The Economics of Air Capture of CO2 in Canada

By

David Hodgson

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Declaration of Committee

Name: **David Hodgson**

Degree: **Master of Resource Management**

Title: **The Economics of Air Capture of CO2 in Canada**

Project No.: **787**

Committee: **Chair: Thomas Budd**
PhD Candidate, Resource and Environmental Management

Mark Jaccard
Supervisor
Professor, Resource and Environmental Management

Bradford Griffin
Committee Member
Adjunct Professor, Resource and Environmental Management

Abstract

The Canadian government has committed to lowering national emissions to net-zero by 2050, but there are many uncertainties that could impact this transition. One of these uncertainties is the cost of emerging direct air capture (DAC) technology used to remove carbon dioxide from the atmosphere, while a second is whether the United States will commit to lowering their emissions to net-zero by 2050. In this study I use the gTech energy-economy model to assess how different assumptions about these uncertainties could impact the Canadian economy through this transition. I model eight different scenarios representing four different assumptions about DAC costs and availability, and two different assumptions about US emissions abatement. I find that higher availability and lower cost of carbon dioxide removal technology like DAC is correlated with a higher Canadian GDP in 2050, and that US abatement significantly affects the availability of these technologies.

Keywords: Direct air capture; Net-zero emissions; Climate policy; Energy-economy modeling; Energy; Economics

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AR	Afforestation and Reforestation
BBB	Build Back Better
BECCS	Bioenergy with Carbon Capture and Storage
CAD	Canadian Dollars
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CGE	Computable General Equilibrium
DAC	Direct Air Capture
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change

Chapter 1. Introduction

Canada has committed to reducing its greenhouse gas (GHG) emissions to 40% below its 2005 levels by 2030, and to achieve net-zero emissions by 2050 (Government of Canada, 2021b). This commitment is part of the Paris Agreement, a global agreement among countries to limit emissions so that global temperature increases from climate change are minimized to less than 2°C, and ideally no more than 1.5°C. Net-zero means that by 2050, Canada must either not be emitting any GHGs, or sequestering the same amount of GHGs from the atmosphere that it is emitting every year. This will occur by "shifting toward technologies and energy systems that do not produce emissions and offsetting any remaining emissions by removing GHGs from the atmosphere and storing them permanently" (Canadian Institute for Climate Choices, 2021, p. 3). The application of direct air capture of CO2 with underground storage, a negative emission technology, is thus growing in importance in the analysis of energy-economy-emissions modellers who assess the likelihood and cost of society achieving GHG targets.

Planning an ongoing transition that will occur over almost thirty years is a challenging task. Some technological solutions, such as increased energy efficiency, non-emitting electricity, and the adoption of electric vehicles, will almost certainly be a part of the energy transition (Canadian Institute for Climate Choices, 2021). But there are a number of other variables for which there is very little certainty. When the ability of a variable to influence the energy transition is large, that uncertainty is worth exploring.

Two of these variables are the costs of direct air capture (DAC) technology and the degree to which the United States will commit to abating its CO2 emissions. The costs of DAC at commercial scale are largely unknown yet will play an enormous role in how widely it will be used (Fasihi et al., 2019). Meanwhile the United States federal government has been very unclear how it will respond to climate change, or if it will at all. The US is Canada's largest trading partner by a wide margin, and how they continue to respond to climate change will have a major impact on Canada's economy.

In this paper, I will be exploring the uncertainty surrounding both DAC technology, and the degree to which the United States will commit to abating its CO2 emissions. I will examine what impact different assumptions surrounding these uncertainties have on the Canadian economy. Carbon dioxide removal (CDR) describes a set of techniques for removing CO2 from the atmosphere and then sequestering it so that it stops contributing to climate change. In the short term, deployment of CDR will likely be used to offset emissions (IPCC, 2018). DAC is a method of CDR that involves using one of two chemical processes to capture CO2 directly from the atmosphere. Once captured, the CO2 can be stored underground where it no longer contributes to the greenhouse effect causing climate change (Canadian Institute for Climate Choices, 2021).

A major policy being used in Canada to lower emissions is a federal carbon price – firms in Canada are forced to pay a tax for every ton of CO2 that they pollute. Carbon prices appeal to economists because they allow firms the flexibility to choose when and how to lower emissions, with rational firms choosing to abate in situations where doing so is cheaper than paying the carbon price. CDR options like DAC allow firms a third option; they can abate, pay the carbon price, or offset emissions with CDR. Theoretically, firms will then choose to offset emissions in situations where doing so is cheaper than either abating or paying the carbon price. In practice, this would mean large amounts of offsets beyond the point where paying for an offset is cheaper than paying the carbon price. Accordingly, the costs of CDR options like DAC are crucial in determining how fast and economically efficient Canada's transition to a net-zero economy will be, as well as what that economy will look like.

Presently, the costs of DAC are extremely high relative to the cost of abating or paying the carbon price. These costs are expected to decline though. DAC's cost will be influenced by its rate of adoption in a well-known feedback effect with new technologies: as their adoption climbs, their cost falls (Loschel, 2002). What is still unclear is DAC's rate of adoption, and how quickly that rate of adoption will lower its cost.

Another significant source of uncertainty is the direction of US abatement. The United States is presently very politically divided between its two major political parties. The Democratic Party widely supports reducing CO2 emissions, while its opponents in the Republican Party have historically opposed any kind of climate policy. Because effective climate action requires sustained political support, this political division creates considerable uncertainty about the US commitment to abating its emissions. This is important because the United States is Canada's largest trading partner by a large margin and is a particularly outsized trading partner when it comes to energy. The extent of US abatement, or lack thereof, will have major implications for the Canadian economy.

With existing information, the uncertainties around DAC cost and US abatement are considerable. However, acquiring a better understanding of the implications of those uncertainties can allow decision makers to plan for different possible futures. For instance, if a future where DAC costs are extremely high results in considerable difficulty in achieving net-zero targets, decision makers may wish to plan for that by investing in DAC or other CDR methods in order to minimize risk. Alternately, if there is little difference between a future with high DAC costs, and no DAC available at all, this kind of investment might be a waste of resources.

In this paper I will explore the uncertainties related to direct air capture technology and US abatement, and how they relate to the Canadian economy in the context of its transition to net-zero emissions. In particular, I will be exploring the impact of different assumptions about DAC cost and US abatement on Canadian GDP, and its sectoral output. My hypothesis is that lower DAC capital costs will lead to a higher Canadian GDP by offering Canadian firms an alternative to either abating or paying the carbon price. My hypothesis on US abatement is that a net-zero US economy will have a more mixed impact on the Canadian economy but will ultimately be a positive. I expect that US abatement will deprive Canada of a major export market, which will negatively impact the economy; I doubt that increased Canadian exports of goods that are conducive to a zero-emission economy will be able to completely fill the void left by exports of emissions-intensive goods. I expect that US abatement will lower their demand for fossil fuels, which Canada exports to the US in large amount. They will likely demand more goods that are conducive to a zero-emission economy, but I doubt that it will be enough to completely make up the difference. On the other hand, a net-zero US economy will lead to more investment in zero-emission goods, which will speed up their deployment and lower their cost. I expect that US investment in DAC, in particular, will benefit Canada by causing a more rapid drop in the cost of this potentially critical technology. I further hypothesize that cheaper DAC capital costs will correlate with a Canadian economy that is more resource and emissions intensive, by allowing emissions-intensive industries to offset emissions instead of abating.

Chapter 2. Background

2.1 Canada's Net-zero Transition

To meet its target of net-zero emissions, the Canadian federal government has introduced numerous pieces of legislation to lower emissions. These include a variety of incentives for funding low-emission technology, such as the Incentives for Zero-Emission Vehicles program, investments in the adoption of clean technology and processes in heavy industry through the Net Zero Accelerator, and funding renewable energy and electrical grid modernization projects through the Smart Renewable Electrification Pathways Program. The government has also implemented significant regulations on fossil fuel use, such as a ban on conventional fossil fuel plants in Canada by 2030. There are many policies which would contribute significantly to net-zero that have not yet been implemented, but which the federal government has committed to. These include a federal mandate that 50% of light-duty vehicles sold in Canada must be zero-emission by 2030 and 100% by 2035; a federal mandate that 35% of medium and heavy duty vehicles sold in Canada be zero-emission by 2030, and 100% by 2040; a clean electricity standard requiring that all electricity in Canada must be net-zero emission be implemented by 2035 (ECCC, 2022). Arguably the most significant federal policy both in potential for abatement and political impact is the federal carbon price, requiring polluters in Canada pay a price for every ton of CO2 emitted. This is a carbon price introduced at $20 per ton of CO2 in 2018, and rising by $10 annually, hitting $50 in 2022. It is scheduled to rise by $15 per year until it reaches $170 in 2030, beyond which no increases have yet been announced (ECCC, 2022). These policies may be sufficient to achieve Canada's 2030 target. However, to meet the 2050 target of net-zero emissions, further policies, or added stringency on existing policies will likely be necessary.

Emitting technologies contribute to climate change, incurring costs to society that are not reflected in their price. The aim of these federal policies (along with many others not listed) is to change towards technologies and behaviours that do not produce greenhouse gas emissions. They accomplish this by either directly mandating the use of a non-emitting technology or by adding a cost to emitting technology thereby increasing their cost relative to competing technologies that produce fewer or no GHGs. These policies accomplish that by making a technology that produces greenhouse gasses more expensive, thereby increasing its cost relative to competing technologies that produce fewer or no GHGs.

Not all policies are equal in attempting to lower emissions. There are a number of criteria along-which policies can be evaluated, including environmental effectiveness, political acceptability, and economic efficiency. Environmental effectiveness refers to how much a policy will reduce emissions. Political acceptability refers to how likely the public is to support a given policy. Economic efficiency will reduce emissions at the lowest possible cost to the economy. The economic efficiency of different climate policies varies significantly, with some resulting in drastically lower gross domestic product (GDP) for the same amount emissions reductions (Canada's Ecofiscal Commission, 2019). A more economically efficient policy allows the economy to abate while minimizing negative impacts on peoples' quality of life. A highly economically inefficient policy will also likely be politically unpopular and could negatively affect the public's willingness to abate emissions.

The transition to a net-zero emissions economy will significantly impact the shape of Canadian economic and energy systems. The easiest areas of the economy to move away from fossil fuels are the transportation and electricity sectors, where zero-emission technology has already been widely deployed and can continue to be deployed in a manner that is straightforward (Jaccard, 2020). More emissions-intensive sectors of the economy, such as heavy industries like steel production, will face a more complicated transition (Canadian Institute for Climate Choices, 2021). In all likelihood, it is these hard-to abate sectors that will benefit the most from the ability to offset their emissions through CDR.

2.2 Carbon Dioxide Removal Options

Direct air Capture is the commonly used term describing a process by which CO2 is captured out of ambient air. The process involves passing air through chemical filters or solutions, and then applying heat (and with one process, chemicals) to isolate the CO2 outside of the natural environment. The air returns to the environment without CO2.

DAC is one of many CDR options that can be used to offset emissions. Although DAC employs advanced technology, many CDR options employ natural processes. The CDR method that is currently most-widely used around the world is afforestation and reforestation (AR). This works by planting trees which then absorb carbon in their trunks until they die, at which point most CO2 is released into the atmosphere. Once a forest is planted it will sequester CO2 until it reaches a stable state, at which point the forest will store CO2, but will no longer continue to absorb it. Further, forests are vulnerable to disruptions like forest fires – which are likely to be exacerbated by climate change (IPCC, 2018). AR will continue to sequester additional CO2 only as long as more forests are planted.

An alternative to plant-based storage is geological storage, which is how CO2 is stored through DAC. CO2 can be stored underground in a number of geological formations, the largest being saline aquifers. These formations collectively contain enough storage space for between 1,678 GtCO2, and over 11,000 GtCO2, which is enough to store all CO2 that has been emitted globally since the industrial revolution, even at the lowest end of that range (Fasihi et al., 2019).

A method of CDR that combines natural and technological techniques is bioenergy with carbon capture and storage (BECCS). With this process, "biomass growth such as trees or crops first removes carbon during the growing cycle, followed by capture of emissions when burned as a fuel source, with injection and permanent storage underground as for other sources of CO2" (Larkin, 2021, p. 27). The benefit of this approach compared to afforestation or reforestation, is that whereas a forest will stop sequestering carbon once it is fully grown, BECCS can continually sequester carbon by harvesting and regrowing biofuel, avoiding carbon emissions upon a plant's death or harvest.

BECCS and DAC are both reliant on the capture and storage of CO_2 through technology. They also both present the ability to store an almost unlimited amount of CO_2, as long as there is storage space for it. There are advantages and disadvantages to both technologies. BECCS creates energy (such as electricity) while sequestering CO_2 which can then be used in the economy; meanwhile DAC is highly energy-intensive (IPCC, 2018). This means that while BECCS complements the transition to a clean energy grid, DAC runs counter to it, creating additional demand in a grid where existing sources of electricity are attempting to be replaced. BECCS is also better understood. Presently, DAC has only been deployed on a small pilot scale, with one large-scale plant expected to begin operating in 2024 at a scale of 1 Mt per year (Galluci, 2021; Sigurdardottir & Rathi, 2021). BECCS, by contrast, is based on better-understood technology, and is already being used to create energy while sequestering CO_2, capturing 1.5 Mt of emissions in 2019 (Consoli, 2019). Thermal coal power plants can also be retrofitted to use biofuel as their feedstock instead of coal, allowing for a way to employ BECCS on a wide scale that is significantly less capital-intensive than building built-for-purpose biofuel power plants (Qvist et al., 2021). This means that there is less uncertainty related to BECCS than to DAC.

