

Fig. 1 shows shares of sectoral emissions, emissions intensity by sector, and shares of GDP by sector for Canada and the US [19–22]. In Canada, large shares of emissions are produced by its transportation and oil and gas sectors, with moderate shares from agriculture, forestry and waste (AFW), utilities, and manufacturing,[1] while US emissions are primarily generated by transportation and utilities. These are also the most emissions intensive sectors in the US, along with AFW, emitting high amounts of GHGs per dollar GDP generated, whereas in Canada oil and gas, utilities, and AFW all share slightly more moderate emissions intensities (see second panel of Fig. 1). Further, the bottom of Fig. 1 depicts the higher concentration of US GDP in the services sector, while in Canada GDP is spread over oil and gas extraction, manufacturing,

[1] Manufacturing refers to durable and non-durable industries. We discuss manufacturing both collectively and as durable vs. non-durable throughout this paper. Manufacturing industries include clean fuels production, chemicals, steel, cement, fabricated metals, aluminum, foundries, machine and vehicle manufacturing, pulp and paper, resin and rubber production, food and beverage, clothing / textiles, and electronics manufacturing.

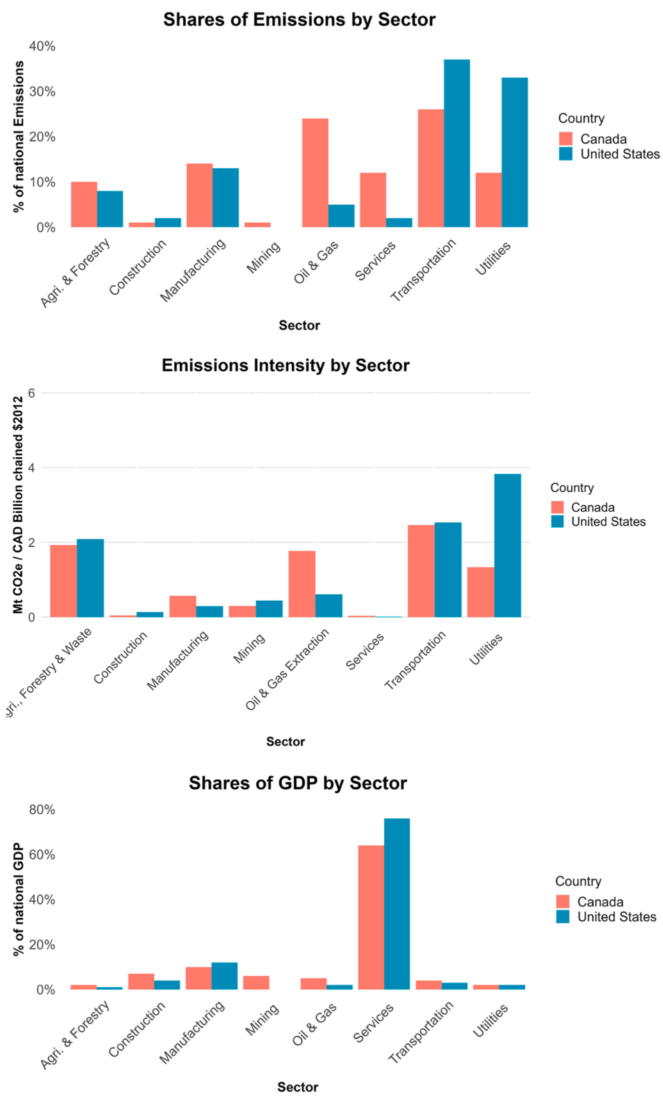

Fig. 1. From top to bottom: share of emissions by sector; emissions intensity by sector; share of GDP by sector (all in 2020). Emissions include all process and combustion CO_2, CH_4, and N_2O. “Oil & Gas Extraction” includes emissions and GDP generated from the production and processing of oil and natural gas, but excludes petroleum refining, oil and gas transmission, and gas distribution. Petroleum refining is allocated to “Manufacturing”, transmission to “Transportation”, and gas distribution to “Utilities”. “Utilities” includes electricity generation, gas distribution and wastewater treatment. “Agri., Forestry & Waste” includes agriculture, forestry and waste management (including landfills).

construction, and services.

We highlight two key contrasts between these countries: (1) Canada derives more of its total GDP from oil and gas extraction than does the US while also producing a disproportionate amount of emissions from this sector [20,22]; (2) in 2020, US electricity generation was nearly fours times as emissions intensive as Canada’s, primarily due to the higher proportion of coal-fired thermal generation in the US and Canada’s ample large-hydroelectric sources. Thus, while Canada has historically had a more emissions intensive and economically important oil and gas extraction sector, the US faces the challenge of a more carbon-intensive electricity grid that must simultaneously increase in size while also decarbonizing. Even without knowing the differences in abatement options and costs in each country it is likely that, given their current distributions of emissions and GDP, Canada and the US will be differently impacted by net zero emissions pathways.

The implications of a net zero target when compared to past emissions commitments are non-trivial. First, net zero emissions necessities significantly larger scale, economy-wide reductions in unabated GHGs and will require abatement from nearly all sectors of the economy [23]. Relatively inexpensive emissions abatement actions, or “low-hanging fruit”, will need to be quicky implemented alongside immediate planning for reduction paths in harder-to-abate end-uses and sectors. The total cost of reducing emissions to net zero will depend in part on how consistent near-term policy and technology choices are with long-term milestones and outcomes. Second, the target of net-zero implies the allowance for some quantity of residual emissions, with the requirement that these be offset by permanent sequestration of captured CO_2. Because of this, the overall impacts of reaching net zero are likely to hinge significantly on the availability and cost of emerging negative emissions technologies – adding substantial uncertainty to the path forward.

To aid decision makers with the plethora of uncertainties associated with technology advancement and the long-term impacts of policy choices, researchers construct and apply energy-economy-emissions (EEE) models to estimate the range of effects that GHG reduction policies and technologies might have on emissions, energy use, and economic performance. Some EEE models focus on specific sectors while others provide holistic insights on the economy-wide impacts of a system shock. EEE models can be particularly useful when several are used to analyze the same problem or question. In recognition of this, the Energy Modelling Forum at Stanford University has a long tradition of inviting modelling teams to participate in comparative studies in which critical assumptions are coordinated across all participating teams. Most recently, from 2021 to 2023, the forum designed and steered the energy modelling forum 37 (EMF37) study, which focusses on deep decarbonization and high electrification scenarios for North America.

EEE models participating in EMF37 included optimization, integrated assessment, partial equilibrium, and computable general equilibrium models, among other types. Our team, a collaboration of modellers at Simon Fraser University and Navius Research Inc., applied the gTech computable general equilibrium model (CGE), owned and maintained by the Vancouver-based consulting firm, Navius Research, to the US and Canada to simulate sixteen net zero scenarios and one reference / baseline scenario. gTech is general equilibrium in its representation of macroeconomic linkages and feedback, while also possessing technological richness and behavioural realism, providing useful insights for our research question. As part of EMF37, we compared net zero scenario results from gTech to other North American models. Where possible, modelling teams aligned technology representation (cost, efficiency, emissions, etc.), non-energy system emissions assumptions, and policy design to examine how deliberate variation of these levers might affect net zero outcomes in 2050, relative to a scenario with only existing climate policy.

Our modelling team was particularly interested in the comparative economic effects of net zero trajectories in Canada and the US, given the similarities and differences between these two energy-economy systems. Complementing the suite of literature stemming from the EMF37 study, we aim in this paper to provide greater insight to net zero results by focusing on the interactions, similarities and contrasts of the Canadian and U.S. energy-economy systems.

3. Methods

3.1. Scenario design

The EMF37 study analyzes results of 16 EEE models - all simulating a “common set of deep decarbonization and high electrification scenarios,” (See Browning et al. 2023 in this issue [5] for further study rationale). Net zero scenarios vary by assumptions on policy stringency, technology availability and advancement, and assumed behavioural change in key sectors. Our team submitted results for sixteen net zero scenarios and one reference scenario, falling into the following categories: Overall (2), Carbon Management (5), Transportation (5), and Buildings (5). The following section briefly describes each scenario category and how they were implemented in the gTech model while the Appendix provides further detail.

The "Overall" scenario category aims to provide baseline results from each model, absent advanced assumptions. Thus, the *Reference* scenario contains only implemented or legislated policies in each country and baseline assumptions on technology availability and cost,[2] and has no cap / constraint to reduce emissions in either Canada or the US. This scenario provides a common benchmark for analyzing alternative net zero scenarios. However, because the version of gTech we used does not account for economic detriment caused by climate damages, the *Reference* scenario is unrealistically optimistic about future economic growth. An integrated assessment model simulating the connections between the economy, emissions, global temperature, and climate damages would be better suited in providing a realistic contrast between net zero and business-as-usual economic growth, but these models tend to have less detail on specific policy and technology levers. Note that the US Inflation Reduction Act is not included in the Reference scenario as it had not yet been enacted during the EMF37 scenario design phase.

As the second scenario in the Overall category, *NZ Reference* represents a net zero pathway with no advanced assumptions, and therefore contains only reference policy and technology parameters, with the addition of a cap-and-trade policy starting in 2025 to reduce CO_2 emissions linearly to net zero by 2050. Canada and the US were each subject to separate cap and trade policies with credit trading available between constituent sectors and regions. To align with the wider EMF 37 study, a land use, land use change and forestry (LULUCF) annual net carbon sink of 800Mt was assumed in the US and 100Mt[3] in Canada. By EMF37 design, non- CO_2 emissions were not included in the emissions cap. All sixteen net zero scenarios contain identical net zero cap-and-trade policy trajectories.

The Carbon Management scenarios were designed to explore the impacts of significant improvements in performance and cost of carbon capture and storage, hydrogen production and use, and direct air capture technology. Each of these system-wide technologies could have significant impacts on decarbonization pathways for the rest of the energy system through their potential to remove residual emissions or reduce the need for electrification of end-uses.

The Transportation scenarios were designed to examine how technology advancement, policy implementation, and behavioural change could influence the transportation sector's decarbonization pathway. In the Advanced Transportation Technologies (*TSG advTech)* scenario, costs of electric, plug-in hybrid and hydrogen fuel cell vehicles, and of second-generation biofuels, were reduced. In the Advanced Transportation Policies (*TSG advPol)* scenario, transportation policies are implemented with rising stringency beginning in 2025. Where provinces / states already had transportation policies in place, the more stringent version of the policy took precedence. The Advanced Behavioural Assumptions (*TSG advBehav)* scenario represents a decrease in consumer aversion to zero-emission vehicle technologies through alteration of non-financial cost parameters for low-emitting vehicles and fuels.

The Buildings scenarios contain varying combinations of aggressive electrification and / or aggressive energy efficiency, achieved via regulatory mechanisms (compulsory standards) and / or market mechanisms (voluntary subsidies). Electrification and energy efficiency standards were implemented using a similar mechanism to a ZEV mandate: requiring increasing shares of electric or high efficiency buildings technologies to comprise new sales. The energy efficiency standard is fuel-agnostic, while the electrification standard does not require a certain level of efficiency. Market mechanisms for buildings electrification and energy efficiency were simulated by subsidizing a group of qualifying technologies. Table 1 summarizes the scenarios submitted to the EMF37 study by the SFU-Navius modeling team using the gTech CGE model.