There are also areas where DAC outperforms BECCS, a major one being land use. BECCS is highly land-intensive, as the biofuel must be grown before it can be used as energy. Land that is used for growing biofuel cannot be used for other productive uses, such as growing food and providing housing, or employing other land-intensive CDR measures like reforestation. The amount of land, water and fertiliser available are all constraints on amount of biofuel that can be used for BECCS. Further, agricultural output can often result in trade-offs, as increased crop yield has often come at the expense of other goods, including ecosystem services (Martin et al, 2018). While some studies have found a high amount of space available for tree or crop planting, some of these studies have been criticized for including productive grasslands as savannahs as possible candidates, even when they are acting as effective sources of carbon sequestration, havens for biodiversity, and essential habitat for some species (Veldman et al, 2015). Another complication is that BECCS is not the only application of biofuels for reducing emissions, and that using biofuel for BECCS limits the availability of biofuels to provide a cost-effective near-zero emission option in other sectors where abatement is difficult, such as long-haul freight or aviation.

By comparison DAC is not at all land-intensive, meaning uptake avoids the same competition for land (IPCC, 2018). Further, DAC can be built independent of the time and location of emissions; emissions from anywhere in the world can theoretically be offset anywhere else using DAC. A practical benefit is that DAC could be built directly on top of geological storage sites, eliminating costs for transporting CO2. By contrast BECCS requires inputs that must travel to a site, and the number of sites that are close to both biofuel production and CO2 storage is limited.

The IPCC has found that CDR is essential to meeting the Paris Agreement's 1.5 °C target (2018). They also note that neither DAC nor BECCS is essential for meeting that target, but that the absence of either makes meeting it more difficult and tends to be associated with much lower energy consumption (2018). More scenarios were able to meet the target without DAC than without BECCS. In contrast, a report from Rhodium Group suggests that both BECCS and DAC will be needed for the United States to achieve net-zero by 2045, and at least BECCS will be needed to achieve net-zero by 2050 in the United States (Larsen et al., 2019).

2.2.1 Key uncertainties in DAC's potential and cost in Canada

Required or not, DAC could potentially make the transition to a net-zero economy considerably cheaper. Not all emissions are equal economically, as some are much easier to get rid of than others while maintaining the same quality of life. Abatement in sectors such as electricity and transportation is relatively straightforward, as there are already zero-emission alternatives to fossil fuel technologies that have been widely implemented. However, when it comes to other sectors of the economy, especial industry, knowledge of how to decarbonize lags (Bataille et al., 2018). Heavy industry will be the hardest sector to decarbonize for a number of reasons, including "heterogeneity (i.e. almost every facility worldwide is different, producing a wide array of product qualities and variations), GHG intensity, trade exposure, cost sensitivity, and long lived facilities" (Bataille et al., 2018, p. 962). These industries will end up facing very high abatement costs relative to other sectors if they are unable to innovate affordable methods for lowering emissions. This would likely harm the Canadian economy by raising costs for emissions-intensive goods. The transition to net-zero may also raise demand for certain emissions-intensive goods, as wind turbines require steel, and batteries require rare metals (Diner, 2018). DAC may present a way to cheaply produce emissions-intensive goods, as low-cost DAC could allow emissions to continue as long as they are offset. Canada could theoretically achieve its goal of net-zero emissions while continuing to emit substantial volumes of CO2, as long those emissions are offset ton-for-ton by some kind of CDR.

The degree to which DAC will play a role in limiting global warming is heavily dependant on its costs, which are highly uncertain. Through improvements in technology and economies of scale, DAC capital costs are expected to decrease as more is deployed (Fasihi et al., 2019). However, it is not yet known how much and how quickly investments in and deployment of DAC will lower its costs (Canadian Institute for Climate Choices, 2021; IPCC, 2018). Several studies have attempted to estimate the costs of DAC and how quickly they are expected to fall. Many of these studies offer estimates within a similar range, but there are other dissenting opinions (IPCC, 2018; Fasihi et al., 2019). It is impossible to know which of these estimates will prove most accurate ahead of the technology's implementation. Some have advocated for direct public investment in DAC technology in order to ensure faster technological development, finding "evidence to demonstrate the potential for policy to propel DAC to market" (Larsen et al., 2019, p. 5).

Presently, DAC is mostly being funded by investors who see the technology as being profitable, necessary, or both in the long-term. However, some DAC firms have started raising market revenue. Climeworks in Iceland, the company responsible for the largest DAC facility currently in operation, is not yet profitable but has started generating revenue from customers such as Microsoft and Shopify, who are paying for DAC to offset their firms' emissions in an attempt to achieve net-zero emissions (Sigurdardottir & Rathi, 2021). The role that climate policy experts see for DAC in the short term is chiefly as an offset by removing CO2 (Canadian Institute for Climate Choices, 2021), although it could also be used to create emissions-neutral synthetic fuel (Larsen et al., 2019). In the long-term, DAC could potentially be employed to return the earth to its pre-industrial CO_2 levels (IPCC, 2018).

2.3 Carbon Offsets

The idea of 'offsetting' carbon emissions by compensating with reductions in another area has led to several schemes attempting to create a market for these offsets. These schemes attempted to allow a polluter in one place to avoid reducing their emissions by purchasing a credit indicating that they had paid for emissions to be reduced or avoid somewhere else. The implementation of this idea has mostly failed. Some famous examples include the Kyoto Protocol's Clean Development Mechanism, as well as Joint Implementation. The problem with these offsetting systems was that credits for both programs often did not represent real emissions reductions, with a study on Joint Implementation finding that 75% of credits issued in it likely did not represent real reductions (Song and Moura, 2019). These programs provided credits for activities like tree preservation or power plant efficiency upgrades. The problem with this, is that it is often extremely difficult to ensure that an offset was due to an offset payment. A power plant efficiency upgrade might have taken place anyway, and trees are often preserved for reasons other than CDR. A study of a more recent offset program found that 37% of trees preserved by the program were already part of protected areas (Song and Moura, 2019). This has made many policymakers dubious of carbon offset schemes.

However, DAC and BECCS, have unique qualities that make them ideal for carbon offsets. Trees provide many benefits aside from sequestering carbon, such as cooling cities and providing fruit, meaning that there are many reasons to plant or preserve them aside from their ability to store carbon. By contrast, there is no human benefit to capturing CO_2 from the atmosphere and storing it underground other than abating global warming. DAC and BECCS technologies are both extremely expensive. These activities will not occur on their own, and will only take place out of a desire for CDR. Further, CO_2 from BECCS and DAC will be stored underground. The integrity of this underground storage is strong, with an estimated 70% of stored CO_2 being able to remain safely stored for 10,000 years (IPCC, 2018). This relative permanence provides a certainty that other forms of offsets cannot. These unique characteristics make DAC and BECCS much better candidates for offsetting than other forms of CDR or emissions reductions. As long as an offset market around these technologies is rigorously regulated to ensure that stored CO2 is equal to the amount paid for in offsets, DAC and BECCS represent an effective way of allowing polluters to offset their emissions.

2.4 Key uncertainty in US abatement and its impact

The Paris Agreement calls for greenhouse gas emissions to be reduced so that global temperatures in the 21st century rise by a maximum of 2 °C, and ideally no more than 1.5 °C (Denchak, 2021). The mechanism to achieve this is through countries setting their own nationally determined contributions towards that target. The idea behind this mechanism is that ambition to lower emissions will steadily increase through transparency and peer pressure, rather than adversarial negotiation (Roberts, 2021). There is some evidence that this approach is working. The website Climate Action Tracker reports that existing policies and actions will limit warming to between 3.6°C and 2.1°C of warming (2021). This shows that existing policies are still insufficient, as the optimistic scenario of 2.1°C still fails to meet the Paris Agreement's target. However, the likely extent of warming is declining as more countries set increasingly ambitious targets and policies. RCP8.5 – the worst-case scenario modeled by the IPCC in 2014 which estimated around 5 °C of warming – becomes "increasingly implausible with every passing year" (Hausfather and Peters, 2020). Therefore, although global emissions are not presently on track to meet the Paris Agreement targets, it is still possible to achieve them as long as global policy action continues to ramp up (IPCC, 2018).

Canada's increasingly strong climate policies have created a sense of confidence in its commitment towards addressing climate change. This is not unique to Canada. China, responsible for more than a quarter of the world's total annual emissions, has committed to leveling off its rising emissions by 2030 and getting to net-zero by 2060 (Finamore, 2020). There is some evidence to believe that this commitment is credible and sincere, with one analyst pointing to the fact that the target announcement was highly publicized, and that China has a history of under-promising and over-delivering on climate commitments (Finamore, 2020). As China is a one-party state, this is unlikely to change.

There is similarly high confidence in the abatement plans of the European Union, the third largest emitter in the world when its members are grouped collectively. The EU has committed to the same net-zero by 2050 target as Canada and is implementing increasingly stringent policies to achieve that target, despite pushback from some members (Climate Action Tracker, 2021). Most-recently, Germany announced it was moving up its date for net-zero emissions in electricity from 2050 to 2035 (Delfs and Dezem, 2022). Though net-zero emissions are far from guaranteed, the trajectory of Canada, China, and the EU are clearly towards abatement.

United States is a different case. The recently passed Inflation Reduction Act is a considerable victory for climate action in the country home to the second highest greenhouse gas emissions in the world, containing provisions for the abatement of emissions across the US economy. A preliminary study estimates it will “cut US net greenhouse gas emissions down to 31% to 44% below 2005 levels in 2030—with a central estimate of 40% below 2005 levels—compared to 24% to 35% under current policy” (King, Larsen, and Kolus, 2022). There are several caveats, however. Although the bill will quicken the pace of US abatement, the 2030 US emissions target is 50% below 2005 levels, meaning that even with the bill, the US is still not on track to meet its climate commitments.

Furthermore, the Inflation Reduction Act does not contain a carbon price (though it does contain a price on methane, another potent greenhouse gas) or serious emissions regulations, instead relying mostly on spending initiatives. These policies may be able to make the difference in abating less expensive emissions, such as in switching to lower emissions sources of transportation and electricity generation but will likely face bigger hurdles in dealing with more difficult-to-abate emissions, such as those produced by heavy industry. There, near-zero emission production methods are still largely in their infancy, and typically much more expensive than traditional methods. It remains to be seen if near-zero production will be able to achieve lower costs than traditional methods. If they cannot, then prices or regulations will likely be necessary to make-up the difference. The Act has successfully put the US on a positive trajectory, but further legislation will be required to achieve net-zero emissions. The likelihood of that legislation is dubious.

The United States is deeply divided on the issue of climate change. During the 2020 presidential election, Donald Trump ran on a platform of supporting the oil and gas sector and cutting Democratic environmental regulations, while his opponent Joe Biden ran on a platform of setting a target of net-zero emissions by 2050 and implementing policies to achieve that target (Moore, 2021). The Inflation Reduction Act ultimately passed through the Senate by the barest possible margins, as every Democratic Senator voted for the Act, and every Republican voted against. This put the Act at the mercy of the most moderate Democratic Senators, leading to a policy that was considerably watered down compared to the legislation Biden originally campaigned on (Prokop, 2021; Kane, 2022).

As achieving net-zero emissions is an enormous undertaking, it will require sustained action on emissions. If the Inflation Reduction Act is the last piece of federal climate legislation, the country will likely be unable to meet its climate commitments. If Republicans retake the executive and legislative branches of the Government, further action is highly unlikely, and even the Inflation Reduction Act itself could be repealed. Some US states have also begun implementing climate policies, but only 12 currently have a price on carbon (Centre for Climate and Energy Solutions, 2021). These states only represent about 22% of US emissions – even leaving aside the fact that not all the emissions in those states can be priced as a result of the trade exposure to heavy industry – leaving most emissions unpriced (Energy Information Administration, 2021). Furthermore, the Trump administration repeatedly fought against state-level climate legislation, and a future Republican administration could do so again (Nilsen, 2019). Federal leadership is therefore necessary. Sustained action on climate change in the United States will require either significant and sustained federal Democratic victories, or a change in Republicans' views on climate change. While neither of these is impossible, both are currently unlikely. This set of circumstances has led to an high degree of uncertainty with regards to US commitment to abatement on climate change.

The direction of US climate action carries serious implications for the Canadian economy. The economies of Canada and the United States are tightly knit, enjoying the largest bilateral trade relationship in the world, with $1.6 trillion U.S. of trade and investment in 2020 (International Trade Administration, 2021). The United States is Canada's largest trading partner by far, with more than 70% of Canadian exports and 60% of Canadian imports in 2021 being with the United States (Global Affairs Canada, 2021). Canada's close connection with an economy that is more than ten times larger means that much of the Canadian economy is dependent on economic trends in the United States.

A major component of this bilateral relationship is energy. The energy sector makes up more than 10% of Canadian GDP. Exports make up 81% of Canadian crude oil production, 43% of natural gas, 75% of uranium and 10% of electricity generated in Canada. In total, close to 60% of Canadian energy production goes to the United States. In the other direction, 74% of Canadian energy imports come from the United States; this accounts for 22% of Canadian oil consumption and 26% of natural gas consumption (Langlois-Bertrand et al., 2021). The kinds of goods – and related services – that are demanded in the United States will have a major impact on what is produced in Canada. Likewise, the kinds of goods produced in the United States will have a major impact on the availability and price of goods in Canada. The degree to which the US abates its emissions could have a major impact on determining which Canadian industries will be competitive over the next 30 years.