3.2. The gTech model

CGE models like gTech can assess the effects of economic or policy changes on gross domestic product (GDP), national welfare, industry output, labour markets, and environmental variables. Useful to our analysis, these models simulate the production, trade, and use of energy and non-energy commodities throughout and between regions. However, most conventional CGE models treat technological change in an abstract, general way via elasticities of substitution and trend coefficients, limiting the types of policies that can be assessed. To this end, gTech has been deliberately designed to explicitly simulate capital stock turnover through disaggregated technology choices of households and firms [25]. This "bottom-up" feature of gTech was derived initially from the CIMS partial-equilibrium simulation model, whose market share equation simulates the shares of technologies as they satisfy investment needs for new energy supplies and demand for end-use services [26]. New technology market shares in the energy supply and demand sectors result from (1) retirement of old capital stock, (2) forced retirements (e.g., due to policy), and (3) increasing demand due to exogenous forecasts of economic activity or endogenous demand for energy supply. A technology's capital costs, operating costs, non-financial costs, lifespan, and energy requirements are used to determine its life-cycle cost per unit of energy produced / energy service supplied. Non-financial or "intangible" costs are derived through stated preference and revealed preference studies to approximate how consumers (households) perceive alternative technologies beyond only financial costs [25,27–29]. In gTech, this market share allocation process is retained by integrating the market share equation into constant elasticity of substitution functions, which traditionally characterize a sector's production activity in CGE models. Thus, gTech's disaggregated technology choice simulation and general equilibrium framework endogenize sectoral activity to determine energy supply and demand *and* technology market shares in each time period. The gTech model can therefore simulate how technology advancements and government policy - such as prescriptive regulations, flexible regulations, taxes or carbon pricing, and subsidy or incentive programs – can influence long-term technological change, energy production and use, resultant emissions, and economic outcomes.

The version of gTech we used was calibrated using the following sources: Environment and Climate Change Canada's National Inventory Report [19], Statistics Canada's Supply-Use Tables [30], Natural Resources Canada's Comprehensive Energy Use Database [31], Statistics Canada's Annual Industrial Consumption of Energy Survey [32], Statistics Canada's Report on Energy Supply and Demand [33], Canada's Energy Future 2021 [34], State Energy Data System [35] EIA Crude Oil Production [36], EIA Natural Gas Gross Withdrawals and Production [37], Supply-Use tables from IMPLAN, and EIA Consumption and Efficiency Data [38–40].Projected economic growth in the Reference

[2] Subsequent to the design and implementation of our scenarios, additional federal climate regulations were drafted and implemented. These include *Canada's Electric Vehicle Availability Standard* (implemented early 2024) and its *Clean Electricity Regulations* (to be released). Recent analyses have demonstrated that, in addition to quickening Canada's emissions reductions by 2035, these policies could slightly reduce economic output (i.e., −0.5% by 2030 in Alberta, one of Canada's most emissions intensive electricity grid) relative to only legislated policies [24]. This is immaterial for our study because we use the Reference scenario only for comparison of net zero scenarios to a common baseline, and our net zero scenarios already decarbonize electricity generation by 39-70% by 2035 relative to 2020 levels. Further, our scenarios containing advanced transportation policy assumptions include net zero policy combined with zero emissions vehicle regulations reaching 100% of new sales by 2035.

[3] We note that given recent analyses [19], a 100Mt LULUCF GHG sink for Canada might be overly optimistic, particularly in the near term, given recent trends in biomass harvesting and forest fires. Future analyses could evaluate net zero scenarios with a smaller assumed LULUCF sink.

Table 1
Scenarios modelled by the SFU-Navius modelling team, using the gTech model. Scenarios codes with an asterisk indicate the representative scenarios used as the focus of analysis in the results section.

Emissions target	Scenario category	Scenario code	Assumptions	Description / model implementation
No target	Overall	Reference*	Reference	No emissions reduction target. Baseline policy and technology assumptions.
Net zero by 2050		NZ Reference*	NZ Reference	Emissions cap brings US emissions to 800Mt by 2050 and Canada's emissions to 100Mt by 2050.
	Carbon management	CMSG advCCS	Advanced CCS	Carbon capture and storage (CCS) technologies are available at higher capture efficiencies. CCS, carbon pipeline and carbon storage costs decline more quickly (than under reference assumptions)
		CMSG advH2	Advanced H2	Capital costs of hydrogen production technologies decline more quickly (than under reference assumptions) with cumulative adoption.
		CMSG advDAC*	Advanced DAC	Capital costs of direct air capture technologies decline more quickly (than under reference assumptions) with cumulative adoption.
		CMSG noDac*	No DAC	Direct air capture is unavailable in all years.
		CMSG allAdv*	All Advanced Carbon Management	Combined advanced CCS, H2, and DAC technology assumptions.
	Transportation	TSG advTech	Advanced technology	Electric, plug in hybrid, hybrid, and fuel cell vehicle capital costs decline more quickly with cumulative adoption. Second generation liquid biofuels and RNG reach lower prices (than under reference assumptions). Increased fuel cell vehicle power and fuel cell storage.
		TSG advPol	Advanced policy	US and Canada: federal vehicle emissions standard; ZEV mandate implemented federally in Canada and US, with new ZEV sales target reaching 100 % and 70 % by 2050, respectively; Canada's Clean Fuel Standard; Federal Low Carbon Fuel Standard in US; Federal purchase subsidies for plug in hybrid vehicles and EVs.
		TSG advBehav	Advanced behavioural assumptions	Electric, plug in hybrid, hybrid and fuel cell vehicle non-financial (intangible) costs decline more quickly with cumulative adoption, to represent lessening risk adversity. Second generation liquid biofuels and RNG reach lower prices (than under reference assumptions). Increased fuel cell vehicle power and fuel cell storage. Lowered non-financial (intangible) costs for fuel-cell vehicles.
		TSG advTechPol	Advanced technology and policy	Combined Advanced Technology and Advanced Policy scenario assumptions.
		TSG allAdv*	All Advanced Transportation	Combined Advanced Technology, Advanced Policy, and Advanced Behaviour scenario assumptions
	Buildings	BSG agrEE	Aggressive energy efficiency, using standards and market mechanisms	Compulsory standard requiring increasing shares of new buildings technologies to be energy efficient or "net zero ready", structured similarly to a ZEV mandate. Non-compulsory market mechanisms represented by federal-level subsidies for energy efficient buildings technologies.
		BSG mrktElecEE	Electrification and energy efficiency market mechanisms	Non-compulsory market mechanisms represented by federal-level subsidies for electric buildings technologies and fuel-agnostic energy efficient buildings technologies.
		BSG stndElecEE	Electrification and energy efficiency standards	Compulsory standards implemented to 1) require increasing shares of new buildings technologies to be electricity powered and 2) require an increasing share of new buildings technologies to be energy efficient or "net zero ready".
		BSG agrElec	Aggressive electrification, using standards and market mechanisms	Compulsory, fuel-agnostic standard requiring increasing shares of new buildings technologies to be electric, similar to a ZEV mandate. Market mechanisms represented by federal-level subsidies for electric buildings technologies.
		BSG allAdv*	All Advanced Buildings	All standards and market mechanisms used in combination to induce greater electricity use and energy efficiency in buildings.

scenario is generated endogenously based on labour supply and productivity estimates from the Office of the Parliamentary Budget Officer for Canada and the Energy Information Administration for the US [41, 42]. The model represents eleven regions, including British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, an aggregation of remaining Canadian provinces / territories, Washington, Oregon, California, and an aggregation of remaining US states. It contains seventy-four energy demand and supply competition nodes and three hundred and forty-six competing technologies and processes. Regions and sectors interact via trade of commodities, policy transfers (e.g., permit trading), and government taxation / revenue distribution.

Our net zero scenarios were implemented in gTech to effect changes in the relative costs of emissions abatement options throughout the economies of Canada and the United States, through both policy and technology advancement. The following section discusses the results of our simulations.

4. Results & discussion

In our analysis we compared emissions, energy use, technology stocks, and economic results from sixteen net zero by 2050 (NZ) scenarios and one reference scenario to characterize economic outcomes in Canada and the US. While useful to compare all net zero scenarios to a common benchmark, we reiterate that the Reference scenario represents an unlikely future, where the economies of Canada and the US continue to grow without hindrance from climate change damages. For most of our discussion we instead focus on economic growth and emissions relative to a base year (2020). We also note here that while CGE models like gTech capture some innovation effects through production functions, or specifically in the case of gTech via declining cost functions, unprecedented technological change is unlikely to be adequately represented. The benefit of unpredicted breakthrough innovations in performance or cost of key technologies, enabled by stringent policy, are therefore not captured in our modelling but could have positive effects on economic costs. Conversely, unpredicted breakthroughs in extraction technology that help fossil fuels remain economically attractive, for example, are similarly unrepresented in our modelling. Noting these caveats, we begin with high-level insights on economic growth by country and by sector (Section 4.1), before digging into the specific causes of sectoral impacts and the effects of individual scenario assumptions (Section 4.2). We conclude our discussion of results by expanding on electricity supply and demand dynamics (Section 4.3) and the evolution of oil and gas production (Section 4.4).

4.1. GDP impacts

Over the next three decades both the US and Canadian economies are projected to grow robustly in real terms under all scenarios. Canada's economy grows by 49 % from 2020 to 2050 when averaged across all NZ scenarios in comparison to 59 % under the *Reference* scenario.[4] The US economy grows by an average of 75 % from 2020– to 2050 averaged across all NZ scenarios and by 86 % under the *Reference* scenario. In reality, these apparent differences between GDP growth under the net zero and reference scenarios would be much smaller, considering the numerous benefits of GHG emissions mitigation. Fig. 2 displays GDP growth for six representative scenarios as a percentage change from 2020 GDP: *All Advanced Buildings, Advanced DAC, All Advanced Transportation, No DAC, NZ Reference*, and *Reference*. National GDP results from these six scenarios capture the range of economic responses in 2050 from all seventeen scenarios modelled for this study. Unsurprisingly, in both countries the lower bound of economy-wide GDP growth is a net zero scenario without DAC available while the upper bound is a scenario with lower cost DAC technology. Also, for both Canada and the US, focus on advanced policy and technology in transportation results in higher economic growth in interim years than focus on the buildings sector, but results from these scenarios converge as the 2050 target is reached (blue vs. green lines).

We found that Canada's economic responses to a net zero trajectory are more sensitive to alternative assumptions than those of the US, resulting in slightly more variance between the sixteen net zero scenarios in 2050 (Canada's 2050 GDP responses SD= 0.029 compared to SD= 0.026 in the US). Specifically, the Canadian economy responds more positively than the US to cost reductions in direct air capture (orange line), largely because this enables Canada's emissions-intensive oil and gas and manufacturing sectors to grow production to a greater extent than in other NZ scenarios (details on oil and gas sector responses provided in Section 4.4).

While both the Canadian and US economies continue to grow under all net zero scenarios, some sector-level responses differ between the two economies. Fig. 3 shows GDP in 2050 of major economic sectors as a percentage change from 2020 GDP for six scenarios: *Reference No DAC, All Advanced Buildings, NZ Reference, All Advanced Transportation,* and *All Advanced Carbon Management*.

In Canada, nearly all economic sectors experience increased economic output by 2050 relative to 2020 levels. The exceptions are its mining and durable manufacturing sectors, which decline relative to 2020 in nearly all scenarios (durable manufacturing only grows beyond 2020 GDP in *CMSG advDAC* - when DAC is very cheap). Currently, Canada's manufacturing sector is about twice as emissions intensive as its US counterpart due to its greater share of steel, fabricated metals, cement and other emissions intensive manufacturing (versus lighter manufacturing). Under stringent net zero policy, both countries' manufacturing sectors experience reduced growth in net output and exports by 2050 (relative to the *Reference* scenario), and accordingly demand less raw materials, including metals and minerals. Lower domestic demand combines with reduced exports of mining outputs to cause economic stagnation or decline in the mining sector. The overall effect on both mining and manufacturing is more prominent in Canada because (1) it exports a larger share of its mining outputs, versus the US, (2) emissions-intensive industry comprises a larger share of its overall manufacturing sector, and higher production costs cause exports of emissions-intensive and trade-exposed (EITE) goods to stagnate or decline as the net zero target is approached, and (3) under the national cap, credits generated by negative emissions are primarily used by its oil and gas sector, while in the US credits are predominantly purchased by its manufacturing sector. Thus, Canada's manufacturing sector fares worse than its US counterpart due to rising production costs combined with higher trade exposure (which has knock-on effects on mining). All other economic sectors in Canada continue to grow out to 2050 under all net zero scenarios. GDP generated by Canada's utilities sector doubles or triples by 2050 in a net zero future due to increasing demand for electricity. Similarly, GDP from Canada's agriculture and forestry sector increases by 50–120 % by 2050 due to increased use of biomass residues as inputs to biofuel production and bioenergy combustion with carbon capture and storage (BECCS). Growth in this sector is highest in a scenario without direct air capture as negative emission options are restricted to BECCS.