More generally, it is also likely that US abatement would impact the size of its economy. It is generally accepted that abating emissions to net-zero will result in smaller economic growth than no abatement (Field and Olewiler, 2015). Trade is beneficial for economic growth, providing domestic producers with a larger export market, and domestic consumers with cheaper goods through imports (The World Bank, 2018). A smaller US economy lowers the demand for the export of Canadian goods, as well as the supply of cheaper American goods. Because of this, US abatement could lead to a smaller Canadian economy by limiting how much we are able to trade.

A further consideration is that the United States moving towards net-zero will impact which technologies they invest in. Rather than investing in improved methods of oil-recovery or fossil fuel engines for instance, they might invest in electric vehicles and solar power. Given how tightly knit the Canadian and US economies are, the nature of technological innovation in the United States will impact Canadian technology as well.

2.5 US Abatement and DAC

There is an important overlap in the uncertainties surrounding DAC costs and US commitment to abatement. The degree of global investment and deployment of DAC "is a significant but highly uncertain factor in overcoming challenges to the successful commercialization and scaling of [DAC]" (Canadian Institute for Climate Choices, 2021). The United States is the world's largest economy and second-largest polluter, and a federal US net-zero strategy would likely involve dramatically more investment in DAC than under the status quo. US firms are already investing in DAC (Sigurdardottir & Rathi, 2021). A federal US carbon price would likely expedite this trend by providing a direct financial incentive for US companies to purchase DAC as an offset. There is also evidence that US commitment to abatement would involve some direct investment in DAC. The 45Q tax credit was introduced as a subsidy for carbon capture and storage technology and carbon sequestered through DAC will also be eligible for the tax credit (Bomgardner, 2020; Carbon Engineering, 2019). In addition to this existing DAC subsidy, the BBB Act is currently proposing further public investments for carbon capture and storage technology (Friedman & Davenport, 2021). Given the government's willingness to invest in DAC and similar technology already, it is reasonable to speculate that a federal climate strategy could involve further investments. One study found that investing $240 million from the US federal government into DAC could make the difference between whether DAC becomes a competitive industry (Larsen et al., 2019). These public and private investments in DAC could lower its costs through economies of scale in production and improvements in the technology through learning experience (Fasihi et al., 2019). This would in turn lower costs for DAC deployment in Canada.

2.6 Recent Assessments of DAC

To better understand the state of modelling surrounding the role of DAC, US abatement and the uncertainties of these variables in Canada's pathway to net-zero, I conducted a literature review of recent net-zero modelling reports. I reviewed the two most up-to-date reports that model Canada's pathways to net-zero emissions, *Canadian Energy Outlook 2021* by the Trottier Institute and the Canadian Institute for Climate Choices' (now the Canadian Climate Institute) report *Canada's Net-Zero Future*. I also examined two net-zero modelling reports with a global focus, the International Energy Agency's 2021 report *Net-zero by 2050*, and the International Panel on Climate Change's *Special Report on Global Warming of 1.5°C*. Both reports provide recent analysis on global pathways to net-zero conducted by respected international organizations.

2.6.1 Trottier Institute – *Canadian Energy Outlook 2021*

The Trottier Institute's report examines five different scenarios in which Canada respectively does not institute an abatement policy, maintains current abatement policy, and attempts to achieve net-zero in 2045, 2050 and 2060. The study provides a comprehensive look at how the energy transition will play out in the Canadian economy. Little analysis was performed on the impact of American abatement uncertainty, however. The authors note the importance of US trade to the Canadian economy throughout the study, but in discussing how they modelled the US importance, they note only that they assumed "decreases in demand for exports result from price assumptions […] reflecting a certain level of climate action around the world" (Langlois-Bertrand et al., 2021, p. 05). There is no explicit mention of how they modeled the United States alone. When it comes to DAC, there are only hints to how it was modelled. On pages 105, 111, and 114 the report refers to how changes in the use and availability of other technologies increase or decrease the need for DAC, or how in others a problem leads to "resort[ing] to DAC" (p. 105-114). I infer from this language that DAC is used as a backstop technology. This means that they did not model separate prices for DAC, but rather modeled other variables, and assumed a certain level of DAC in order to arrive at the target.

2.6.2 Canadian Institute for Climate Choices – *Canada's Net-Zero Future* (2021)

This report assesses several pathways through which Canada could meet its target of net-zero emissions by 2050. Like the Trottier Institute's report, this report conducts very little analysis of abatement in the United States and how it will affect Canada. The study's annex includes summaries of reports examining US abatement pathways, and the companion piece to the report notes that gTech, the model used for analysis, is capable of modelling US emissions, but no further detail on assumptions of US abatement is provided (Canadian Institute of Climate Choices, 2021; Navius Research, 2021, p. 6). Unlike Trottier's report, this report does explicitly model DAC in an uncertainty analysis and does so in detail. DAC was made unavailable in some scenarios, while in others DAC was modelled with its capital cost starting at $368 per tonne of CO2 and declining to a potential floor of $125 per tonne of CO2 in 2050 (Navius Research, 2021, p. 20). The report discusses in detail how the costs of DAC interact with other variables in impacting Canadian abatement, with the report's companion piece labelling DAC a key driver of emissions reductions. DAC uncertainty has been modelled extensively here.

2.6.3 The International Energy Agency – *Net-zero 2050* (2021)

This report models what is needed globally to achieve net-zero emissions by 2050 using the World Energy Model and Energy Technology Perspectives models. Rather than exploring multiple pathways, the report goes into extensive detail on the pathway that it deems "the most technically feasible, cost-effective and socially acceptable" (IEA, 2021, p. 3). It provides extensive analysis on what technologies will need to be deployed to meet the net-zero target, as well as what policies are needed to see that deployment. The report talks generally about the kind of changes needed but does not do this specifically on a country-by-country basis, so there is no mention of abatement of a single country like the United States. In discussing DAC, the report notes that direct air capture and storage represents one of the three largest opportunities for technological innovation, providing vital contributions to CO2 reductions (IEA, 2021, p. 15). As the report focuses on only one pathway however, DAC uncertainty is not explored.

2.6.4 Intergovernmental Panel on Climate Change – *Special Report on Global Warming of 1.5°C* (2018)

This report examines the impacts of what 1.5°C would look like for the world, as well as what kinds of technological and policy measures are compatible with no more than 1.5°C of warming. The report does not explicitly discuss the abatement measures of specific countries like Canada or the United States, but it does repeatedly discuss the role of DAC in a world of no more than 1.5°C of warming. All pathways modelled in the report that are consistent with that target required at least 100 gigatons of CDR, and up to 1000 gigatons of CDR, over the 21st century, although the report considers all methods of CDR and not just DAC. In discussing DAC specifically, the report notes that two major challenges are the unknown costs and the amount of energy DAC requires (IPCC, 2019). The report offers a wide range of between 0.5 and 5 gigatons of CO2 sequestered through DAC per year by 2050 (IPCC, 2019). This report notes that expert opinion on DAC is highly fragmented and that DAC's "possible role in cost-optimized 1.5°C scenarios is not yet fully explored" (IPCC, 2019, p. 346). There is little deep analysis of how DAC uncertainty will impact the energy transition, especially as it pertains to individual countries.

2.7 Need for Study

All four reports I reviewed confirm that DAC, and the degree to which its costs allow it to be a viable option, will have an enormous impact on the path to net-zero emissions, both in Canada and globally. The Trottier Institute's report also emphasizes the importance of the United States' economy to Canada's economy, and especially to the Canadian energy sector. The direction of these variables could have a substantial impact on the shape of Canadian abatement. Despite the importance and uncertainty of DAC and US abatement, the amount of modelling that has examined either of these variables is limited. None of these reports modelled the uncertainty surrounding US abatement, and only the Canadian Institute of Climate Choices' report explicitly modelled DAC uncertainty. This suggests a value to exploring the role these uncertainties will play in the Canadian economy's transition to net-zero emissions.

Chapter 3. Methodology

This chapter provides a brief overview of what tools I used to conduct my research, why I used them, and how they work. I start by explaining what energy-economy modelling is, and why I chose to use it to conduct my analysis. I provide an overview of the gTech model and why I selected it, as well as a more in-depth look at the two most relevant elements of the model for my research, the declining capital cost function and the way regions are modelled. Lastly, I describe my eight scenarios and the decisions I made in setting up my modelling runs.

3.1 Energy-Economy Modeling

A variable like DAC cost is worth exploring because it could have such a large impact on energy and emissions policy. Yet addressing the impact of two highly uncertain variables three decades into the future is an extraordinary task. Jaccard notes that:

"Since technological change is a long-run phenomenon that occurs as society's capital stock grows and is renewed, the likely outcome of alternative policies is inevitably uncertain, and more so the further one projects into the future. But even though future technological evolution and the behavior of consumers and businesses are uncertain, this is no excuse to engage in unsupported speculation about the future adoption of new technologies. A speculative or wishful scenario of the future, with negligible connection to real-world evidence, is ultimately unhelpful to policy makers and may lead to [induced technological change] policies that are ineffective or have unintended consequences" (2009, p. 311).

Models allow researchers to examine the future in a manner that is grounded in evidence and experience. I chose to use an energy-economy model for my study, because of the suitability of these models for the analysis of future uncertainties. Quantitative energy-economy models are frequently employed to explore a range of possible futures under different assumptions (Sovacool et al., 2018). Hoyle provides an overview of energy-economy models, loosely defining them as: "a network of mathematical relationships that describe a system. Models combine relationships (e.g., equations) with data and parameters. Parameters are variables embedded in the relationships that are internal to the model, and that can be estimated from data. In other words, models use parameters to convert real-world data into values that can be input to relationships, which in turn describe a system." (2020, p. 15).

Notably, models are based on real-world data, and are able to determine the outcome of a huge number of interwoven variables. These facts mean that we are not simply speculating about the future, but making an estimate based on the best-available data we have in the present.

The ability of models to deal with a huge number of variables is also important, as it means that the likelihood of unintended consequences from an assumption about a particular technology or a policy is drastically reduced. Major policies and technologies can often have spillover effects in areas of the economy that are seemingly unrelated. Attempting to analyze the impact of a policy or technological assumption through a spreadsheet tool could be less reliable. If the assumptions in that spreadsheet are developed independently, without reflecting the dynamic interdependencies of these assumptions, the results may not account for consequences that were not predicted by the researcher. Quantitative energy models are more robust, accounting for dynamic interdependencies of different assumptions. This is another major benefit to energy-economy modelling; unexpected consequences of different assumptions can be found and analyzed where they might not be with other research methods. This makes them well-suited to analyzing policies and technologies that have a major impact across a country's economy whose consequences might not be predictable.

3.2 The gTech Model

I conducted my research using the gTech model. gTech was developed and continues to be updated by Navius Research, a Vancouver-based consultancy. gTech is a computable general equilibrium (CGE) model. CGE models simulate regional, national, or international economies by showing transactions between different parts of the economy with equations determining how each sector behaves. These equations are based on the assumptions that firms are profit-maximizing, consumers are utility-maximizing, and that the economy tends towards an equilibrium; supply and demand will balance each other across all markets (Sovocool et al., 2018).

While containing all of the aforementioned traditional CGE model components, gTech is also technologically explicit; meaning that it represents individual, energy-using technologies and their stocks in each simulated time period. The model simulates competition between different technologies for market share, and ultimately the energy used and emissions generated within the economy. The behaviour of these equations is defined by their parameters, which are estimated based on historical market data. Technological explicitness in a general equilibrium model means that total inputs equal total outputs for individual technologies. For instance, heavy oil may be produced in Alberta, represented as an output. That oil may be used as an input for oil refining sectors in Alberta or exported to other regions where it will be used as an input for various economic processes there. Importantly, the technologies used to extract, refine, and transport oil are all represented in terms of their costs, lifetimes, energy-use, and emissions.

gTech is uniquely well-suited for my research. For modelling DAC, its technological explicitness is key, as it allows an accurate picture of what sort of role this particular technology will play in the energy transition under different conditions. DAC costs will play a major role in the choice that economic actors make between abating, paying the carbon price, and offsetting, and both the technological explicitness and general equilibrium features of gTech allows this choice to be represented endogenously (simulated within the model). Most energy-economy models contain only BECCS as a CDR option, while gTech also contains DAC as a parameterized sector (Keller, 2017; IPCC, 2018).

Just as importantly, gTech is one of very few models that examines more than one country, containing a model of the United States' economy, and how it interacts with Canada. Lastly, as a CGE model, gTech allows me to examine the impacts of both of my variable dimensions across the entire Canadian economy. I can examine different industries and see how they perform based on the variability of US abatement and DAC cost. This allows me to understand the role of these variables on a sector-by-sector basis, as well as across the economy.

3.2.1 Declining capital cost

Typically, costs of installing a technology are expensive when the technology first enters a market but decline over time. This decline in the cost of new technology is modelled using a declining capital cost function. This function represents how an accumulation of experience with the production and use of a technology during its diffusion into a market result in a lower capital cost. This decline has been empirically observed for a variety of technologies involved in the energy transition, such as solar photovoltaics, wind power, and biomass for electricity (Loschel, 2002). Many technologies also benefit from economies of scale, lowering their costs as deployment widens. There is already evidence that at least one form of DAC technology will benefit from these economies of scale (Keith et al., 2018).

gTech's declining capital cost function for DAC reduces its cost based on stock that has already been deployed and is in use. The decline in cost is highest at the beginning of the technology's deployment, with the cost reduction diminishing as more DAC uptake occurs throughout the economy. Eventually, the adoption curve reaches an asymptote, and DAC capital costs are unchanging thereafter. This function only affects how the model treats DAC capital costs, and has no impact on DAC operating, maintenance and fuel costs, or intangible impacts on DAC availability.