Economic responses in the US tell a similar but not identical story. The US mining sector experiences slight economic decline *only* in a scenario without DAC available (*CMSG no DAC*) and in a scenario without advanced assumptions elsewhere in the economy (*NZ Reference*). Both EITE and light manufacturing continue to grow in the US and demand outputs from the mining sector in all scenarios; aided by the availability of negative emissions credits in later years. Utilities and agriculture and forestry experience even greater growth in GDP from 2020 to 2050 (compared to Canada) due to more steeply rising demand for electricity and biofuels for the US manufacturing sector. Real GDP continues to grow in all other sectors in the US across all net zero scenarios.

4.2. Scenario level insights on emissions and GDP impacts

We now discuss the comparative economic and emissions responses that emerge from analysis of individual net zero scenario pathways for Canada and the US. We note that because gTech simulates a dynamic energy-economy system, each scenario results in differing levels and distribution of energy supply and demand, as well as technology market shares / uptake, affecting economic and emissions outcomes. We grouped our discussion of these outcomes into (1) impacts on key sectors occurring across all net zero scenarios, (2) net zero scenario assumptions resulting in lowest versus highest national economic performance, and (3) the impact of alternative scenario assumptions on individual sectors. We add context to this discussion by first examining how each country achieves their 2050 net zero emissions target. Fig. 4 shows sectoral emissions projections from 2020 to 2050 in Canada and the US, when averaged across all net zero scenarios. While there is agreement across all scenarios that Canada's oil and gas, manufacturing and transportation sectors, and the United States' utilities, manufacturing and transportation sectors play important roles in each country's decarbonization, we discuss later how emissions and sectoral economic responses vary between net zero scenario designs.

In both countries, manufacturing faces rising costs of fossil-derived secondary energy carriers (i.e., refined petroleum products) due to carbon pricing, and must adopt technologies fueled by electricity, biofuels, and hydrogen, or fuel switch to natural gas from more emission's intensive fossil fuels. In non-durable manufacturing, use of electricity, biofuels and spent pulping liquor increases and displaces some natural gas consumption. In contrast, durable manufacturing primarily reduces its emissions intensity of production by displacing coal in thermal end-uses with fuel-switching to natural gas and biofuels. Across virtually all scenarios, emissions reductions in manufacturing collectively contribute 14 % of Canada's total emissions reductions, and 13 % in the US. The obvious exceptions are when DAC is extremely cheap, lessening the need for emissions abatement in manufacturing, and when DAC is unavailable, increasing the need for abatement elsewhere.

While the emissions responses and decarbonization pathways of manufacturing in Canada and the US are similar across alternative net zero scenarios, their economic responses differ. As mentioned, a larger proportion of Canada's manufacturing sector output is attributed to

[4] Reference case economic growth is an endogenous function of labour force, productivity, and population growth projections, as well as any interactions with reference scenario policy.

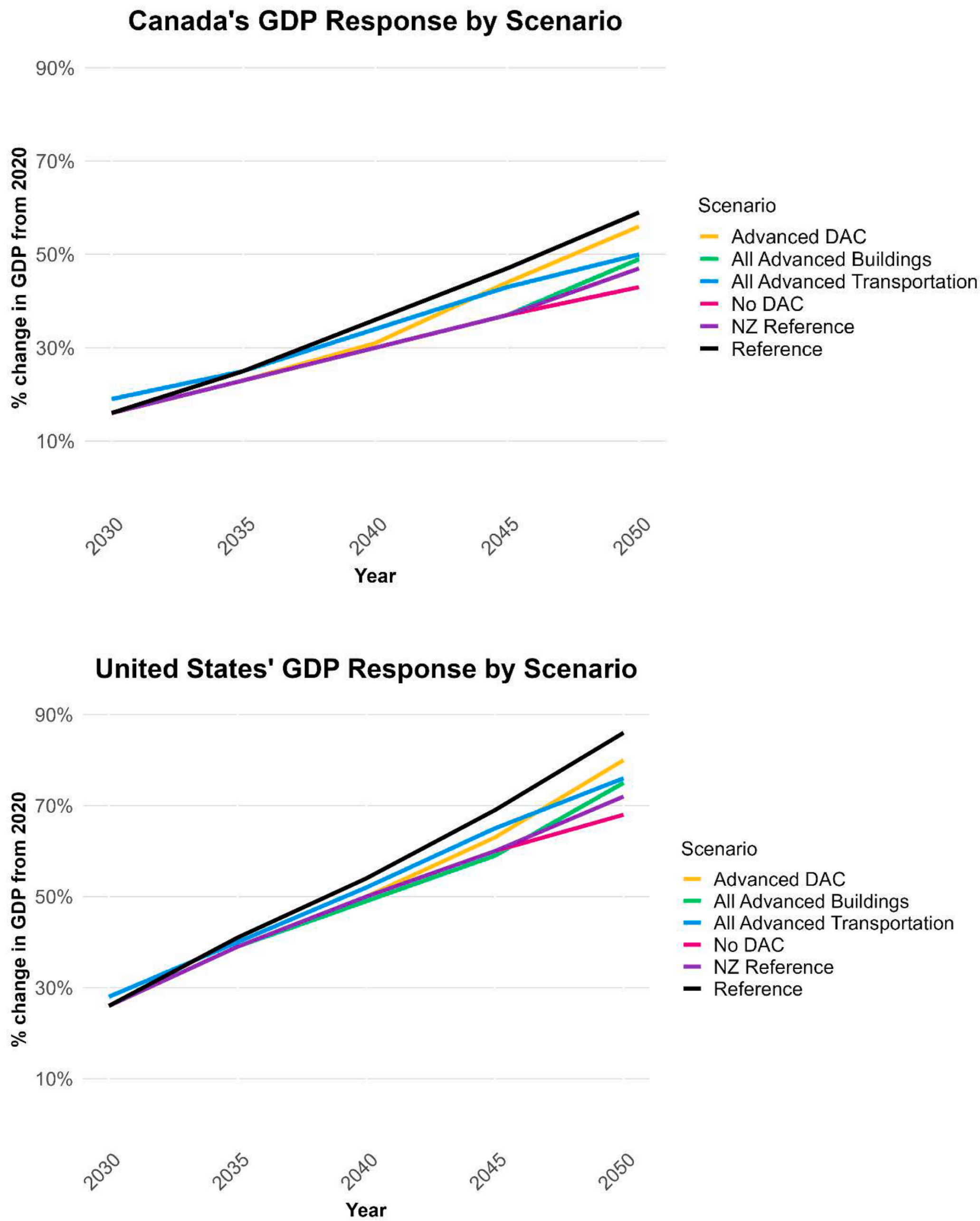

Fig. 2. Percentage change in (deflated) GDP relative to 2020, shown for six representative scenarios. All Advanced Buildings = BSG allAdv; Advanced DAC = CMSG advDAC; All Advanced Transportation = TSG allAdv; No DAC = CMSG noDAC; NZ Reference = NZ Reference; Reference= Reference. For visual clarity, results are shown only for model years 2030–2050.

emissions intensive processes like steelmaking, cement, and pulp and paper mills, whereas a greater portion of manufacturing output in the US is attributed to less emissions intensive processes such as vehicle and electronics production. It is more expensive for Canada's manufacturing sector – as a whole - to decarbonize, and therefore it does so largely through reductions in output which results in economic stagnation or decline.

The decarbonization of transportation varies only slightly by country, and to a modest extent between some scenarios. On average, emissions reductions from this sector account for just over 20 % of all reductions in 2050 for both countries. Our modelling results show that decarbonization of transportation in both countries occurs through partial electrification of personal transport, mode-switching to transit, and by fuel-switching to hydrogen, electricity, biofuels, and natural gas in medium and heavy trucking. Of note is that advanced transportation policies induced greater additional electrification of personal transport in the US than Canada's counterpart. In the US, more stringent transportation policies resulted in electricity providing 67–82 % of final energy demand in personal transport, versus 29–35 % in all other net zero scenarios (a 38-47 % increase). In Canada, advanced transportation policies resulted in electricity supplying 70–89 % of personal transport energy, and 47–54 % in all other net zero scenarios (a 23-35 % increase). This contrast occurs because (1) in the absence of advanced policy, it is more economical to use electricity elsewhere in the US economy, namely its services sector, and (2) some parts of Canada already have more stringent policy to mandate adoption of zero emissions vehicles even in the *Reference* and all other net zero scenarios. This result – of electricity supplying only a third of final energy to personal transport in the US and half in Canada in non-transportation focussed scenarios – is also partly due to the higher efficiency of electric vehicles compared to internal

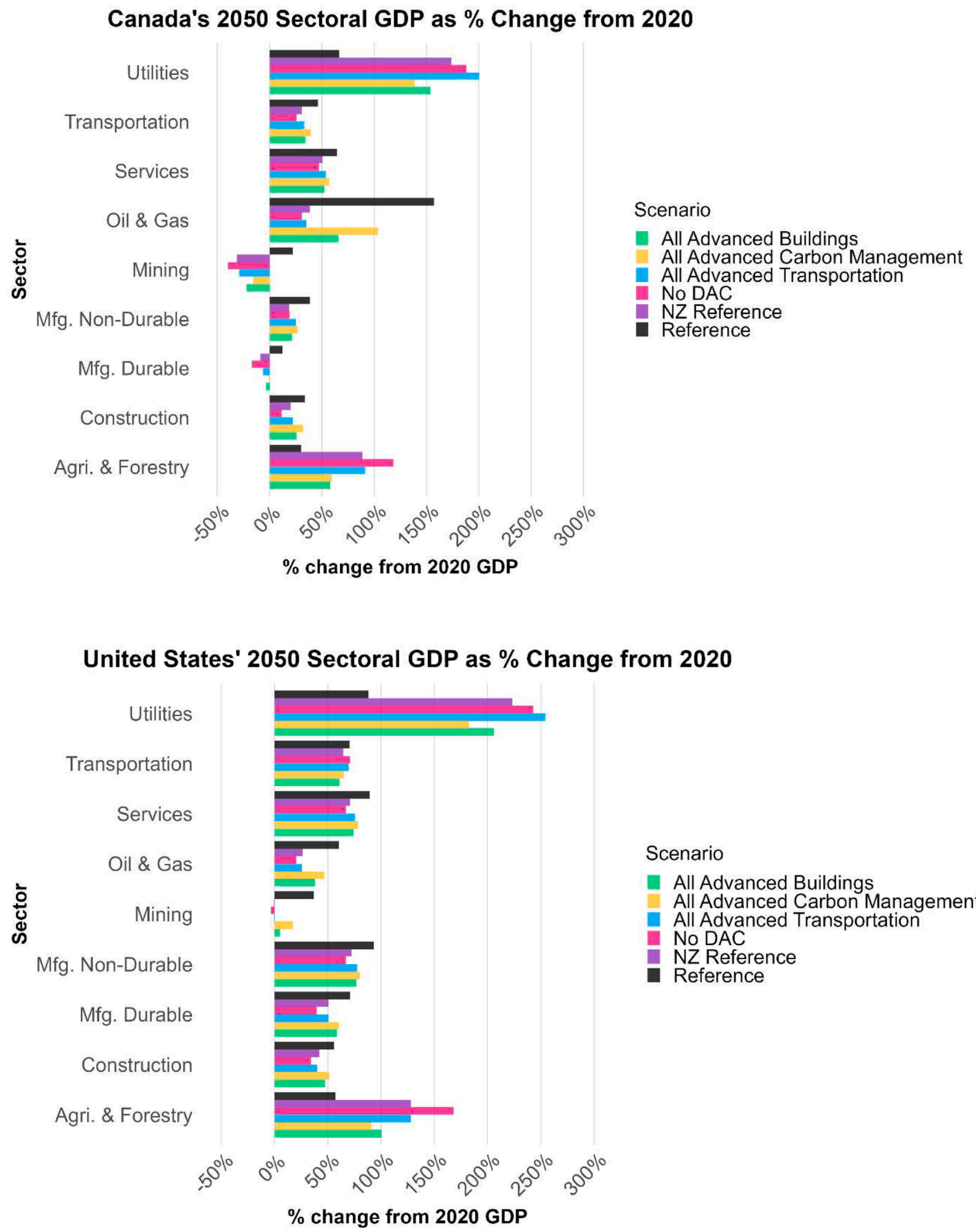

Fig. 3. Sectoral GDP in 2050 for the Reference scenario and five representative net zero scenarios, shown as a percentage change from 2020 GDP. Reference = Reference; No DAC = CMSG noDAC; All Advanced Buildings = BSG allAdv; NZ Reference = NZ Reference; All Advanced Transportation = TSG allAdv; All Advanced Carbon Management = CMSG allAdv.

combustion engines. By 2050, 52–93 % of all personal vehicles in the US are electric, and 70–96 % in Canada. Thus, while personal transportation decarbonizes to a greater extent in Canada than in the US even without additional policy assumptions, both countries exhibit similar types of responses to advanced transportation assumptions. In nearly all scenarios, heavy trucking and medium-duty vehicles in both countries decarbonize primarily through fuel switching to biofuels, then electrification, then some uptake of hydrogen fuel cell vehicles (the exception is in advanced transportation scenarios, which promote more electricity and hydrogen use in medium and heavy-duty vehicles).

In contrast to the transportation sector, the responses of the other top sectoral contributors to emissions reductions (utilities in the US and oil and gas in Canada) are different between each country. Disparities in each country's sectoral 2020 emissions profiles result in differing sectoral contributions to emissions reductions. In Canada, 31 % of emissions reductions can be attributed to oil and gas and 10 % to utilities under the *NZ Reference* scenario, while in the same scenario US oil and gas is responsible for only 11 % of emissions reductions by 2050 and utilities for 33 %. These sector's relative contributions remain similar regardless of scenario assumptions. The exception is when DAC becomes very cheap (i.e., in *CMSG advDAC*), reaching \$112/t CO_2e by 2050 in contrast to \$279/t CO_2e by 2050 under *NZ Reference*. In an "inexpensive DAC" net zero future, Canada's oil and gas sector contributes only 7 % of gross emissions reductions to the national effort, thanks to carbon dioxide removal accounting for 67 %. This stark contrast to other net zero scenarios shows that Canada's otherwise top contributor to emissions reductions -oil and gas, would easily continue to generate significant GHGs if negative emissions options are cheap. In contrast, the United States' top contributor to emissions reductions, utilities, decarbonizes regardless of negative emissions technology cost; still contributing 22 %

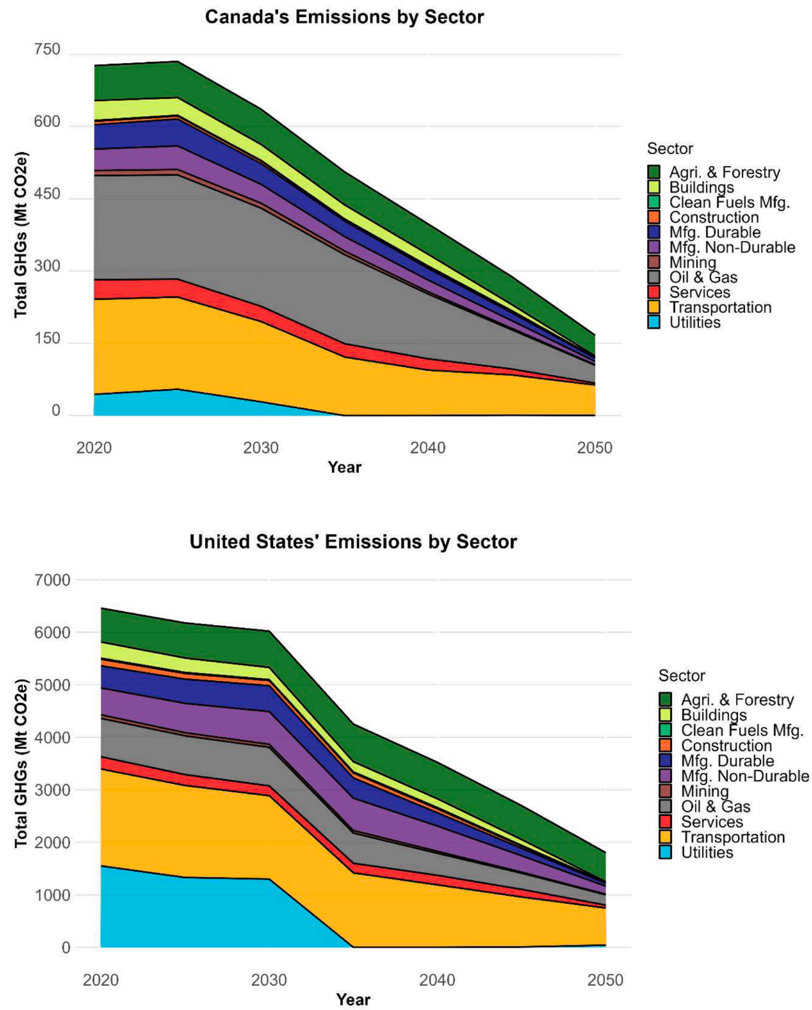

Fig. 4. Emissions by sector from 2020 to 2050, averaged across all net zero scenarios.

of total reductions even when DAC is very cheap. This is because while oil and gas products can be exported from Canada for use elsewhere, and therefore could remain economical to produce even in a net zero future (depending on rest-of-world (ROW) action and oil price assumptions), electricity is increasingly demanded domestically in the US and therefore subject to increasing carbon pricing. To summarize, oil and gas is the largest contributor in Canada to emissions reductions in most net zero scenarios, and utilities is the largest contributor in the US. However, the extent that Canada's oil and gas sector decarbonizes varies widely depending on if cheaper abatement options are available, while utilities in the US must significantly decarbonize in any net zero future.

Understanding how the biggest sectoral contributors to emissions reductions respond to net zero policy, we now dig into how specific scenario assumptions affect total economic performance. The economies of both countries share the same three lowest performing net zero scenarios (from lowest to third lowest): (1) net zero policy with DAC unavailable (*CMSG noDAC*), (2) net zero policy with no other supporting policies (*NZ Reference*), and (3) net zero policy plus lower costs of hydrogen production and pipelines (*CMSG advH2*). The reasons for *CMSG noDAC* causing slower economic growth are unsurprising: all parts of the economy must abate more if DAC isn't an option, which becomes more costly as the net zero target is approached. *NZ Reference* performs relatively less well than other scenarios because, although it uses only economically efficient carbon pricing to drive decarbonization, it contains no advanced assumptions on technology improvements or cost declines. In contrast, while *CMSG advH2* contains advanced assumptions about cost declines in hydrogen production sectors and hydrogen pipelines, hydrogen is still not competitive as an alternative fuel in most parts of the economy. Effectively, this means that a scenario with carbon pricing plus advanced supply-side hydrogen assumptions performs about equally to a reference assumption net zero scenario (i.e., *NZ reference* and *CMSG advH2* have very similar economic outcomes).

While Canada and the US share the same three lowest performing scenarios, their top three differ. In both countries, scenarios with very cheap DAC (*CMSG advDAC*) or with slightly cheaper DAC plus cheaper and more efficient carbon capture and storage (CCS) (*CMSG allAdv)* result in the highest overall economic growth. The third-best performing scenario is where Canada and the US differ. In Canada, cheaper CCS with higher capture efficiency (*CMSG advCCS*) results in the next best 2050 GDP - even in the absence of cheaper DAC - because it enables oil and gas and manufacturing to continue production to a greater extent than in other scenarios. In contrast, the third-best performing scenario in the US is one where buildings energy demand is reduced quickly in the near term, reducing total energy demand in later years and therefore total costs of energy supply. Specifically, *BSG stndElecEE* contains regulations which require increasing adoption of efficient and / or electric buildings technologies starting in 2025. By 2050, this scenario has the lowest building sector energy demand, leaving less expensive electricity and natural gas available for use by DAC facilities and CCS technologies. Thus, Canada's economy does best in any scenario with advanced assumptions for DAC and CCS, and the US does best firstly when DAC is cheap, then when its clean electricity supply is used efficiently across the economy.

4.3. Electricity supply and demand dynamics

Many of the economic impacts we discuss and their sensitivities to alternative net zero scenario assumptions can be partially explained by differences in the electricity supply and demand dynamics of Canada and the US. We discuss here how each country's electricity supply sectors are different to begin with, how they evolve on a path to net zero, and how electricity consumption patterns change out to 2050. As shown in Fig. 5, Canada's electricity consumption in 2020 was dominated by buildings (light green) and manufacturing (navy blue), however, oil and gas (grey), agriculture and forestry (dark green), and transportation (orange) still consumed over a fifth of Canada's electricity. In contrast, electricity consumption in the US was more concentrated in buildings and manufacturing, which together used 95 % of US electricity in 2020. These differences in the current distribution of electricity consumption have implications for how each economy responds to increasing demand for electricity.

In a net zero future, both countries' transportation sectors comprise a larger share of final demand for electricity. Our results project that by 2050 transportation will (on average) use 12 % of electricity in the US and 17 % in Canada, versus 0.3 % and 1.5 % in 2020, respectively. Carbon dioxide removal (light purple) is also expected to consume, on average, about 4 % of electricity in each country by 2050 (though this is highly contingent on the price of DAC). By 2050, total consumption of electricity increases by over 50 %from 2020 in Canada, and by about 60 % in the US, depending on the NZ scenario. As a share of all secondary energy consumption, electricity use in Canada increases on average from 16 % in 2020 to 25 % in 2050, and from 15 % to 27 % in the US. The total supply and distribution of electricity use varies across scenarios, depending on whether specific electric technologies are subsidized or if adoption is required (for example, through a ZEV mandate). However, our results indicate that the US undergoes a more dramatic reallocation of electricity across its economy due to its highly concentrated consumption profile of electricity at present (i.e., in buildings and manufacturing). The US faces pressure due to electrification on several fronts: (1) through the need to increasingly allocate electricity to other parts of the economy - especially transportation in early years, (2) to do this under increasingly stringent carbon pricing or equivalent regulations, which raise the end-user price of electricity in the interim as the US moves away from more emissions-intensive generation, and (3) through the need to devote capital expenditure to investments in clean electricity supply. These pressures impact the services sector in the near term as it currently consumes the most electricity (via buildings) and is almost entirely reliant on it as an energy carrier. Increasing costs in the US services sector are primarily responsible for the slightly slower

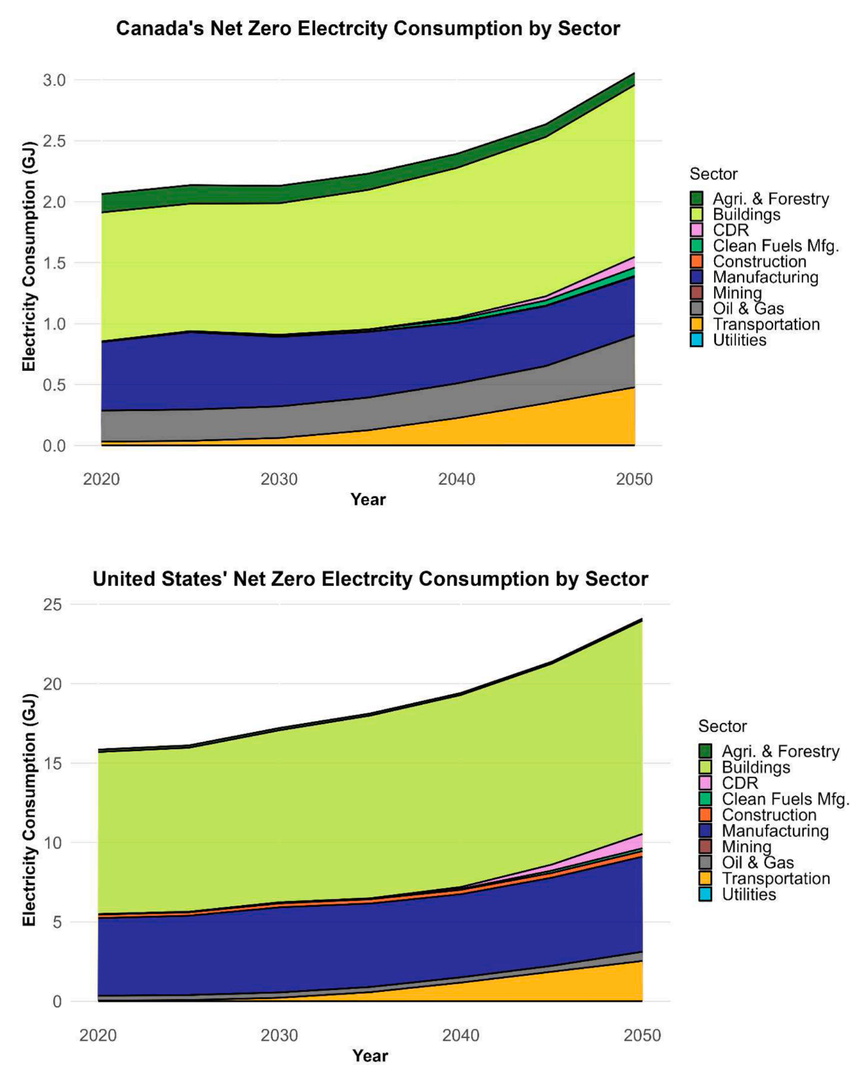

Fig. 5. Electricity consumption (GJ) from 2020 to 2050, by sector, for Canada and the United States.

economic growth projected under net zero scenarios, relative to the Reference scenario. Canada is less sensitive to this phenomenon than the US because its economic activity and electricity consumption are less concentrated in services (buildings) and because its electricity supply is less carbon intensive at present.