The shape of a declining capital cost function is unique to each technology in the model and is defined by the parameter values used, which are estimated based on research or data on each technology. gTech has several pre-programmed estimates for what the shape of the DAC declining capital cost curve will look like. These estimates are based on the work of Keith et al. (2018), Fasihi et al. (2019), and Larsen et al. (2019). All of these papers assess what the theoretical minimum cost of DAC technology will be, while Fasihi et al. (2019) also examine how quickly costs will decline based on the level of investment in DAC. Due to the high uncertainty surrounding DAC's declining capital costs discussed in Chapter 2, it is not possible to be completely certain on how quickly or to what degree DAC capital costs will fall.

3.2.2 Regions

gTech simulates the energy-economies of both Canada and the United States, but is mainly used to study Canada, with the American energy-economy being more regionally simplified by comparison. The model simulates 12 regions in total: the 10 Canadian provinces individually, the three Canadian territories as an aggregated region, and the United States as one region. These regions interact "via (1) the trade of goods and services, (2) capital movements, (3) government taxation (within Canada only) and (4) various types of "transfers" between regions" (Navius Research, 2021, p. 6). Trade occurs based on supply and demand for goods within the simulated regions, with added costs and margins associated with transportation and interregional tariffs. In some instances, such as for electricity and oil trading, transmission line and pipeline infrastructure are also a requirement for trade. Notable for this study is that international DAC offsets are not permitted; firms demanding DAC to offset their emissions may purchase it in other provinces, but not in another country. For instance, an emissions-intensive manufacturing firm in Ontario may offset their emissions by purchasing DAC credits in Alberta but cannot do so through DAC in the United States. The main type of "transfer" in the model that is relevant for my study, is the transfer of policy credits. For instance, a Canada-wide cap-and-trade system could allow for the trading of credits between provinces. If firms in one province, such as Quebec, are able to decarbonize quickly, they may sell credits to firms in another province, such as Alberta, which might decarbonize more slowly. This allows provinces with more expensive emissions to decarbonize more slowly, having their emissions covered by permits from provinces with cheaper emissions.

3.2.3 Biofuel supply

gTech models a number of different bioenergy sources, including first generation fuels derived from crops like corn or renewable natural gas from landfills, and second-generation biofuels derived from forestry harvest residue and agricultural residue leftover from harvest like treetops and corn stover. The availability of residue for second generation bioenergy is defined for each source each year as a function of agricultural and forestry activity. Third generation bioenergy derived from algal biomass are not included in the model. Agricultural production in gTech is constrained assuming a fixed land-base, so it will not allow runaway production of biofuels. Production is assumed to take place without harming soil fertility. In 2015, gTech has fixed assumptions for the amount of residue available for bioenergy, while in future years, availability is function of agricultural and forestry activity. Bioenergy production is therefore not fixed in gTech, but has significant constraints placed upon it to mimic the fact that biofuels are land-intensive, limiting the extent to which production can be expanded. Accordingly, the bioenergy market in gTech is relatively inelastic.

3.3 Modelling Assumptions and Scenarios

3.3.1 Scenarios

All my scenario runs begin in 2015 and finish in 2050, with gTech simulating in 5-year increments. I introduced no policy changes for historical years 2015 and 2020. I created eight different scenarios of Canada's transition to net-zero based on the uncertainty surrounding two variables. These variables are: (1) whether the United States will commit to abating greenhouse gas emissions to net-zero, and (2) how quickly DAC capital costs will decline as it is implemented – that being my hypothesized shape of its declining capital cost function.

For the United States, I modelled two alternative trajectories. The first I call United States no abatement (USna). Here, the US does not implement any major climate legislation. No new legislation is introduced, and existing state-level legislation, such as the cap-and-trade systems that are currently in place in 12 US states, is assumed to be repealed. While this might be unlikely, the hostility of the Republican party towards existing climate legislation makes this a legitimate possibility. The incentives introduced by the Inflation Reduction Act were also not modelled, as the modelling I conducted predates its passage. The second trajectory I call United States net-zero (USnz). In this trajectory, the United States introduces a federal cap-and-trade system for GHG emissions in 2025, becoming progressively more stringent over time. The caps of this system are set to meet the United States' two announced climate targets of a 50% reduction of emissions by 2030 relative to 2005 levels, and net-zero emissions by 2050. All revenue from this policy is returned to US households equally. I did not model land-use change explicitly, instead assuming that by 2050 the United States is able to sequester between 950 Mt and 1020 Mt (depending on scenario) from land-use change. This is slightly higher than the historical average of US land-use change emissions, which varied from between 792 Mt and 909 Mt between 1990 and 2019 (EPA, 2021). Other countries such as Canada have implemented widespread tree-planting programs in conjunction with stringent emissions policies (Natural Resources Canada, 2020). I assume that the United States will do this as well, accounting for the difference between historical and assumed land-use change emissions.

Damages caused by climate change will have a significant impact on the global GDP, with more emissions resulting in increased damages at an exponential rate. One study estimates that 3.2°C of warming will result in a North American GDP 9.5% lower than a world without climate change, while 2°C of warming only results in a North American GDP 3.1% lower than without climate change (Swiss Re Institute, 2021). As the US represents a major share of global emissions, it is likely that in scenarios where they abate to net-zero, climate-related costs would be significantly lower than in scenarios where they do not. Additional US abatement would likely have spillover effects resulting in further global abatement as a result of the country's economic and political power (carbon duties on countries without strong climate policy, for instance). However, this study does not examine the economic damage from climate change, only costs associated with abatement. GDP costs from the impacts of climate change are therefore assumed to be zero across all scenarios, even if this would likely not be the case in reality.

I assume that DAC becomes available starting in 2030, as it is very unlikely that the technology will become commercially viable prior to that (Fasihi et al., 2019). For DAC cost declines, I modelled four alternative trajectories based the declining capital cost function used for DAC. These trajectories are based on the work of Keith et al. (2018), Fasihi et al. (2019), and Larsen et al. (2020). Energy, operation, and maintenance costs of DAC are assumed to be identical across all trajectories.

1. noDAC. The first trajectory assumes that DAC is not available and is referred to as no DAC.
2. expDAC. The second trajectory assumes that DAC is available, but that the most pessimistic estimates of DAC cost declines prove to be accurate, with a much slower decline in cost than in other trajectories. I refer to it as expensive DAC.
3. refDAC. The third trajectory is based on the best-estimate of Navius Research for DAC cost decline; I refer to it as reference-cost DAC. It represents the most plausible estimate of declining DAC costs based on existing literature.

4. chpDAC. The fourth trajectory assumes that the most optimistic estimates of declining DAC costs prove accurate, with rapid cost reductions occurring over a relatively short period . I refer to it as cheap DAC.

I chose to model chpDAC and expDAC because they represent the highest and lowest current estimates of what declining DAC capital costs could look like. refDAC also made sense to model, as a more realistic midpoint between these extremes. I also decided to run the model without DAC to examine how much of an impact the technology has, especially compared to expDAC. For the United States abatement policy, I chose only the extreme trajectories, either getting to net-zero or not acting at all. This is because unlike with DAC, where cost decline estimates and trajectories can be extracted from the literature, there is little political compromise to be found between those demanding net-zero emissions, and those indifferent to climate change.

The four trajectories for DAC cost decline and two trajectories for US abatement are then paired up with each other, resulting in the eight scenarios displayed in Table 1. In scenario refDAC-USnz, for instance, the United States has implemented policies to get to net-zero by 2050, and DAC capital costs follow the best-estimate trajectory. Going forward, I will be referring to my scenarios based on the codes displayed below.

Table 1 – Overview of scenarios

	United States no abatement	United States net-zero
No DAC available	noDAC-USna	noDAC-USnz
Highest DAC costs	expDAC-USna	expDAC-USnz
Reference DAC costs	refDAC-USna	refDAC-USnz
Lowest DAC costs	chpDAC-USna	chpDAC-USnz

3.3.2 Canadian Policies

I held Canadian abatement policies constant throughout these scenarios. My aim with these policies was to meet Canada's abatement targets of reducing emissions 40% below 2005 levels by 2030 and achieving net-zero emissions by 2050. I assumed 100 Mt of emissions would be offset by land-use change in 2050, which is slightly less than was assumed by the Canadian Institute for Climate Choices (2021). I sought to achieve Canada's targets by implementing policies that I think are likely to be a part of its emissions reduction. This mostly involved policies that have already been announced, or those that are currently being considered by the Canadian government. By modelling a likely pathway of Canadian abatement, I was then able to analyze the impact of the two variables I modelled on Canada's path to net-zero. One policy that is currently being explored that I chose not to model was carbon duties on countries that are not abating (Department of Finance, 2021). This is because whether or not these policies are implemented would be dependent on US abatement, and I wished to hold all Canadian policies constant across scenarios.

The key driver of emissions reductions that I modelled was a cap-and-trade system replacing Canada's carbon tax in 2025. Even though Canada is really using a carbon tax, a cap-and-trade scheme is very similar in its effect to a carbon tax, as both act as a carbon price, creating a cost to polluting carbon across the economy. A cap-and-trade system works by auctioning off permits that allow the holders to pollute a set amount of carbon. By controlling how many permits are auctioned off, the government controls the amount of pollution that can be emitted. The caps I set are shown in table 2. Permit-holders are then allowed to buy and sell pollution permits from each other, which is what creates the carbon price. The key difference between this and a carbon tax is that implementing a carbon tax sets a known price that induces an unknown level of emissions reductions, while implementing a cap-and-trade system sets a known level of emissions reductions, with an unknown corresponding carbon price. I chose to use a cap-and-trade scheme because it ensures that all runs are able to reach the same emissions levels. This allows me to examine what the impact of the same amount of abatement has on the carbon price and economy, which is what I'm interested in for this research. The carbon price should vary depending on the cost of abatement, which is noteworthy when examining the impact of DAC because it offers polluters the ability to offset.

Table 2 – Canadian Emissions cap (in Mt) by year

Year	2025	2030	2035	2040	2045	2050
Emissions Cap in Mt	600	450	350	250	180	100

I assumed that 90% of the revenue from this system would be returned to Canadian households equally, while 10% would be used to reduce corporate income taxes. I also modelled the output-based pricing system already implemented by the federal government along with this cap-and-trade system. The aim of this policy is to shield Canadian industry from application of the carbon price to all emissions because heavy industry faces uniquely difficult abatement conditions (Government of Canada, 2021c) No increases in stringency have so far been announced for this policy, so I assumed that intensity benchmarks for both combustion and process emissions would get 20% more restrictive every 5 years until 2040, and then 10% more restrictive every 5 years until 2050 when the system is removed.

I also modelled several emissions regulations. Some of these have already been implemented by the federal government, while others have only been discussed. These include a national mandate that 50% of light duty vehicles be zero-emission by 2030, and 100% by 2035. I modelled a similar mandate for heavy-duty vehicles getting to 100% by 2040. I also imposed a ban on new coal power plants starting in 2030, alongside a mandate requiring 90% of Canadian electricity to be zero-emission by 2030, and 100% by 2035. I imposed a Canada-wide standard on the emissions-intensity of fuels starting in 2025 and becoming progressively more stringent over time. The emissions-intensity levels and timeline for increases in stringency were based on those already in place and announced in British Columbia. Lastly, I kept existing provincial legislation in place except where I imposed a similar piece of federal legislation. For instance, Quebec's cap-and-trade system was kept in place until 2020 but repealed in 2025 at which point it was replaced with the federal cap-and-trade system.

Chapter 4. Results

4.1 Key results

The results of the modelling show that Canada reaches its emissions targets, including net-zero by 2050 across all scenarios. The United States also reaches net-zero emissions in scenarios where that target is set. Both scenarios without DAC are able to meet net-zero emissions, demonstrating that DAC is not essential for achieving that target in Canada. This finding is consistent with the IPCC's modelling result that DAC is not necessary for achieving net-zero emissions globally (2018). However, higher Canadian DAC deployment is positively correlated with higher Canadian GDP.

The amount of DAC deployed varies across the scenarios. US abatement and cheaper DAC correlate with more DAC deployment. Cheaper DAC cost (and consequently higher DAC deployment) correlates positively with Canadian GDP. The impact of US abatement on Canadian GDP is mixed, correlating positively in scenarios with cheap or reference cost DAC, and negatively with expensive DAC and no DAC availability. A higher carbon price in Canada correlates with lower GDP. A higher carbon price forces Canadian firms to cut emissions more deeply, forcing them to find more expensive low-emission alternatives to traditional technology. Canadian GDP varies by about ten percent, or $255 billion, between chpDAC-USnz and noDAC-USna, the scenarios with the highest and lowest respective GDP.

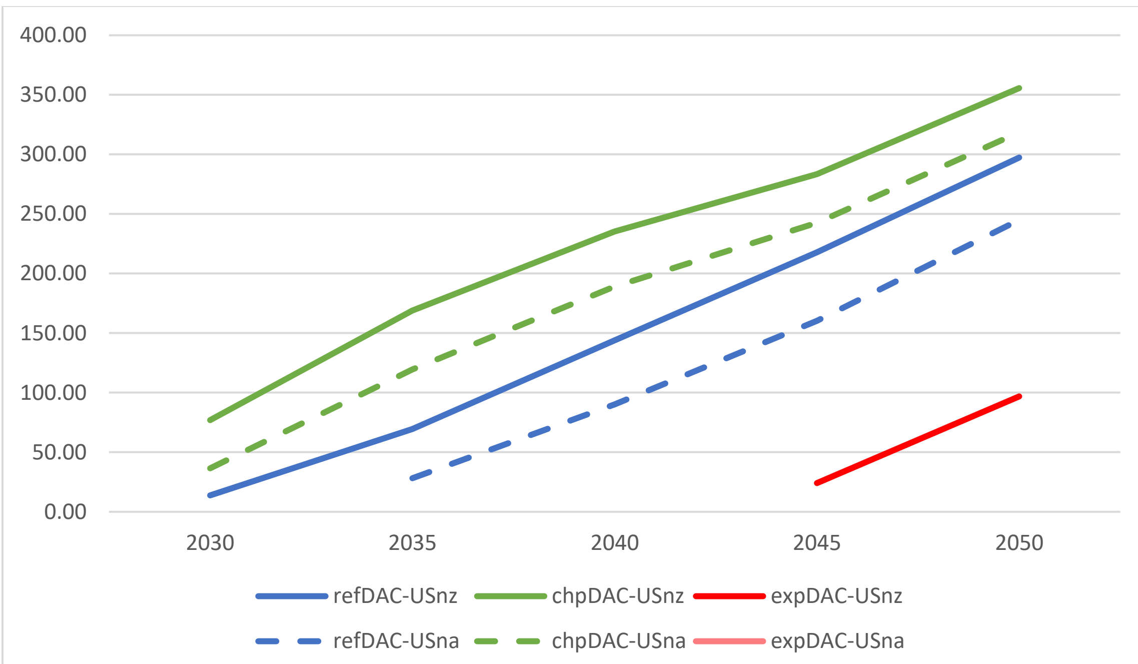
4.2 DAC deployment

DAC becomes available to be deployed as a technology in the model after 2025. Only chpDAC-USnz, chpDAC-USna, and refDAC-USnz see more than a negligible amount deployed in 2030. refDAC-USna sees large-scale DAC deployment beginning in 2035, while expDAC-USnz only sees large-scale deployment beginning in 2045. Other scenarios do not see DAC deployment.

The amount of DAC deployed in 2050 ranges significantly across the scenarios where it is available from less than 1Mt in expDAC-USna, to 356 MtCO2 in chpDAC-USnz. 356 Mt of CDR is a substantial amount of DAC; it would be enough to offset nearly half of

Canada's 730 Mt of emissions in 2019. Although large, this amount is within the range offered by the Canadian Institute for Climate Choices (2021). Figure 1 shows the amount of DAC deployed in Canada across various scenarios. Years in which less than 1Mt is deployed are not displayed on the graph, which is why expDAC-USna is absent. A notable feature of the graph is that the slope of DAC uptake is similar across all scenarios. This is unsurprising due to the cap that was set on Canadian emissions, which is increasingly stringent until 2050 when it falls to zero.

Figure 1 – Emissions (in MT) sequestered with DAC by 5-year intervals (non-cumulative)

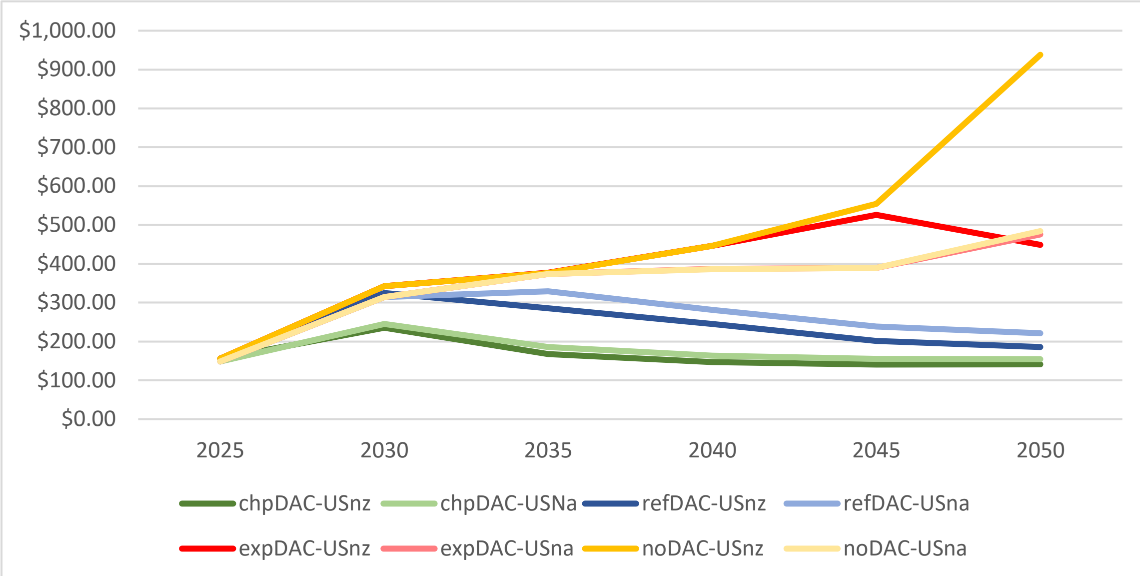


Cheaper DAC costs and US abatement both correlate positively with DAC uptake in Canada. In every scenario, US abatement results in higher DAC uptake than no US abatement for the same DAC costs. This result is due to demand for DAC in the US. Although US demand for DAC cannot be fulfilled by DAC in Canada, the increased deployment of DAC in the US results in more investment and faster technological learning than when Canada is the only market for DAC represented in the model. In turn, this investment has the spillover effect of lowering the capital costs of DAC in Canada, resulting in faster and wider deployment. The difference between expDAC-USnz and expDAC-USna is most striking. In expDAC-USna, DAC is not deployed on a wide scale, with the technology remaining too expensive to ever become a competitive industry. The amount of DAC deployed in expDAC-USna is negligible, even in 2050. With expDAC-USnz, however, the additional demand for DAC in the US lowers the technology's capital costs by enough that it enters the market in 2045, offsetting just under 100 Mt of emissions in Canada by 2050. This means that if the highest present estimates of DAC capital cost in the literature hold true, DAC may need to demand in other countries to become a competitive industry in Canada. While US abatement is a significant factor in determining DAC deployment, DAC cost is the more significant determinant. More DAC is deployed in chpDAC scenarios than in refDAC scenarios, and more DAC is deployed in refDAC scenarios than expDAC scenarios regardless of US abatement. This finding means that the independent speed at which DAC costs decline are a larger determinant in its pathway to a competitive industry in Canada than whether the US attempts to achieve a net-zero economy.

4.3 Canadian Carbon Price

The Canadian carbon price is qual to the price of pollution permits needed to meet the emissions cap under each scenario. That price fluctuates by an enormous degree across scenarios and over time. This is shown in figure 2, which depicts the price of a pollution permit in Canada by scenario over time. The fluctuation in price is showing the cost of abatement based on the emission cap. The results show that the cost of abating a ton of CO2 varies according to DAC costs and US abatement.

Figure 2 – Canadian carbon price by scenario (in CAD), 2025-2050



The carbon price has two different major influences pulling it in opposite directions across scenarios: tightening emissions caps, and declining costs of technology compatible with a net-zero economy, particularly DAC costs. The emissions cap is constantly dropping, requiring increasing emissions reductions. Without any other factors, this will result in a rising carbon price. This works as an incentive for further abatement, since a higher carbon price with abatement costs held constant makes abatement the comparatively cheaper option for some emissions. At the same time, DAC costs decline as a function of deployment. This means that DAC capital cost is being lowered due to increased deployment in scenarios where it is available.

Profit-maximizing firms will always choose to handle pollution as cost-effectively as possible, whether that is through abatement, offsetting or paying the carbon price. DAC represents a backstop technology here, meaning that its cost represents the ceiling of the costs of achieving a given GHG reduction target. Cheaper DAC lowers the carbon price associated with a given emissions cap because when the price of DAC is lower than the price of abating, firms will choose to purchase DAC instead of abating or paying the price. If DAC is cheap and accessible, and its cost declines with greater market penetration, then once its costs become competitive with the carbon price, it will go on to apply downward pressure on the carbon price. Cheap DAC in a competitive market with a cap-and-trade system will result in the marginal cost of abatement, the carbon price, and the cost of DAC all being roughly equivalent. This dynamic explains why the carbon price eventually begins falling in scenarios with cheap or reference-cost DAC.

The shape of the carbon price curve for both scenarios with cheap DAC shows the impact of a backstop technology. The carbon price reaches its peak in 2030 (the year in which DAC becomes available). With US abatement to net-zero that peak is $235 per ton of CO2, and without US abatement it is $245 per ton. After 2030, the carbon price begins to decline for both scenarios, eventually becoming nearly flat from 2040 to 2050. This is the result of DAC acting as a backstop technology. Although the emissions cap is tightening as much for these scenarios as for others, chpDAC-USnz consistently has a slightly lower carbon price than chpDAC-USna, due to US abatement driving the DAC price slightly lower more quickly.

Both scenarios with reference-cost DAC see a very similar trend with their carbon price curve for the same reasons. The differences are that the price peak is higher at $325 with US net-zero and $315 with no US abatement, and that the price's decline is slower due to DAC being more expensive and having a slower cost-decline. With refDAC-USna, the carbon price is roughly flat between 2030 and 2035, as DAC deployment begins 5 years later.

noDAC-USna sees the carbon price rise quickly until 2035, at which point it rises much more slowly; the 2045 carbon price is only $16 per ton higher than the 2035 carbon price. From 2045-2050, the carbon price goes up much more dramatically, increasing by nearly $100 per ton. This curve is essentially identical to expDAC-USna, due to that scenario never seeing substantial DAC uptake.

noDAC-USnz and expDAC-USnz, also follow an identical curve for most of the time modelled for the same reason – DAC in expDAC-USnz is too expensive to see more than negligible uptake until 2045. Accordingly, the two carbon prices for these scenarios are nearly identical until expDAC-USnz sees DAC costs decline by enough for deployment to begin. The carbon price in each scenario increases sharply from 2025 to 2030, at which point the price in both scenarios sees a slightly less sharp, but steady rise until 2045.

From 2045-2050, the two scenarios diverge sharply, as DAC becomes cost competitive in expDAC-USnz. The result is that expDAC-USnz sees its carbon price fall in 2050 from $526 to $449 per ton of CO2, the result of 24 Mt of emissions offset by DAC in 2045, and 94 Mt in 2050. In contrast, noDAC-USnz sees its carbon price rise very sharply in 2050, reaching a peak of $938 in 2050, nearly double the next-highest scenario which is noDAC-USna at $484. This is a very high carbon tax, as a 2020 net-zero emissions modelling study used a carbon price of $450 in Canada as its high carbon price scenario (Safton, 2020). None of the scenarios were able to meet net-zero emissions by 2050 without exceeding the carbon price that Canada currently has set, which is $170 per ton of CO2. However, both scenarios with cheap DAC come close, only exceeding that carbon price by about $70 per ton and only in one 5-year period.

4.4 expDAC-USna

Because only a negligible amount of DAC is able to be deployed in expDAC-USna, its results vary little from noDAC-USna. Consequently, I will largely be discounting it in my discussion of results. Its results can generally be assumed to be the same as noDAC-USna, and statements like "all results except noDAC-USna" can be assumed to also exclude expDAC-USna.

4.5 BECCS and Biofuel Costs

4.5.1 BECCS

noDAC-USnz sees a carbon price that is nearly double than in noDAC-USna. Because neither scenario includes access to DAC, the difference comes from US abatement. In both scenarios, the inaccessibility of DAC leads to the economy offsetting its most expensive emissions through the use of BECCS. Table 3 shows the emissions offset through BECCS in MT in all scenarios for years when more than a negligible amount (more than 0.1 Mt) is offset in Canada.

Table 3 – Mt of CO2 sequestered using BECCS by year and scenario

	2040	2045	2050
noDAC-USna	1.7 Mt	16.3 Mt	55.2 Mt
noDAC-USnz	Negligible	8.8 Mt	40.7 Mt
expDAC-USnz	Negligible	1.5 Mt	2.7 Mt

Scenarios where DAC is unavailable see by far the highest amount of BECCS deployed. The only other scenario that sees more than a negligible amount of BECCS is expDAC-USnz. In this scenario DAC is deployed in lower quantities and later than in all scenarios with reference-cost or cheap DAC. BECCS is used to offset a substantial amount of emissions in both scenarios where DAC is unavailable. BECCS deployment on a wide scale (more than 1 Mt of negative emissions) begins in 2040 for noDAC-USna and 2045 for noDAC-USnz, and then rises considerably for both scenarios in 2050. Most of this BECCS is taking place to generate electricity through retrofitted fossil fuel plants; the largest contributor is electricity generation in Ontario. However, electricity is not the only source of BECCS for either scenario. Some emissions are being sequestered by using BECCS for industrial purposes, including vehicle manufacturing, hydrogen production through steam methane reformation and cement manufacturing.

The fact that BECCS only occurs in scenarios with no or limited DAC available shows that the main reason for its use is as CDR, rather than to produce valuable zero-emission energy. Some form of CDR is extremely valuable to the economy due to its ability to offset emissions that are expensive to abate. When DAC is unavailable, BECCS becomes much more valuable and sees more uptake.

Just as the availability of carbon offsets are highly valuable for a net-zero Canadian economy, these offsets are also valuable for a US net-zero economy. When the US abates to net-zero and DAC is unavailable, US demand for BECCS rises dramatically. This creates a corresponding increase in demand for biofuel, leading in turn to prices for the biomass used in making biofuel to skyrocket. Table 4 shows the impact of US abatement on biofuel prices by comparing the degree to which several commodities see their prices rise between noDAC-USna and noDAC-USnz. All products listed are either biofuels, inputs used in creating biofuels, or constraints in the model on the production of biofuels. The table shows that US abatement raises the cost of some goods, such as agricultural and forestry residue, which increase to nearly nine times their cost when the US is not abating. Other price increases are more modest by comparison, but still substantial. It is worth noting that noDAC-USna is itself a scenario with relatively high biofuel prices due to demand for BECCS in Canada. The price of agricultural residue in noDAC-USnz is an astonishing sixty-six times higher than in chpDAC-USna.