Digging into each country's current composition of generation sources explains why US electricity supply and demand might be under more economic pressure than in Canada, at least in the short term. As shown in Fig. 6, in 2020 the US generated most of its electricity through thermal combustion, mostly of fossil fuels, while Canada's generation was largely from hydropower. More thermal generation means that to decarbonize its electricity sector the US will need to retrofit existing generation plants with CCS, switch to biomass combustion, and / or rapidly build out its renewable generation with energy storage while phasing out thermal generation facilities, possibly before their planned end-of-life. Canada already has a relatively low-emitting grid but may face challenges in the more distant future in a scenario where additional clean electricity capacity is required but opportunities to expand supply are constrained to the build-out of variable renewables (i.e., if no new large hydro is permitted, CCS is too expensive, and / or nuclear expansion is limited). Fig. 6 also shows how shares of electricity generation by source evolve towards a net zero future. Overall, both countries rapidly increase variable renewables generation, but the US does so at a larger scale than Canada. The average result is that by 2050 most electricity generation in the US is from variable sources (59 %), while only a third of generation is variable in Canada. This puts Canada's grid at an advantage due to the lower need for demand side management and / or storage solutions that are required with higher shares of non-dispatchable generation sources. Again, this is in large part the result of Canada's dispatchable hydropower endowment which helps offset the variability of other non-dispatchable renewables like wind and solar.

Overall, the US is starting from a position of greater reliance on fossil fuel combustion for its electricity generation, and therefore a greater share of national emissions produced by electricity supply, combined with concentrated electricity consumption in buildings / services and manufacturing. In contrast, Canada's electricity is already less carbon intensive, the effects of higher cost electricity would be more dispersed through its economy, and carbon pricing policy would not have as large an immediate impact on its electricity sector. These differences between each country's prospects for rapid electrification have implications for their overall costs and optimal pathways of achieving net zero emissions; the US must not only rapidly build out new clean electricity capacity, but also decarbonize its existing generation before emissions policies become too costly for much of rest of the economy to efficiently fuel-switch to electricity.

4.5. *Oil and gas sector impacts*

To conclude our results discussion, we probe the evolution of each country's oil and gas / fossil fuel sectors[5] throughout alternative net zero pathways. The fossil fuel industry in an emissions neutral future is on average a smaller contributor to GDP in both countries than in the *Reference* scenario. Under *Reference*, fossil fuel industry GDP grows by 130 % in Canada and by 53 % in the US by 2050, relative to 2020. Under the *NZ Reference* scenario, it grows by 30 % in Canada and 21 % in the US. While these results are generally mirrored in the other net zero scenarios, an exception is that under a scenario with advanced DAC assumptions (*CMSG advDAC*), fossil fuel industry GDP in the US surpasses Reference growth projections. This occurs because, 1) across all net zero scenarios, the US exports more crude oil to ROW than in *Reference* (due to oil price assumptions, see below), and this is further enabled when DAC is very cheap, and 2) the US increases natural gas extraction beyond *Reference* levels to meet higher demand for use in DAC facilities. In contrast to the US, Canada's natural gas extraction, crude oil production and exports to ROW are lower compared to *Reference* scenario projections in *all* net zero scenarios due to Canada's higher production costs. Fig. 7 shows how the shares of GDP generated by each fossil fuel industry sub-sector evolve over time under the *NZ Reference* scenario.

We emphasize that projected exports of crude oil to ROW are contingent on future oil price assumptions. For our analysis we chose a neutral forecast of oil prices [34], based on the low probability that all countries would reach net zero emissions by 2050. However, we recognize the great uncertainty in predicting oil demand and the stickiness of evaluating only one forecast. Future researchers could adjust oil price projections to evaluate the impact on Canadian and US oil production in a CGE framework under similar net zero scenarios.

Under *NZ Reference,* the US increases physical crude oil production and GDP (shown in red), mostly for export to ROW, while Canada's physical crude oil production decreases by 6 % relative to 2020 (even as GDP grows due to modestly rising crude oil prices). This reduction in crude production from 2020 levels is in the general range of other recent estimates for Canada's and / or global oil production, depending on assumptions of future demand [13,15,43].

Under the *NZ Reference* scenario in both Canada and the US, GDP from refining makes up a smaller share of fossil fuel industry GDP while crude oil production comprises a larger share. Both countries decrease refining sector activity (shown in green) relative to 2020 (1) due to falling producer prices for refined petroleum products in Canada and the US due to carbon pricing lowering demand, and (2) because the refining industry faces steadily increasing prices for energy inputs, especially clean energy sources. A key distinction is that in Canada, a decrease in refining activity is contingent on carbon management solutions: if these are available and cheap, Canada increases refining sector output, while refining in the US declines from 2020 levels regardless of scenario assumptions. This occurs because when DAC becomes available and cheap, Canada dramatically reduces its efforts to use biofuels, consuming less biofuels in 2050 under *CMSG advDAC* than in *Reference* or any net zero scenario. This is important because, while diesel demand from medium and heavy-duty transportation is lower in all other NZ scenarios than in *Reference* (biofuels provide at least 50–70 % of final energy in 2050 to heavy trucking in both Canada and the US), in *CMSG advDAC* diesel consumption is higher; making domestic refining even more economically viable. This trade-off between use of biofuels as a decarbonization pathway and building out DAC facilities is more pronounced in Canada than in the US, in part due to lower biofuel use projections in the US even in the *Reference* scenario.

Under all net zero scenarios, bitumen from Canada becomes less valuable as producer costs increase and crude oil production slows or declines. As a result, bitumen production in Canada (dark blue) is projected to generate a decreasing share of fossil fuel industry GDP, but still grows modestly from 2020 to 2050. For both Canada and the US, crude oil remains a valuable export and as domestic refining declines in most scenarios, crude oil production becomes a larger contributor to fossil fuel industry GDP. Lastly, in the *NZ reference* scenario, natural gas extraction GDP declines from 2020 in the US but continues to increase steadily in Canada, albeit contributing a smaller share of GDP to the fossil fuel sector. This occurs because while Canada's domestic demand for natural gas falls to 59 % of 2020 levels, mostly due to slowing oil sands operations, in the US natural gas consumption remains at 83 % of 2020 levels and a significant part of this remaining demand is met through Canadian imports. The exception to this story is when Canada's fossil fuel sectors can operate closer to *Reference* levels under advanced DAC assumptions, and its natural gas is therefore more valuable domestically. In this scenario, the US increases its own gas production rather than importing from Canada. In fact, under *CMSG advDAC,* both Canadian and US natural gas extraction GDP increases beyond reference

[5] The fossil fuel sector refers to all oil and gas sub-sectors, plus coal extraction.

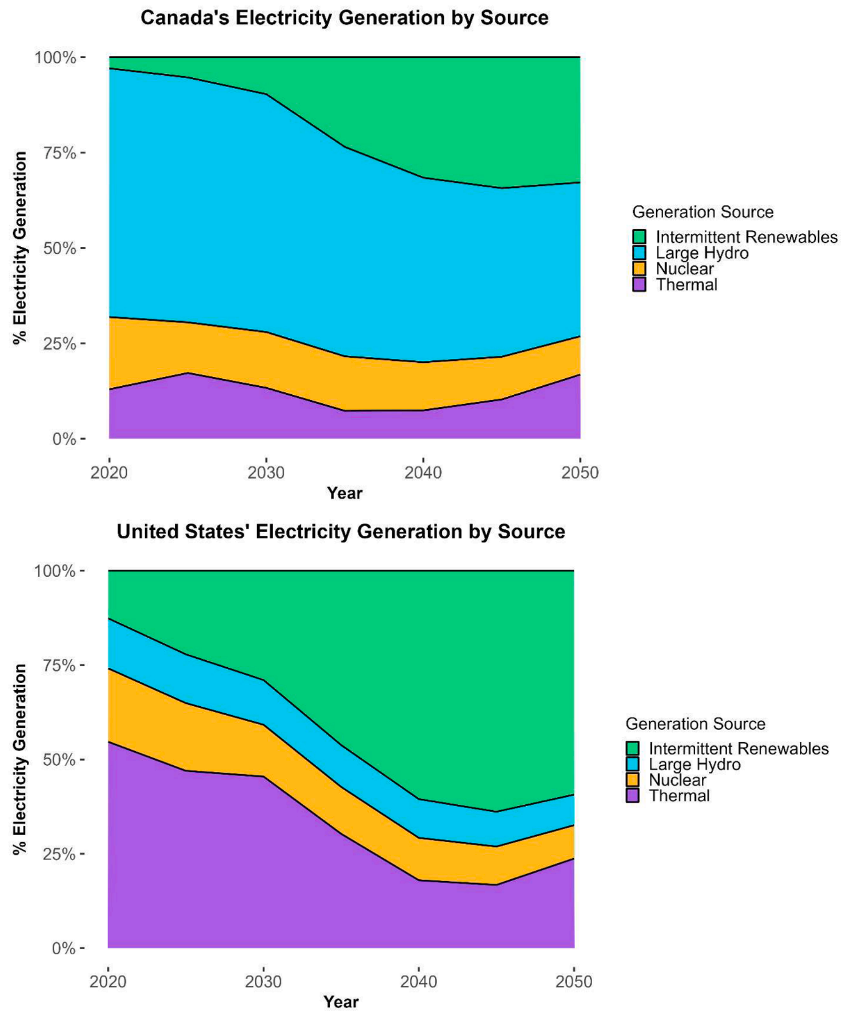

Fig. 6. Electricity generation by source for Canada and the US (average results across all net zero scenarios).

levels due to new demand by DAC facilities (and the ability to still use some natural gas elsewhere in the economy).

Across all net zero scenarios, GDP from the fossil fuel industry is expected to grow by 22–101 % in Canada and by 16–56 % in the US, relative to 2020 levels. In scenarios where fossil fuel industry GDP is lowest, crude oil production for export to ROW becomes more important to the industry as a whole. GDP growth in fossil fuel production and processing is a function of changes in physical output and changes in prices, with much determined by levels of foreign demand and whether any domestic sectors can still consume fossil products. Thus, it is worthwhile to reiterate that although we discuss overall projected growth of GDP in oil and gas sectors across all net zero scenarios, this is not necessarily a prediction of a likely outcome. Because ROW is not modelled endogenously, exports of fossil products accepted by ROW remain similar to Reference scenario levels across all scenarios. Thus, while Canada and the US shuffle production between oil and gas subsectors (i.e., refining vs. crude production) due to changes in domestic demand, overall levels of oil and gas production decline only modestly (Canada) or plateau (US) in the years reaching 2050. GDP growth is somewhat maintained because output prices rise alongside our assumed oil price trajectory (which implies some continued demand for oil from ROW). In reality, for Canada and the US to pursue stringent emissions targets ROW would likely need to be acting similarly. However, even with much of the world rapidly switching away from fossil fuels, global demand for crude oil could plateau or grow due to increasing demand from medium and low-income countries [43,44]. Conversely, global oil demand could plummet if all countries work together to rapidly decarbonize. Thus, the extent to which the Canadian and US oil and gas sectors remain productive and economical in our scenarios is largely a function of highly uncertain global oil demand assumptions.