Table 4 – Price increase of commodities used in biofuel production in noDAC-USnz compared to noDAC-USna

Commodity	Price increase in noDAC-USnz compared to noDAC-USna
Agricultural residue	888.12%
Forestry residue	861.98%
Agricultural and forestry residue for second generation biofuels	217.06%
Land for corn production*	171.60%
Land for canola production*	139.95%
Renewable natural gas	82.26%
Hydrogenated renewable diesel	77.12%
Canola	74.40%
Agricultural land for other production	47.43%

*These commodities are constraints on biofuel production

US demand for BECCS drives up demand for biofuel. As biofuel is a highly land-intensive good, supply is unable to keep up with demand in the model, resulting in a massive increase in the price of biofuel inputs. This is why the carbon price for Canada is so high in noDAC-USnz; DAC is unavailable, and US demand for biofuel prevents Canada from using BECCS to fully compensate for the lack of DAC. Canadian GDP ends up performing very poorly under noDAC-USnz because the economy's only available CDR option has become extremely expensive. 15 Mt of emissions that can be offset in noDAC-USna must instead be abated in noDAC-USnz. Because the economy is already very close to net-zero, these emissions are some of the costliest in the economy to abate, so the carbon price must rise considerably.

4.5.2 Biofuel price differences

The most extreme impact of US abatement on biofuel prices is seen in the difference between noDAC-USna and noDAC-USnz in 2050 due to the need for BECCS in scenarios without DAC. However, biofuel prices vary considerably across all scenarios. US abatement correlates with higher prices of commodities associated with biofuels across scenarios, while cheaper DAC correlates with a lower need for biofuel across scenarios. This trend is shown clearly in Table 5 which shows the absolute price (in CAD) of a gigajoule of bioenergy from agricultural residue in 2050 by scenario. Prices vary across other commodities, but the impact is most apparent in agricultural residue, which is a major input of biofuel production. Across all DAC cost trajectories, scenarios with US abatement results in more expensive biofuel than those with no US abatement over time. The impact is highest with no DAC availability, and lowest with cheaper DAC. Even with the cheapest DAC costs, however, the price of agricultural residue more than doubles in 2050 with US abatement to net-zero.

Table 5 – Agricultural residue cost by scenario and year

Scenario and Agricultural cost	noDAC -USnz	noDAC -USna	expDA C-USnz	refDA C-USnz	refDA C- USna	chpDA C-USnz	chpDA C-USna
Agricultural residue cost in 2050	36.85	3.73	4.75	2.95	1.05	1.11	0.56
In 2045	7.65	1.07	6.8	2.52	0.59	0.95	0.56
In 2040	4.11	1.28	4.11	3.8	0.59	1.19	0.5

The table shows that both more expensive or unavailable DAC and US abatement result in much higher agricultural residue prices. Biofuels are considered emissions-neutral fuels, making them a valuable source of energy in a low-emission economy. US abatement increases demand for biofuels by adding an enormous economy looking to abate emissions, while cheaper DAC decreases demand for biofuels by offering an alternative form of CDR (as well as lowering the need for biofuels for abatement in other areas. High demand mixed with a constrained supply result in drastically higher biofuel prices, in turn leading to higher carbon prices. This explains why abatement costs are consistently higher from 2035-2045 in noDAC-USnz and expDAC-USnz than in noDAC-USna, as shown in Figure 2.

4.6 Canadian GDP

Canadian GDP grows significantly from 2020 to 2050 in every scenario, with some scenarios seeing considerably more growth than others. Figure 3 displays Canadian GDP in 2050 by scenario. DAC has a large and clear impact; lower DAC cost correlates positively with Canadian GDP. The difference in GDP between noDAC-USna and chpDAC-USnz in 2050 is $90 billion, and the difference in GDP between noDAC-USna and chpDAC-USna in 2050 is $255 billion. There is no scenario in which a cheaper DAC cost assumption results in lower GDP. The difference in GDP outcomes is generally smaller as DAC gets cheaper. The GDP difference between expensive DAC and no DAC is larger than the difference between reference-cost DAC and expensive DAC; and the difference between reference-cost DAC and expensive DAC is larger than the difference between reference-cost DAC and cheap DAC.

Figure 3 – Canadian GDP (in billions CAD) in 2050 by scenario

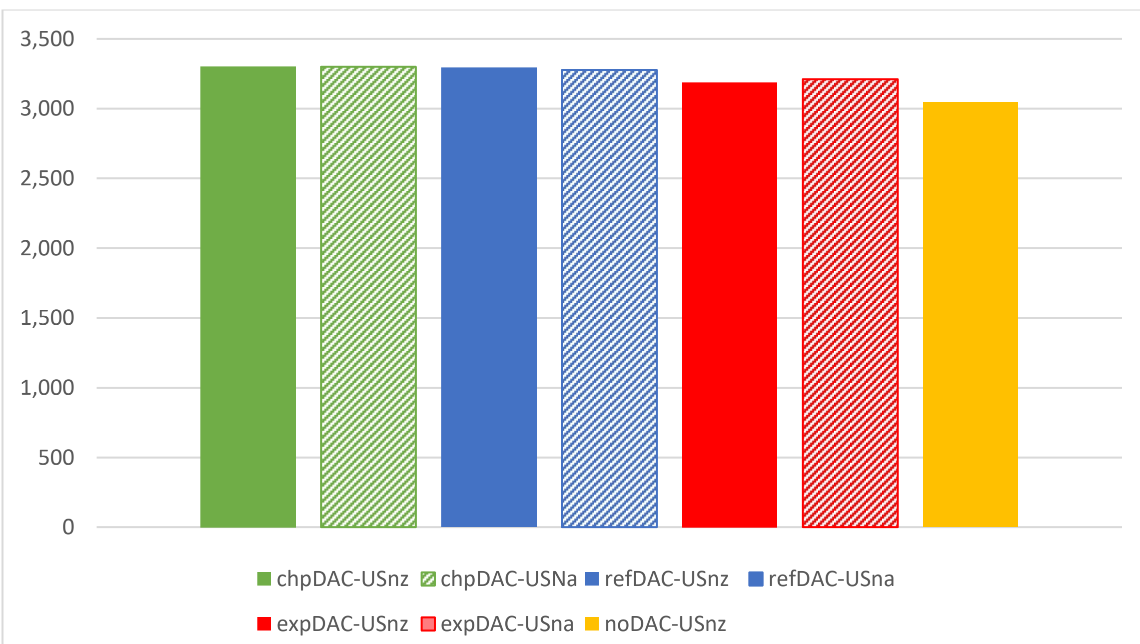
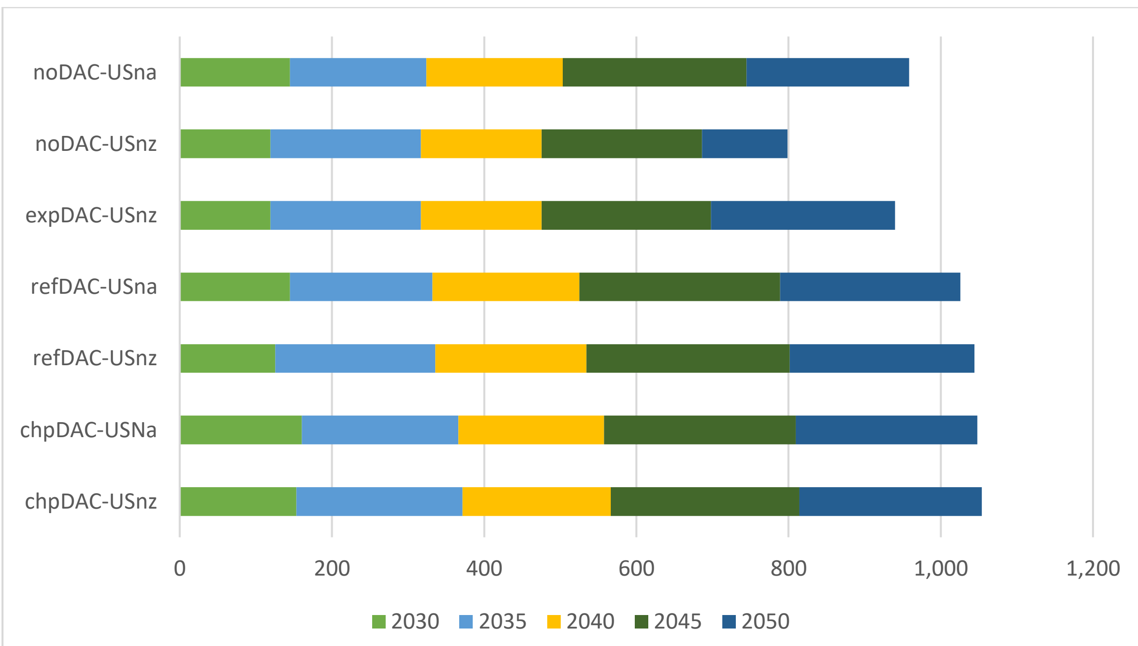


Figure 4 shows the increase in Canadian GDP by scenario from 2030 to 2050. The graph begins in 2030 because differences in GDP increase are negligible before this point. The years with the largest average GDP increases are 2035 and 2045; this pattern is consistent across scenarios, suggesting that this is likely due to the emissions cap in these years being comparatively less stringent on the economy. The graph shows that although noDAC-USnz has a consistent shortfall in GDP growth compared to most other scenarios, the biggest discrepancy by far is in 2050. Using a carbon price to abate results in the cheapest emissions in the economy being abated first, with the last remaining emissions being the most expensive. The results in the graph suggest that overcoming the last few expensive emissions will be the most economically challenging part of the net-zero transition for an economy with limited capability to offset emissions.

Figure 4 – GDP Increase 2025-2050 (in billions CAD) by scenario



4.6.1 DAC impact on Canadian GDP

expDAC-USnz has less than a third as much DAC uptake in 2050 as chpDAC-USnz, and yet its GDP is much closer to chpDAC-USnz than it is to noDAC-USnz. This result led me to hypothesize that DAC deployment has diminishing marginal economic utility. In other words, that a small amount of DAC deployed would be proportionally more valuable to the Canadian economy than a large amount.

I attempted to analyze the relationship between DAC and GDP. However, the relationship is very complex with many variables at play, including the carbon price, DAC cost, emissions, as well as DAC and GDP themselves. I used a CGE model for my analysis, which always returns to an equilibrium. Because of this, it is very difficult to isolate specific variables and determine a causal relationship. I was not able to arrive at any significant conclusion in this relationship. I discuss the analysis I performed further in the appendix.

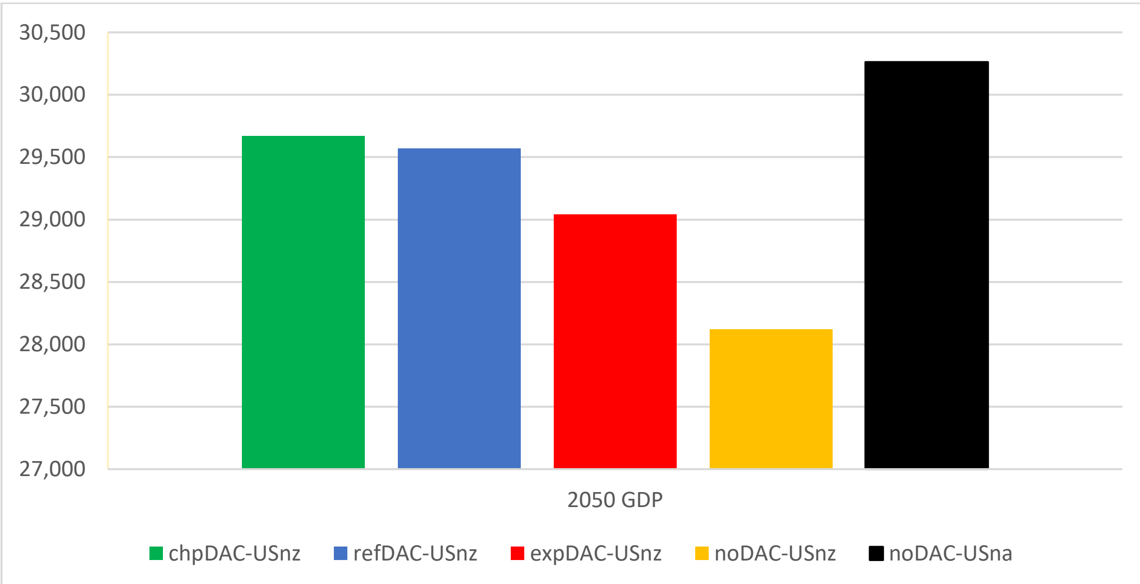
4.6.2 US abatement and Canadian GDP

The impact of US abatement is complex. With cheap or reference-cost DAC, US abatement correlates positively with Canadian GDP. In scenarios with expensive DAC or no DAC availability, US abatement correlates negatively. This is because US abatement exhibits three different dynamics that impact Canadian GDP.

First, US abatement results in much more investment in clean technology than Canadian abatement alone. This is important for DAC in particular, as more investment leads to faster deployment and cost decline. This dynamic correlates positively with Canadian GDP.

Second, US abatement has a negative impact on the US economy. This is shown in Figure 5, which shows US GDP in 2050 by scenario. I show only one scenario with no US abatement in this graph, because US GDP varies little between scenarios in which they are not abating. The graph shows that DAC cost has a considerable impact on US GDP, with the economy performing better with cheaper DAC. It also shows that even with cheap DAC, the US economy performs worse than with no abatement, by more than half a trillion dollars. A smaller US economy means a smaller market with which Canada can trade, limiting our economic growth opportunities. This dynamic correlates negatively with Canadian GDP.

Figure 5 – US GDP in $CAD billion in 2050 by scenario



Third, when DAC is unavailable, US abatement leads to high consumption of biofuel in the US so that BECCS can be used to offset emissions. This increased demand and higher biomass prices lead to a reduced use of BECCS in Canada. This dynamic correlates negatively with Canadian GDP. Notably, this dynamic only takes place in scenarios with expensive DAC or no DAC availability.

Across all scenarios where DAC is available, US investment in DAC impacts results. This is demonstrated by the larger DAC deployment in Canada in scenarios with US abatement than in scenarios without US abatement. In all scenarios, the size of the US economy impacts results. This dynamic leads to an improvement in Canadian GDP when the US does not abate, as that is when their GDP is largest. However, this impact is lessened in scenarios with lower DAC costs, because cheap DAC correlates with higher US GDP relative to other scenarios with US abatement. The result is that chpDAC-USnz and refDAC-USnz have higher GDP than their counterparts where the US does not abate. The impact of biofuels has already been discussed in Section 4.5.

With expDAC-USnz, the impact of the US investment in clean technology is significant, as there is almost no DAC uptake in Canada in expDAC-USna. Nevertheless, DAC deployment only begins in 2045 for expDAC-USnz, 15 years later than both scenarios where DAC cost is cheap. This means that until 2045, growth is much slower for both the US and Canada. This exacerbates the impact of a smaller US economy, as growth is slower for a long period of time. In contrast, in expDAC-USna the Canadian economy is able to benefit from a larger US economy and the availability of biofuels.

4.7 Canadian economy by province

Relative differences in GDP by province are generally not very large across scenarios. Provinces tend to account for a similar percentage of total Canadian GDP in each scenario. There are a few exceptions to this. Alberta's economy does best in chpDAC-USna, accounting for 19.1% of Canada's GDP. Its performance is weakest under noDAC-USnz. This is unsurprising, as Alberta's economy is presently based largely around emissions-intensive goods like oil, much of which is exported to the United States. With a smaller market for these goods, and no way to cheaply offset them, Alberta's economy does comparatively poorly. Saskatchewan sees little change in its share of GDP across scenarios. This was surprising to me, as Saskatchewan's economy is roughly as emissions intensive as Alberta's in 2020. The reason for its lack of variation in 2050 is that although the Saskatchewan economy is currently emissions-intensive, it also has a high capacity to produce biofuels. Accordingly, DAC helps offset emissions when it is available, but the province is also able to profit in scenarios where biofuel demand (and price) rises due to DAC being unavailable.

Newfoundland and Labrador perform considerably better when the US abates to net-zero, with the difference being largest when DAC is unavailable. Newfoundland's economy experiences a recession between 2030 and 2050 in every scenario modelled, but its GDP falls by considerably less with US abatement. The biggest difference in GDP is when DAC is unavailable, where US abatement results in Newfoundland's economy being $4 billion larger, making up 0.78% of Canadian GDP instead of 0.63%. This is almost entirely due to increased metal mining and construction in the province, which is home to deposits of nickel, cobalt, and copper, which are inputs into batteries (Roberts, 2022).

Ontario's economy makes up a larger portion of the Canadian economy when DAC is more expensive or unavailable. In its weakest scenario, chpDAC-USnz, it accounts for 39.5% of Canadian GDP, while in its strongest scenario, noDAC-USna, it accounts for 40.2%. This is due less to differences in output in Ontario and more to differences in output in other provinces leading to Ontario doing comparatively better, as Ontario's economy is less emissions and resource intensive than other provinces.

Quebec's GDP varies little across scenarios. The only exception to this is that aluminum production in Quebec performs significantly better with US abating to net-zero and cheaper DAC. Aluminum is emissions and energy-intensive and is an input to a wide variety of manufactured goods. US abatement makes the production of aluminum in the US more expensive. Quebec, which has an abundance of clean hydroelectricity is therefore able to develop a competitive advantage. Meanwhile, cheaper DAC offsets process emissions from production, making aluminum production cheaper everywhere.

4.8 Canadian Energy Consumption by Scenario

Higher energy use in 2050 is positively correlated with higher economic activity, and cheaper DAC across scenarios; US abatement results in less energy consumption the cheaper DAC costs are, and results in more energy consumption only with DAC unavailable. noDAC-USna energy consumption is about 1.5 exajoules lower than noDAC-USnz consumption. This result was unexpected due to the low GDP of noDAC-USnz. The source of this difference mostly comes from increased Canadian natural gas usage with CCS, which is considerably cheaper with US abatement to net-zero as a result of reduced demand for the good. noDAC-USna is the only scenario which has lower energy consumption in 2050 than it does in 2020, albeit only by about 0.1%. This scenario has energy consumption of 11.54 exajoules, while chpDAC-USnz sees the highest energy consumption at 15.35 exajoules. Cheaper DAC correlating with more energy make sense, as DAC not only allows for a slower energy transition that limits the need for innovations like energy-efficiency, but DAC itself is a highly energy-intensive technology. A further explanation of this finding is that scenarios with more DAC have higher GDP, which results in a larger economy in which energy is used. This modelling is consistent with other modelling conducted by the IPCC, which suggests that a smaller amount of CDR correlates with a world with lower energy consumption (2018).

4.9 Canadian economy by industry

There are substantial variations in the output of different industries across scenarios. The construction sector is a huge beneficiary of DAC. The sector's economic output is $23 billion higher under the scenario with the lowest amount of DAC deployed, expDAC-USnz ($201 billion in 2050), than under noDAC-USnz ($178 billion in 2050). Differences between scenarios with DAC are more modest; refDAC-USna sees the largest construction sector at $207 billion in 2050.

Canadian electricity generation and distribution are consistently more productive with less or no DAC, and with US abatement across all scenarios. Electricity sector output in 2050 is $60.5 billion with noDAC-USnz, while it is only $55.3 billion with chpDAC-USna. This is because DAC allows for continued use of fossil fuels in sectors that would otherwise have to convert to clean electricity, and US abatement creates a larger market for clean Canadian electricity to be sold to.

Transportation sees remarkably little variation across scenarios, consistently making up about 5% of Canadian GDP. This shows that the transportation industry is able to effectively decarbonize without DAC, and with constraints on biofuel production.

The Canadian services industry remains the largest sector of the economy by far across scenarios, making up between 68.7% and 70.6% of Canadian GDP. Services make-up a smaller portion of the economy when DAC is cheaper. There are two likely causes of this trend. One is that services are not an emissions-intensive sector of the economy, and cheaper DAC therefore allows emissions-intensive sectors to do relatively better. The second is that cheap DAC results in a lower carbon price. Because 90% of revenue from the carbon price is recycled into households, the services sector benefits from higher carbon prices. This trend is shown in Table 6, which shows services as a percentage of GDP in 2050, and the Canadian carbon price. Note that except for refDAC-USnz and chpDAC-USna, a higher carbon price results in services contributing more to the total economy.

Table 6 – Canadian services as a percentage of GDP in 2050 by scenario, and the carbon price (in CAD) in those scenarios

	noDAC -USnz	**noDAC -USna**	**expDAC -USnz**	**refDAC-USna**	**refDAC-USnz**	**chpDAC -USna**	**chpDAC -USnz**
Services as a percentage of Canadian GDP in 2050	70.64%	69.79%	69.66%	69.22%	68.82%	69.06%	68.74%
Canadian carbon price in 2050 in 2050	$938	$484	$449	$221	$186	$154	$142

Table 7 shows manufacturing and resource industry output in Canada in 2050 in billions of dollars Canadian. Overall, emissions-intensive industries tend to do better the cheaper DAC is assumed to be, doing best with cheap DAC and worst with no DAC. Nearly every manufacturing and resource industry performs better with cheaper DAC, with only a few exceptions, such as liquified natural gas. This is unsurprising, as DAC allows for offsets that reduce the need for abatement. What is notable is that the degree to which DAC impacts these industries varies drastically. DAC has a particularly large impact on petroleum refining, which is worth $17.6 billion with chpDAC-USnz, five times larger than noDAC-USnz, at only $3.4 billion. Natural gas and chemicals also perform much better with cheaper DAC, achieving a GDP approximately 50% higher in chpDAC-USnz than in noDAC-USnz. All oil sectors also perform better with cheaper DAC available, although by a much more modest amount by comparison.

The impact of US abatement is more mixed, with some industries doing better with US abatement to net-zero, and some doing better with no abatement. In particular, the liquified natural gas, petroleum refining, paper, chemical manufacturing, mining, and forestry sectors do noticeably better with US abatement to net-zero across all scenarios, while the light oil and oil sands sectors perform better with no US abatement. While increased oil refining coinciding with US abatement may seem counterintuitive, it is likely the result of US abatement driving up the cost of emissions-intensive industries in the US, resulting in more competitive refining in Canada. These are all currently emissions-intensive sectors. US abatement to net-zero will lower demand for these kinds of products, but will also make their production more expensive in the United States. Industries that perform better with US abatement to net-zero likely see US demand decreasing by a smaller amount than US production costs, while the opposite is true for sectors that thrive with no US abatement. Mining output likely increases in response to a higher demand for inputs for clean technology. Many minerals that can be found in Canada, such as lithium, cobalt and copper, are necessary inputs for low-emission technology like batteries.

Table 7 – Output (in billions CAD) of Canadian Resources and Manufacturing by scenario

Industry and Scenario	chpDAC-USnz	chpDAC-USna	refDAC-USnz	refDAC-USna	expDAC-USnz	noDAC-USnz	noDAC-USna
Manufacturing	**361.06**	**354.49**	**354.93**	**347.25**	**316.23**	**287.81**	**338.18**
Liquefied Natural Gas	5.91	5.18	6.33	5.30	7.70	7.22	4.66
Petroleum Refining	17.59	13.07	16.62	11.55	4.02	3.38	8.04
Hydrogen Production	2.42	2.21	2.40	2.09	1.28	0.91	1.66
Metal manufacturing	11.51	11.44	10.96	10.86	9.62	8.69	9.51
Paper	14.35	12.41	13.76	11.21	12.49	11.26	9.62
Non-Metallic Minerals	6.77	6.42	6.53	5.94	5.79	5.21	5.14
Chemicals	39.56	34.61	37.84	32.19	30.82	27.27	29.23
Other Manufacturing	264.77	271.96	260.90	271.11	249.01	230.40	275.18
Resources	**258.68**	**253.92**	**252.68**	**246.32**	**234.17**	**222.59**	**226.27**
Natural Gas	44.46	42.14	41.52	38.92	34.74	30.41	31.02
Conventional Light Oil	13.38	13.44	12.36	12.49	10.26	8.28	11.50
Coal Mining	0.25	0.23	0.18	0.15	0.14	0.05	0.13
Oil and Gas Services	18.06	18.11	18.07	18.05	17.18	14.15	15.01
Conventional Heavy Oil	14.55	14.53	13.94	13.97	12.21	11.05	12.93

Oil Sands (Mining and Extraction)	14.99	15.03	14.93	14.97	14.36	14.35	14.45
Oil Sands (In Situ)	19.70	20.51	18.15	19.36	14.03	14.09	15.56
Fuel upgrading	1.76	1.68	1.82	1.55	1.40	1.40	1.12
Mining	39.06	36.88	38.52	35.76	38.61	38.24	33.51
Agriculture	75.12	74.95	75.75	74.82	74.26	73.30	75.20
Forestry	17.35	16.43	17.45	16.29	16.96	17.28	15.85

Looking at the overall size of manufacturing and resources as a share of the economy, there is substantial variation in their share of the Canadian economy across scenarios. Manufacturing forms 10.8% of Canadian GDP at its peak in chpDAC-USnz, but only 9.3% at its low point in noDAC-USnz, generally accounting for a larger share of the Canadian economy when the total economy is larger (and therefore when DAC is cheaper and more available). Resources follow a similar trend. The resource share percentage of the Canadian economy is also highest in chpDAC-USnz at 7.8%, while it is lowest in noDAC-USna at 7%.

4.10 Gross Emissions

Canadian net emissions are the same across all scenarios due to the identical emissions cap put in place. However, because the availability of negative emissions varies by scenario, there is a substantial difference in gross emissions between results. When negative emissions are not counted, Canadian emissions in 2050 range from 455 Mt in chpDAC-USnz, to 141 Mt in noDAC-USnz. Because of the regulations in place across scenarios, emissions from electricity are always zero (or less than zero in scenarios with BECCS deployment), and emissions from car and truck transportation are zero.

In scenarios with no DAC availability, the largest portion of emissions remaining in 2050 are from agriculture and air travel. Air travel accounts for around 30 Mt in both scenarios without DAC availability. Meanwhile, emissions attributed to agriculture account for 57 Mt of emissions in noDAC-USna, and 49 Mt of emissions in noDAC-USnz. Other emissions in these scenarios come from industry, especially oil, gas and aluminum production. Oil sands in-situ mining is the largest single industry polluter, responsible for about 5 Mt of emissions in both scenarios without DAC.