5. Conclusions

In this study we examine how economic responses to alternative net zero emissions pathways might differ between the US and Canada. We base our scenario design on the wider EMF37 study but analyze results from only one energy-economy-emissions model, gTech. Use of a single model is a limitation to be addressed by future studies on the comparative economic effects of a net zero transition in Canada and the US. Another limitation of our research is that we do not simulate an accurate reference scenario in terms of GDP because our reference scenario assumes no damages from not acting to achieve net-zero emissions globally by 2050. Finally, we recognize the inherent limitation of evaluating scenarios under one trajectory of global oil prices and encourage others to expand on this aspect of our work as global projections are updated.

In all sixteen net zero scenarios, we find that a main pillar of Canada's ideal net zero pathway is to capitalize on negative emissions technologies and existing clean electricity. Canada's economy is more dependant on emissions intensive industries such as durables manufacturing and oil and gas, and therefore has a larger breadth of responses to alternative assumptions about how negative emissions technologies might be able to offset residual emissions in these sectors.

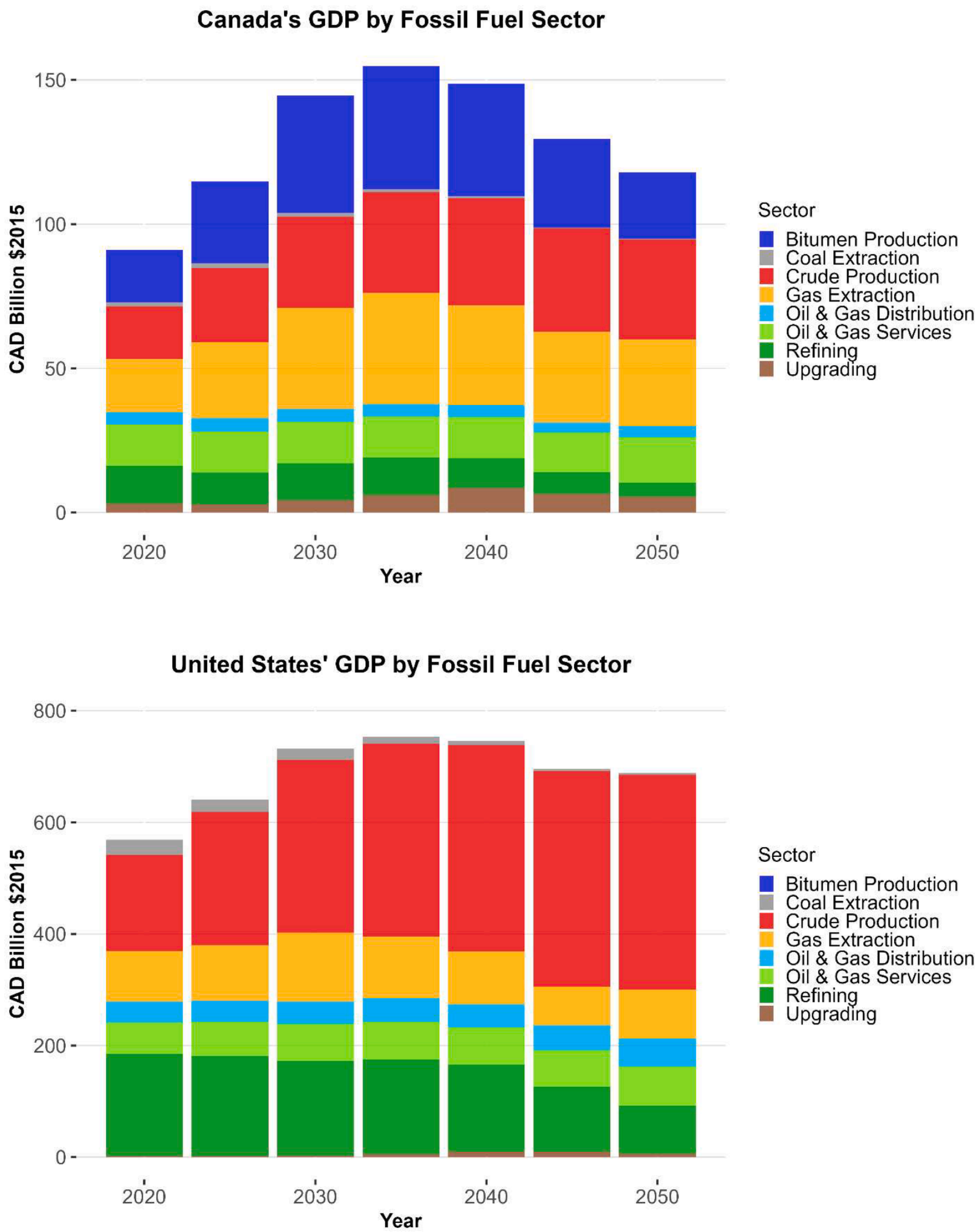

Fig. 7. Income GDP (deflated) of fossil fuel industry sub-sectors in Canada and the US under NZ Reference.

Canada's weakness is in its current concentration of economic activity in emissions intensive industries, and thus its reliance on rapid roll-out of negative emissions solutions, while its strength is in its already largely renewables-based electricity grid, which enables easier, near-termdecarbonization of transportation and buildings.

In the United States, key pillars of decarbonization will be to (1) ensure efficient use of its currently limited clean electricity supply by promoting energy efficient buildings technologies in the near term, and (2) to quickly expand zero-emission electricity generation, much of it likely to be renewables. While the electricity sector must decarbonize significantly in all net zero scenarios and contribute more to total US emissions reductions than in Canada it is also responsible for significant GDP growth in 2050, primarily because of increased demand for electricity. Helpful to economic growth in the US are policies in the near-term that reduce energy demand from buildings, as this reduces the future electricity cost burden – particularly on its services sector - and frees up clean energy for more valuable uses, such as DAC and transportation.

The potential range of economic impacts that can be expected if Canada and the US reach net zero emissions by 2050 can be partly explained by the design of net zero scenarios in this study. Focusing on policy choices, technological advancements, and behavioural change in different parts of an economy explicably alters the pathway to net zero in terms of sectoral emissions reductions, GDP change, energy prices, and economic output. Scenarios resulting in the lowest economic cost to both economies are those that cause the least structural change in terms of decline in existing sectors. For Canada, this means continued use of some fossil fuels throughout the economy, and especially in oil and gas, enabled by adoption of carbon capture and storage and direct air capture, and production of biofuels. For the United States, this means early expansion and decarbonization of the electricity grid, combined with adoption of carbon capture technologies and efficient use of its available electricity.

The results of this analysis indicate that advanced assumptions about policy, technology and behaviour intersect with each country's current emissions profile and sectoral contributions to GDP to determine likely economic outcomes in a net zero future. An important takeaway is that under any net zero scenario, economic output at the national level is expected to continue to grow robustly in both Canada and the US. The extent to which each country can maximize this growth will depend on technology focus decisions and policy choices made in the near term that ensure negative emissions options, clean and plentiful electricity supply, and efficient use of clean energy resources.

Funding

This work was supported by the Mitacs PhD Accelerate Fellowship [IT36337, 2023]; and the Graduate Dean's Entrance Scholarship awarded by Simon Fraser University [135810050462; 2021].

CRediT authorship contribution statement

Emma Starke: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mark Jaccard:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Jotham Peters:** Validation, Software, Resources, Methodology, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Emma Starke reports financial support was provided by Mitacs Canada. The authors have no additional conflicts of interest to declare. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors wish to acknowledge the contribution of Bradford Griffin, Simon Fraser University, in the conceptualization of various aspects of the article. We also acknowledge the contribution of all Navius Research staff to the design, calibration, testing, and maintenance of the gTech model, and for their help in troubleshooting our simulations and scenario implementation.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2024.100147.

Appendix: Scenario implementation and assumptions

Reference Scenario

Table A.1 details policies included in the Reference scenario. Criteria to include policies was as follows:

- Legislated / implemented as of early 2021. Policies that were announced but lacked regulations to enforce were excluded.
- Compulsory with enforcement mechanism(s)
- Detailed enough to simulate without modeller speculation.

Based on these criteria, the following policies were not included in the Reference scenario:

- Canada's Clean Fuel Standard (2021)
- Canada's Clean Electricity Regulations (2023)
- United States' Inflation Reduction Act (2022)

Unless otherwise specified, all policies implemented in the Reference scenario were implemented across *all net zero scenarios.*

Table A.1
Reference scenario policies.

Reference scenario policies					Parameter by model year							
Country	**Prov/ State**	**Policy**	**Legislated / Implemented / EMF37 assumption (date)**	**Policy details (if applicable)**	**Units**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Canada	ON, MB, SK, AB, YT, NU	Federal fuel charge	*Greenhouse Gas Pollution Pricing Act* - implemented (2018)*;* Fuel Charge and OBPS implemented (2020)	Price per tonne CO_2e applied to fossil-fuel derived secondary fuels. 90 % of fuel charge proceeds are returned directly to households in province / territory where proceeds were collected. 10 % are used to support small and medium sized businesses, rural communities, and Indigenous peoples.	$/tonne	30	95	130	130	130	130	130
	ON, MB, NB, PE, YT, NU, SK	Output-Based Pricing System (OBPS)		Price per tonne CO2e (matching federal fuel charge) applied to emissions over industrial facility emissions intensity limit. Policy sets emissions intensity standards for industrial activities (emissions per unit output). Total annual emissions limit for each facility under policy is calculated by multiplying its output-based emissions intensity standard by total production. Facilities earn surplus credits if they emit less than their annual limit and pay the federal carbon price on emissions over annual limit. Proceeds from OBPS are returned via OBPS Proceeds Fund to support decarbonization of heavy industry.								
	BC	British Columbia Carbon Tax	Implemented (2008)	Carbon tax on purchase of fossil fuels. Revenue is used to transfer rebates to households and to lower personal and corporate income taxes.	$/tonne	40	40	40	40	40	40	40
	QC	Western Climate Initiative	Implemented (2013)	Emissions cap. Member jurisdiction of Wester Climate Initiative (WCI) carbon market. Auction revenue is recycled to households, government, corporations, renewable electricity generation, transit systems, and low carbon technologies.	Mt CO_{2e}	55	50	44	39	35	32	28
United States	CA	Western Climate Initiative / California Cap and Trade	Implemented (2012)	Emissions cap. Member jurisdiction of Wester Climate Initiative (WCI) carbon market.	Mt CO_2e	334	267	201	167	134	100	67
Canada	BC	Renewable and low carbon fuel requirements regulation	Implemented (2010)	Part 1 of the Regulation requires a 5 % annual average renewable content in gasoline and 4 % renewable content in diesel. Part 2 of the Regulation requires fuel suppliers to reduce the average carbon intensity (CI) of their fuels annually	% reduction from 2010 CI levels.	7 %	18 %	30 %	30 %	30 %	30 %	30 %

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Table A.1 (*continued*)

Reference scenario policies					Parameter by model year							
Country	**Prov/ State**	**Policy**	**Legislated / Implemented / EMF37 assumption (date)**	**Policy details (if applicable)**	**Units**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
				to achieve a 30 % reduction by 2030.								
	AB	Renewable Fuels Standard	Implemented (2010)	Requires a minimum annual average of 5 % renewable alcohol in gasoline and 2 % renewable diesel in diesel fuel sold in Alberta by fuel suppliers. To meet the Renewable Fuels Standard, renewable fuels must demonstrate at least 25 % fewer GHG emissions than the equivalent petroleum fuel.								
	SK	Renewable Diesel Act & Ethanol Mandate		Requires fuel distributors to include 2 % renewable diesel content. The province also has a 7.5 % ethanol mandate.								
	MB	Ethanol Mandate & Biodiesel Mandate		Manitoba's Ethanol Mandate requires fuel suppliers in Manitoba to blend at least 10 % of ethanol in their gasoline. The Biodiesel Mandate requires fuel suppliers to blend 5 % renewable content in on- and off-road diesel fuel.								
United States	CA	Low Carbon Fuel Standard	Implemented (2011)	Requires a 20 % reduction in state-wide transportation fuel mix carbon intensity (CI) by 2030 from 2010 levels.	% reduction in CI of fuel mix.	8 %	14 %	20 %	20 %	20 %	20 %	20 %
	OR	Clean Fuels Program	Fully Implemented (2015)	Requires a 10 % reduction in state-wide transportation fuel mix carbon intensity (CI) by 2030 from 2015 levels. This is the original implementation of the regulation (2015). It has since been revised to require a 37 % reduction in CI of transport fuels by 2035.	% reduction in CI of fuel mix.	3 %	10 %	10 %	10 %	10 %	10 %	10 %
	WA	Renewable Fuel Standard		At least 2 % of all diesel fuel sold in Washington must be biodiesel or renewable diesel. At least 2 % of the total gasoline sold in the state must be denatured ethanol.	% of all gasoline / diesel sold required to be ethanol / biodiesel	2 %	2 %	2 %	2 %	2 %	2 %	2 %
Canada	All	Regulations Amending the Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity	Implemented (2018)	Regulations to phase out coal-fired electricity generation by December 31st, 2030 (unless the generation facility has an emissions intensity of 420t CO2e/ GWh no later than 2030).								

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Table A.1 (*continued*)

Reference scenario policies					Parameter by model year							
Country	**Prov/ State**	**Policy**	**Legislated / Implemented / EMF37 assumption (date)**	**Policy details (if applicable)**	**Units**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
		Regulations: SOR/ 2018–263										
	All	Regulations Limiting Carbon Dioxide Emissions from Natural Gas-Fired Generation of Electricity: SOR/ 2018–261	Implemented (2018)	Requirement that natural gas-fired generation have an emissions intensity of 420t CO_2e/ GWh no later than 2030.								
	BC	Clean Electricity Mandate	Implemented (2010)	Generation requirements under the 2010 Clean Energy Act stating that 98 % of electricity generated in province must be from renewable and / or clean sources by 2030.								
	AB	Renewable Electricity Act	Legislated (2016)	The Renewable Electricity Act provides for the development, implementation, and funding of programs to incent the generation of renewable electricity in Alberta and requires the Minister to ensure that by the end of 2030 at least 30 % of the electric energy produced in Alberta will be produced from renewable energy resources.								
United States	CA	Renewable Portfolio Standard	Legislated (2002)	Requires percentage of total retail sales of electricity to increase to 60 % by December 31st, 2030.								
	WA	Renewable Energy Standard	Legislated (2006)	Requires large utilities to obtain fifteen percent of their electricity from new renewable resources such as solar and wind by 2020.								
	OR	Renewable Portfolio Standard	Legislated (2007)	Works in tangent with Oregon's Clean Energy Targets legislation to require increasing percentage of electricity generation from renewable sources and decreasing emissions from electricity generation.								

Net Zero by 2050 – Reference

All policies listed in Table A.1 as part of the Reference scenario are also present in the NZ Reference scenario, unless specified otherwise in Table A.2. NZ Reference differs from the Reference scenario only by carbon pricing policy, as detailed below.

Table A.2
Net zero by 2050 – Reference scenario carbon pricing policy assumption and parameters. Policies details not provided for policies already described in Table A.1.

Net zero - reference					Parameter by model year							
Country	**Provinces/ States**	**Policy**	**Legislated / Implemented / EMF37 assumption (date)**	**Policy details**	**Units**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Canada	ALL	National Cap-and-Trade policy	EMF37 Assumption	National emissions cap on all greenhouse gases, targeting net zero CO_2 emissions by 2050. An annual 100Mt LULUCF sink is assumed. 100 % of revenue is recycled to households as annual lump-sum.	Mt CO_2e	–	728	619	499	389	272	135
	ON, MB, SK, AB, YT, NU	Federal fuel charge	*Greenhouse Gas Pollution Pricing Act* - implemented (2018); Fuel Charge and OBPS in effect (2020)	*See Table A.1*	$/tonne	30	Policy inactive staring in 2025					
	ON, MB, NB, PE, YT, NU, SK	Output-Based Pricing System (OBPS)		*See Table A.1*	$/tonne	30	Policy inactive staring in 2025					
	BC	British Columbia Carbon Tax	Implemented (2008)	*See Table A.1*	$/tonne	40	Policy inactive staring in 2025					
	QC	Western Climate Initiative	Implemented (2013)	*See Table A.1*	Mt CO_2e	55	Policy inactive staring in 2025					
United States	ALL	National Cap-and-Trade policy	EMF37 Assumption	National emissions cap on all greenhouse gases, targeting net zero CO2 emissions by 2050. An annual 800 Mt LULUCF sink is assumed. 100 % of revenue is recycled to households as annual lump-sum.	Mt CO_2e	–	7013	5873	4733	3635	2571	1640
	CA	Western Climate Initiative / California Cap and Trade	Implemented (2012)	*See Table A.1*	Mt CO_2e	334	Policy inactive staring in 2025					

<u>Advanced assumption net zero scenarios</u>

The Transportation (TSG), Buildings (BSG), and Carbon Management (CMSG) scenarios all contain the carbon pricing policies detailed for NZ Reference. Additional policies and assumptions for each scenario are outlined in Tables A.3, A.4 & A.5 below.

Table A.3
Scenario assumptions and parameters for Transportation scenarios.

Transportation study group (TSG) scenarios						Parameter by model year							
Scenario code	**Country**	**Prov/ state**	**Policy / measure**	**Details**	**End-uses / sectors impacted**	**Units**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
TSG advTech	Canada	ALL	Low ZEV capital costs	Faster capital cost decline of zero emission vehicles and batteries with cumulative adoption. Applies to battery electric, plug in hybrid, and fuel cell vehicle technologies.	ZEV light duty vehicles	% change from NZ Reference life cycle cost of technology	-2 %	-3 %	-4 %	-8 %	-9 %	-9 %	-10 %
	United States	ALL					-3 %	-3 %	-3 %	-7 %	-8 %	-9 %	-10 %
	Canada	ALL			ZEV heavy duty vehicles		0 %	0 %	-2 %	-5 %	-7 %	-7 %	-9 %
	United States	ALL					0 %	4 %	-2 %	0 %	-3 %	-11 %	-13 %
	ALL	ALL	Low biofuels production cost	Lowered costs of capital required by biofuels-producing sectors with cumulative production.	Cellulosic ethanol, renewable gas, renewable diesel,								

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Table A.3 (*continued*)

Transportation study group (TSG) scenarios						Parameter by model year							
Scenario code	**Country**	**Prov/ state**	**Policy / measure**	**Details**	**End-uses / sectors impacted**	**Units**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
					renewable natural gas								
	ALL	ALL	Low H2 transportation technology cost	Lowered costs of fuel cell vehicle technology with cumulative adoption.	Light duty, medium duty, and heavy-duty vehicles; buses, freight rail, marine.								
TSG advBehav	Canada	ALL	Low ZEV intangible costs	Faster intangible cost decline of zero emission vehicles and batteries with cumulative adoption. Applies to battery electric, plug in hybrid, and fuel cell vehicle technologies.	ZEV light duty vehicles	% change from NZ Reference life cycle cost of technology	-2 %	-1 %	-8 %	-8 %	-9 %	-9 %	-10 %
	United States	ALL					-3 %	1 %	-1 %	-7 %	-8 %	-9 %	-10 %
	Canada	ALL			ZEV heavy duty vehicles		0 %	5 %	-1 %	-4 %	-10 %	-22 %	-23 %
	United States	ALL					0 %	4 %	1 %	1 %	-3 %	-18 %	-23 %
	ALL	ALL	Low biofuels production cost	Lowered costs of capital required by biofuels-producing sectors with cumulative production.	Cellulosic ethanol, renewable gas, renewable diesel, renewable natural gas								
	ALL	ALL	Low H2 transportation technology cost	Lowered costs of fuel cell vehicle technology with cumulative adoption.	Light duty, medium duty, and heavy duty vehicles; buses, freight rail, marine.								
TSG advPol	Canada	ALL	Strengthened vehicle emissions standards	Applies to all newly adopted light duty vehicles		g CO_2e / vehicle km travelled	167	132	106	105	105	105	105
			BEV Subsidy	Federal purchase subsidy on new battery electric vehicles	Light duty / personal vehicles	CAD $2015 / vehicle	1522	4264	3862	3498	3137	2870	2599
			PHEV Subsidy	Federal purchase subsidy on new plug-in hybrid vehicles	Light duty / personal vehicles	CAD $2015 / vehicle	–	2587	2343	2122	1903	1741	1577
			ZEV Mandate	Flexible regulation requiring increasing share of new light duty vehicle sales to be zero emissions vehicles (EV or PHEV)	Light duty / personal vehicles	% new vehicle sales	–	0.27	0.5	1	1	1	1
			Clean Fuel Standard	Regulation to reduce the life cycle carbon intensity of liquid transportation fuels sold.	Applies to all liquid transport fuels.	Reduction in g CO_2e / MJ	–	6	12	12	12	12	12
	United States	ALL	Strengthened vehicle emissions standards	Applies to all newly adopted light duty vehicles	Light duty / personal vehicles	g CO_2e / vehicle km travelled	167	132	106	105	105	105	105

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Table A.3 (*continued*)

Transportation study group (TSG) scenarios						Parameter by model year							
Scenario code	**Country**	**Prov/ state**	**Policy / measure**	**Details**	**End-uses / sectors impacted**	**Units**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
			BEV Subsidy	Federal purchase subsidy on new battery electric vehicles	Light duty / personal vehicles	CAD $2015 / vehicle	–	2782	2520	2282	2047	1872	1696
			PHEV Subsidy	Federal purchase subsidy on new plug-in hybrid vehicles	Light duty / personal vehicles	CAD $2015 / vehicle	–	1755	1589	1439	1291	1181	1070
			ZEV Mandate	Flexible regulation requiring increasing share of new light duty vehicle sales to be zero emissions vehicles (EV or PHEV)	Light duty / personal vehicles	% new vehicle sales	–	10 %	23 %	37 %	50 %	60 %	70 %
		WA, Rest of US	Low Carbon Fuel Standard	Regulation to reduce the life cycle carbon intensity of transportation fuels sold.	Light duty / personal vehicles	% reduction in carbon intensity from 2015 levels	–	10 %	10 %	10 %	10 %	10 %	10 %
		OR	Low Carbon Fuel Standard	Regulation to reduce the life cycle carbon intensity of transportation fuels sold.	Light duty / personal vehicles	% reduction in carbon intensity from 2015 levels	3 %	10 %	10 %	10 %	10 %	10 %	10 %
		CA	Low Carbon Fuel Standard	Regulation to reduce the life cycle carbon intensity of transportation fuels sold.	Light duty / personal vehicles	% reduction in carbon intensity from 2015 levels	14 %	20 %	20 %	20 %	20 %	20 %	20 %
TSG advTech- Pol	Canada	ALL	Low ZEV capital costs Low biofuels production cost Low H2 transportation technology cost Strengthened vehicle emissions standards BEV Subsidy PHEV Subsidy ZEV Mandate Clean Fuel Standard	*See policy descriptions above.*									
	United States	ALL	Low ZEV capital costs Low biofuels production cost Low H_2 transportation technology cost Strengthened vehicle emissions standards BEV Subsidy PHEV Subsidy ZEV Mandate Low Carbon Fuel Standards	*See policy descriptions above.*									

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Table A.3 (*continued*)

Transportation study group (TSG) scenarios						Parameter by model year							
Scenario code	**Country**	**Prov/ state**	**Policy / measure**	**Details**	**End-uses / sectors impacted**	**Units**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
TSG allAdv*	Canada	ALL	Low ZEV capital costs Low ZEV intangible costs Low biofuels production cost Low H2 transportation technology cost Strengthened vehicle emissions standards BEV Subsidy PHEV Subsidy ZEV Mandate Clean Fuel Standard	*See policy descriptions above.*									
	United States	ALL	Low ZEV capital costs Low ZEV intangible costs Low biofuels production cost Low H2 transportation technology cost Strengthened vehicle emissions standards BEV Subsidy PHEV Subsidy ZEV Mandate Low Carbon Fuel Standards	*See policy descriptions above.*									

Table A.4
Scenario assumptions and parameters for buildings scenarios.

Buildings study group (BSG) net zero scenarios				Parameter by model year							
Scenario Code	**Country**	**Policy**	**Policy details**	**Units**	**End-use category**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
BSG agrEE	Canada	Buildings Efficiency Standard	Compulsory standard implemented requiring increasing shares of new buildings technologies to be electricity powered (structured similarly to a ZEV mandate). Standards are set based on current technology market shares by end use, with a target of 99.99 % efficiency by 2050. * Indicates that the scenario could not solve at 99.99 % efficiency by 2050 and sales requirement was frozen at previous model year(s) level.	% of new sales required to be technology classed as "high efficiency"	Commercial air conditioning	0.74	0.79	0.84	0.9	0.95	0.99
					Clothes dryers	0.54	0.63	0.73	0.82	0.91	0.99
					Retail food building shells	0.69	0.75	0.81	0.88	0.94	0.99
					Commercial heating load	0.98	0.99	0.99	0.99	0.99	0.99
					Commercial hot water	0.73	0.79	0.84	0.89	0.95	0.99
					Office building shells	0.72	0.78	0.83	0.89	0.94	0.99
					Ranges	0.19	0.35	0.52	0.68	0.84	0.84*
					Other building shells	0.79	0.83	0.87	0.91	0.96	0.99
					Retail building shells	0.67	0.73	0.8	0.87	0.93	0.99
					Elementary or secondary school building shells	0.93	0.94	0.96	0.97	0.99	0.99
					Warehouse building shells	0.82	0.85	0.89	0.93	0.96	0.99
					Clothes washers	0.8	0.84	0.88	0.92	0.96	0.99
					Dishwashers	0.2	0.36	0.52	0.68	0.68*	0.68*
					Freezers	0.44	0.55	0.66	0.78	0.89	0.99
					Furnaces	0.54	0.63	0.73	0.82	0.91	0.99

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Table A.4 (*continued*)

Buildings study group (BSG) net zero scenarios				Parameter by model year							
Scenario Code	**Country**	**Policy**	**Policy details**	**Units**	**End-use category**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
					Household air conditioning	0.54	0.63	0.72	0.82	0.91	0.99
					Apartment Building Shells	0.72	0.78	0.83	0.89	0.94	0.99
					Household hot water	0.19	0.35	0.51	0.68	0.84	0.99
					Household lighting	0.36	0.49	0.62	0.74	0.87	0.99
					Single family attached building shells	0.66	0.73	0.8	0.86	0.93	0.99
					Single family detached building shells	0.66	0.73	0.8	0.86	0.93	0.99
					Refrigerators	0.57	0.66	0.74	0.83	0.91	0.99
		Federal subsidies for energy efficient buildings shells and technologies.	Annual federal subsidy for efficient buildings technologies. Annual amount based on energy efficiency provisions in Canada's Budget 2021.	Billion $2015 / year	Air conditioning, clothes dryers, commercial heating, commerical hot water, commercial lighting, ranges, faucets, clothes washers, clothes dryers, freezers, furnaces, household air conditioning, household heating, household hot water, household lighting, refrigerators	0.57	0.52	0.47	0.43	0.39	0.35
	United States	Buildings Efficiency Standard	Compulsory standard implemented requiring increasing shares of new buildings technologies to be electricity powered (structured similarly to a ZEV mandate). Standards are set based on current technology market shares by end use, with a target of 99.99 % efficiency by 2050. *Indicates that the scenario could not solve at 99.99 % efficiency by 2050 and sales requirement was frozen at previous model year(s) level.	% of new sales required to be technology classed as "high efficiency"	Commercial air conditioning	0.8	0.84	0.88	0.92	0.96	0.99
					Clothes dryers	0.54	0.63	0.72	0.82	0.91	0.91*
					Retail food building shells	0.78	0.82	0.87	0.91	0.96	0.99
					Commercial heating load	0.93	0.94	0.96	0.97	0.99	0.99
					Commercial hot water	0.72	0.77	0.83	0.89	0.94	0.99
					Office building shells	0.76	0.81	0.85	0.9	0.95	0.99
					Ranges	0.19	0.35	0.51	0.68	0.84	0.99
					Other building shells	0.85	0.88	0.91	0.94	0.97	0.99
					Retail building shells	0.67	0.74	0.8	0.87	0.93	0.99
					Elementary or secondary school building shells	0.96	0.96	0.97	0.98	0.99	0.99
					Warehouse building shells	0.77	0.82	0.86	0.91	0.95	0.99
					Clothes washers	0.78	0.82	0.87	0.91	0.96	0.99
					Dishwashers	0.2	0.36	0.52	0.68	0.68*	0.68*
					Freezers	0.44	0.55	0.66	0.77	0.89	0.99
					Furnaces	0.5	0.6	0.7	0.8	0.9	0.99
					Household air conditioning	0.57	0.65	0.74	0.83	0.91	0.99
					Apartment Building Shells	0.52	0.62	0.71	0.81	0.9	0.99
					Household hot water	0.17	0.33	0.5	0.67	0.83	0.99
					Household lighting	0.17	0.34	0.5	0.67	0.83	0.99
					Single family attached building shells	0.48	0.58	0.69	0.79	0.9	0.99
					Refrigerators	0.58	0.67	0.75	0.83	0.92	0.92*
		Federal subsidies for energy efficient buildings shells and technologies.	Annual federal subsidy for efficient buildings technologies. Annual amount based on energy efficiency provisions in United States' Budget 2021.	Billion $2015 / year		5.45	4.94	4.47	4.05	3.67	3.32
BSG mrkt ElecEE	Canada	Federal subsidies for energy efficient buildings shells and technologies.	Annual federal subsidy for efficient buildings technologies. Annual amount based on energy efficiency provisions in Canada's Budget 2021.	Billion $2015 / year	Air conditioning, clothes dryers, commercial heating, commercial hot water, commercial lighting, ranges, faucets, clothes washers, clothes	0.57	0.52	0.47	0.43	0.39	0.35
		Federal subsidies for electric buildings technologies.	Annual federal subsidy for electric buildings technologies. Annual amount based on provisions for promoting electrification of buildings in Canada's Budget 2021.	Billion $2015 / year	dryers, freezers, furnaces, household air conditioning, household heating, household hot water, household lighting, refrigerators	0.05	0.05	0.04	0.04	0.04	0.03

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Table A.4 (*continued*)

Buildings study group (BSG) net zero scenarios				Parameter by model year							
Scenario Code	**Country**	**Policy**	**Policy details**	**Units**	**End-use category**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
	United States	Federal subsidies for energy efficient buildings shells and technologies.	Annual federal subsidy for efficient buildings technologies. Annual amount based on energy efficiency provisions in United States' Budget 2021.	Billion $2015 / year		5.45	4.94	4.47	4.05	3.67	3.32
		Federal subsidies for electric buildings technologies.	Annual federal subsidy for electric buildings technologies. Annual amount based on provisions for promoting electrification of buildings in United States' Budget 2021.	Billion $2015 / year		1.35	1.23	1.11	1.01	0.91	0.82
BSG stnd ElecEE	Canada	Buildings Efficiency Standard	*See policy description above.*								
	Canada	Buildings Electrification Standard	Fuel-agnostic standard requiring increasing shares of new buildings technologies to be electricity powered, similar to a ZEV mandate. Standards are set based on current technology market shares by end use, with a target of 100 % electrification by 2050.	% of new sales required to be electric technology.	Commercial air conditioning	0.74	0.79	0.84	0.90	0.95	1.00
					Commercial heating load	0.45	0.56	0.67	0.78	0.89	1.00
					Commercial hot water	0.22	0.38	0.53	0.69	0.84	1.00
					Ranges	0.70	0.76	0.82	0.88	0.94	1.00
					Furnaces	0.29	0.43	0.57	0.72	0.86	1.00
					Household hot water	0.29	0.43	0.57	0.71	0.86	1.00
	United States	Buildings Efficiency Standard	*See policy description above.*								
	United States	Buildings Electrification Standard	Fuel-agnostic standard requiring increasing shares of new buildings technologies to be electricity powered, similar to a ZEV mandate. Standards are set based on current technology market shares by end use, with a target of 100 % electrification by 2050.	% of new sales required to be electric technology.	Commercial air conditioning	0.80	0.84	0.88	0.92	0.96	1.00
					Commercial heating load	0.45	0.56	0.67	0.78	0.89	1.00
					Commercial hot water	0.18	0.34	0.51	0.67	0.84	1.00
					Ranges	0.58	0.66	0.75	0.83	0.92	1.00
					Furnaces	0.23	0.38	0.54	0.69	0.85	1.00
					Household hot water	0.19	0.35	0.51	0.68	0.84	1.00
BSG agrElec	Canada	Buildings Electrification Standard	*See policy description above.*								
		Federal subsidies for electric buildings technologies.	*See policy description above.*								
	United States	Buildings Electrification Standard	*See policy description above.*								
		Federal subsidies for electric buildings technologies.	*See policy description above.*								
BSG allAdv*	Canada	Buildings Electrification Standard	*See policy description above.*								
		Buildings Efficiency Standard	*See policy description above.*								
		Federal subsidies for electric buildings technologies.	*See policy description above.*								

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Table A.4 (*continued*)

Buildings study group (BSG) net zero scenarios				Parameter by model year							
Scenario Code	**Country**	**Policy**	**Policy details**	**Units**	**End-use category**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
		Federal subsidies for energy efficient buildings shells and technologies.	*See policy description above.*								
	United States	Buildings Electrification Standard	*See policy description above.*								
		Buildings Efficiency Standard	*See policy description above.*								
		Federal subsidies for electric buildings technologies.	*See policy description above.*								
		Federal subsidies for energy efficient buildings shells and technologies.	*See policy description above.*								

Table A.5
Scenario assumptions and parameters for carbon management scenarios.

Carbon management study group (CMSG) net zero scenarios						Parameter by model year							
Scenario code	**Country**	**Prov/ state**	**Policy / measure**	**Details**	**End-uses / sectors impacted**	**Units**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
CMSG advCCS	ALL	ALL	Lowered CCS cost	Lowered capital costs of carbon capture and storage technologies with cumulative adoption.	Process CO_2 from cement production, hydrogen production, and natural gas processing. Combustion CO_2 from electricity generation, heat production, and cement production.								
CMSG advH2	ALL	ALL	Lowered H2 Supply costs	Lowered capital costs of hydrogen production technologies based on cumulative adoption	Hydrogen produced via electrolysis and steam methane reformation								
CMSG advDAC	ALL	ALL	Very low costs of DAC	Very low costs of direct air capture, with cumulative adoption.	All sectors.	\$2015 / t CO_2e captured via DAC	n/a	n/a	n/a	n/a	296	125	112
CMSG noDac	ALL	ALL	No DAC available	DAC technology unavailable in	All sectors.								

(*continued on next page*)

Table A.5 (*continued*)

Carbon management study group (CMSG) net zero scenarios						Parameter by model year							
Scenario code	**Country**	**Prov/ state**	**Policy / measure**	**Details**	**End-uses / sectors impacted**	**Units**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
CMSG allAdv	ALL	ALL	All advanced carbon management	all regions in all model years. Lowered capital costs of carbon capture and storage technologies with cumulative adoption. Lowered capital costs of hydrogen production technologies based on cumulative adoption. Low costs of direct air capture, with cumulative adoption.	All sectors.	$2015 / t CO_2e captured via DAC	n/a	n/a	n/a	n/a	n/a	301	179

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