Gross emissions with cheap DAC are much higher than without DAC. It is notable though, that emissions from air travel barely change between scenarios, only increasing by about 2 Mt in both scenarios with cheap DAC. Emissions from agriculture are somewhat higher, accounting for approximately 70 Mt in both cheap DAC scenarios. The same is not true with industries. With cheap DAC, gross emissions are substantially higher than without DAC across nearly every major Canadian industry, notably in oil production, cement, steel, aluminum, petrochemical production, and natural gas for industrial purposes. One particularly big standout is oil sands in-situ mining, responsible for approximately 60 Mt of emissions in both cheap DAC scenarios, a more than tenfold increase compared to when DAC is unavailable. Another standout result with cheap DAC is that the single highest emitter regardless of US abatement is natural gas emissions used as heat input to the DAC process in Alberta. This is responsible for 65 Mt of emissions in noDAC-USna, and 75 Mt in noDAC-USnz. While notable because of their size, and ironic because of the industry, there is little to be analyzed from this statistic. These emissions by definition are offset by DAC. DAC requires a substantial amount of heat to function. One possible source for this is natural gas, but DAC can also purely use electricity (Fasihi et al., 2019). DAC firms will choose whichever is cheaper, noting that choosing to use natural gas incurs additional costs because of the added emissions and thus carbon charges associated with every ton sequestered. Emissions in scenarios with reference-cost and expensive DAC are similar to emissions in cheap DAC scenarios, but at a lower rate, without any major outliers.

Chapter 5. Discussion

5.1 The Importance of Carbon Dioxide Removal

The modelling results make it very clear that CDR could play a very important role in the transition to net-zero. When DAC is unavailable or too expensive to become a competitive industry, the model sees a considerably higher uptake in BECCS in 2050 and the years leading up to it to compensate. In noDAC-USnz, when DAC is unavailable, US demand for biofuel drastically increases the cost of employing BECCS. The result is that Canadian GDP is at its lowest in this scenario by far, especially as 2050 approaches. Further, the importance of CDR rises as climate policies increase in stringency. The GDP of noDAC-USnz consistently grows more slowly than other scenarios, but this trend is at its most severe in 2050 by a wide margin. These results show that offsets could become extremely valuable to the economy in the net-zero energy transition, especially as emissions are reduced closer to net-zero. Inexpensive CDR would give emitters the ability to cheaply offset emissions. The modelling suggests that DAC availability and cost could impact Canadian GDP by hundreds of billions of dollars. The model also shows a clear preference for DAC over BECCS given the choice, as the only scenarios that see more than negligible deployment of BECCS are those in which DAC is unavailable, or extremely expensive.

5.2 DAC Policy

When DAC is cheap and available, it has clear economic benefits. DAC also has characteristics that make it favourable over other methods of CDR. DAC is a true carbon offset – offsets through DAC are measurable, permanent, and will not take place on their own. This is a title it only shares with BECCS. However, the modelling results suggest that BECCS could be constrained by excessive demand, since biofuel production is highly land intensive, and more land cannot be produced. This is significantly less likely to be an issue with DAC, since it does not need to take up very much land to be effective. The areas where DAC does have high demands, such as energy, can be scaled up, allowing the supply of DAC to increase with demand. Energy for DAC will likely be coming from solar or wind, which have their own land requirements, but these are smaller than these can take place on unproductive land like tundra or deserts, while biofuel production competes directly with arable land use. Further, there are many areas where bioenergy may prove to be the cheapest abatement option, such as low-emission fuel for aviation. Bioenergy that is used cannot be used for other abatement measures that it may prove well-suited for, such as near-zero fuel for freight or aviation. This will could raise abatement costs in these sectors. Because of these significant benefits, some consideration is warranted of measures that could be taken to promote the deployment of DAC in Canada.

5.2.1 DAC Offset Credits

One policy change that will likely be necessary to achieve further DAC uptake in Canada is allowing companies that purchase DAC to be given offset credits for their reduced net emissions. All of the modelling conducted for this research assumed that a policy allowing offset credits will be implemented in Canada, but such a policy does not exist right now. It does exist elsewhere though; California allows DAC to be used as a credit in its low-carbon fuel standard (California Air Resources Board, 2021). It is noteworthy that implementing carbon offset credits for DAC in a program like a low-carbon fuel standard will be relatively straightforward, as it is a system already based on credits. Implementing this system alongside the Canadian federal carbon backstop will undoubtedly be more complicated, as many Canadian provinces use their own carbon prices. The system would need to ensure that DAC credits allow firms to offset whatever carbon price is paid in their jurisdiction, whether that is the federal carbon backstop or a provincial carbon price. The system could form provincially, but some federal component would undoubtedly be necessary to avoid issues like double counting of negative emissions. In jurisdictions with a direct carbon tax, carbon offsets could take the form of a negative carbon tax. In practice, this would be a direct payment from the government to firms that have purchased DAC credits equivalent to the cost per ton of the carbon tax.

Regardless of the potential administrative challenges of such a policy, some type of credit or payment will likely be essential for the success of DAC as an offset. Firstly, if DAC purchases do not translate into purchasers paying a lower carbon price, the market for DAC will never be allowed to form. There may still be some DAC purchases from individuals wanting less CO2 in the atmosphere, but voluntary actions to limit climate change tend to be much less effective than financial incentives (Jaccard, 2020). Secondly, DAC technology will progress much more quickly with more money invested into it. Presently only a small number of firms are investing in DAC, mainly (outside of a few niche tax credits, such as the US' 45Q and California's low-carbon fuel standard) for ethical reasons. More investment will yield a faster development of the technology and creating a direct financial incentive for that investment will likely yield considerably more investment. Without an offset mechanism, the opportunity for DAC to become a viable clean technology will be diminished or even squandered.

The policy design details matter, and there are different possibilities for how such a policy could be implemented. DAC accounting is handled in gTech by allowing a DAC credit to be purchased as an offset from anywhere in the country, so long as the DAC takes place in Canada. In practice, however, DAC is not limited to Canada and has already seen uptake in other parts of the world, with the largest operating plant in Iceland, and the largest planned DAC project in Texas (Galluci, 2021; Sigurdardottir & Rathi, 2021).

If other countries implemented DAC accounting systems along the lines of how DAC is modelled in gTech, it would clearly limit the potential of the technology. An alternative system could allow for international purchases. For instance, it might allow a firm in the United States to buy DAC in Canada, and vice versa. An international system such as this would ensure international competition among DAC firms, lowering prices for purchasers of DAC. It is already clear that some countries will have a competitive advantage in DAC. The geological formations that are conducive to storing CO2 are not distributed evenly geographically. Canada is blessed with an enormous amount of potential storage for CO2, especially in western provinces like Saskatchewan and Alberta (Pale Blue Dot, 2020). Enough volume for the storage of 43.6Gt of CO2 has already been discovered, while one estimate is that enough storage for 360Gt of CO2 may remain undiscovered (Pale Blue Dot, 2020). By contrast, many countries do not have any storage capacity for underground CO2 storage. Further, variable DAC costs will be dependent on electricity costs. The amount of relatively inexpensive hydroelectricity in Canada, as well as the potential for other forms of near-zero electricity, like wind energy in Alberta give Canada a potential future edge in having lower variable DAC costs (Rystad Energy, 2022). Allowing international trading of DAC offset credits would likely be advantageous to both Canadian DAC firms, who could deploy more of the technology in Canada, and to Canadian firms seeking offsets, who could benefit from lower prices as a result of more competition.

At the same time, part of the reason for the failure of previous attempts at offsetting has been a lack of accountability in countries with weak institutions (Song and Moura, 2019). If a Canadian firm purchases a DAC offset in another country, it must be clear and demonstrable that that purchase actually results in the capture and storage of the requested amount of CO2. Creating a reputable international offsetting system will not be an easy feat and will take a considerable amount of time and international collaboration. Allowing DAC offsets to be purchased only within Canada has clear downsides, but it might be a way to begin the longer process of creating a credible international offset system. A domestic system could be created whereby Canadian firms can purchase an amount of DAC to be deployed in Canada and avoid paying the carbon price on the amount paid. Over time, other countries with robust climate policies may introduce similar mechanisms. This presents an opportunity for countries with ambitious climate policy to join offset systems together. As these systems mature, those that prove successful in ensuring accountability for offsets could be merged, similar to the way in which Quebec and California have combined their cap-and-trade schemes. Over time, an international market for DAC credits could be created in this manner.

5.2.2 Direct investment into DAC

Another policy decision that could be taken by Canada to increase the likelihood of DAC becoming a competitive industry is more direct public investment in the technology. A 2019 report from Rhodium Group argued that direct investment into DAC from the United States government could be the decisive component for its commercial development, affecting whether the technology is sufficiently developed for use in achieving net-zero emissions in the United States by 2045 or 2050. They note that 9 Mt of DAC capacity is needed by 2030, and that "specific application of DAC–for use in fuels, products, enhanced oil recovery, or sequestration–matters little at this early stage as long as it advances progress toward the 2030 deployment goal" (Larsen et al., 2019). In addition to direct investment, the report argues that the US government can promote demand for DAC through actions like extending federal military procurement to require a certain amount of synthetic fuel produced using carbon acquired with DAC. This fuel would effectively be carbon neutral, with its carbon having been taken out of the atmosphere by DAC. The paper also argues for the inclusion of DAC-based fuels in the US Renewable Fuels Standard, as well as more tax credits to benefit DAC. Others have suggested other forms of subsidies, including loans, and accelerated depreciation (Capanna et al., 2021).

Larsen et al. indicate that the amount in direct investment required for DAC technology to get to the stage it needs to be to achieve net-zero is $240 million USD annually for a decade, a total of 2.4$ billion USD (2019). This is a substantial amount of money for the US, let alone for Canada with an economy less than a tenth as large. However, government support for DAC would not all have to come about through direct investment, as Canada could also use some of the methods suggested by Larsen et al.. Further methods might include direct government purchase of DAC as an offset for hard-to-abate government emissions, such as air travel – although this process would have to be very transparent. Whatever the method of investment, if investments make the difference between whether DAC is a competitive industry, they would almost certainly be worth it. My research shows that with the US abating to net-zero, between no DAC and the scenario with the least amount of DAC deployed (noDAC-USnz and expDAC-USnz) there is a difference of CAD 142 billion in 2050 (total real Canadian GDP in 2021 was about CAD 2.2 trillion). With no US abatement, the difference between no DAC being deployed, and the scenario with the least amount of DAC deployed (comparing noDAC-USna to refDAC-USna) results in a difference of CAD 67 billion in 2050. If government investment in DAC is able to realize its deployment, then the payout from the investment would prove to be enormous.

However, it should be recognized that this investment is risky. There is no guarantee it will make the difference between whether DAC becomes commercially available. To mitigate this risk, Canada could attempt to push for other climate-sincere governments to contribute to investing in DAC technology as well. All countries sincerely attempting to lower their emissions in line with the Paris agreement will benefit from a world in which DAC costs are low enough to be useful in offsetting emissions. It therefore benefits every government to help pursue its development and use. DAC is a technology in its infancy.

Policy decisions affecting its deployment that are made today could have an enormous impact on its deployment over the next three decades and beyond.

5.3 Policy Coordination with the United States

Inaction on climate change in the United States has resulted in few opportunities for coordination on climate change until recently. There has been some sub-national alignment on climate policy, such as Quebec and California joining their emissions trading schemes together, but nothing this significant has taken place at the federal level. Ongoing political division in the United States means that opportunities for federal cooperation are unlikely to present themselves in the short term, but they should still be sought after if and when an opportunity presents itself. The results of my modelling demonstrate that the direction the United States adopts on climate change will have a significant impact on Canada's net-zero strategy.

The size of the American economy means that investment in near-zero emission technology could result in drastically lower costs for these technologies in Canada. This paper has mostly focused on the impacts of this dynamic on DAC, but US investment into other near-zero technologies will likely achieve the same result. At the same time, this study shows that shortages of goods will play an important role in the transition to a near-zero economy can cause significant economic sluggishness and will not remain in borders. Again, the good in question in this study is biofuels, but the same dynamic could present itself in the form of a critical mineral shortage. Policy coordination could help to ensure effective investment and avoid shortages of goods and processes important to the energy transition, as the connectedness of the US and Canadian economies mean that policies adopted in either country will impact both.

As US climate policy evolves, coordinated policy implementation between Canada and the US could help to minimize potential negative impacts of abatement in both countries. There are many ways that this relationship could take shape, but one clearly beneficial early action would be information sharing. Communication of modelling forecasts and climate policy between countries would allow both countries to acquire a better understanding of the other's direction, and potentially enhance analytical accuracy.

Another area could be joining together policy schemes – or at the very least creating schemes with the other country in mind. This could involve joining together incentive structures for DAC for instance.

Chapter 6. Conclusion

6.1 Summary of Research

The goal of my research was to explore the uncertainty surrounding DAC cost and the direction of US abatement on the Canadian economy, and to help fill this knowledge gap by modelling these two uncertainties together. To do this, I used the energy-economy model gTech to model eight different scenarios involving four different assumptions about DAC cost and two different assumptions about US abatement effort. I then analyzed the modelling results, especially as they pertained to the Canadian economy.

My analysis suggests that Canada could meet its target of net-zero by 2050 even if DAC is unavailable, and regardless of the direction of US abatement. However, the availability of DAC and the direction of US abatement have a significant impact on the Canadian economy, and the two variables have a strong impact on each other; DAC availability improves the ability of the US to abate with a strong GDP, and US abatement leads to faster DAC uptake. Assumptions about DAC cost and the direction of US abatement play an important role when modelling the potential uptake of DAC and its impacts. Cheaper DAC allows Canada to meet its emissions target with a considerably higher GDP than without it. DAC cost has a major impact on the make-up of the Canadian economy; emissions-intensive industries tend to perform much better with cheaper DAC. US abatement has a significant impact on DAC uptake in Canada, and when DAC is unavailable or extremely expensive it also affects the availability of biofuel for BECCS in Canada.

What is underlined by this research is that the ability to offset some emissions with CDR proves extremely valuable to the Canadian economy. The importance of CDR peaks as gross emissions approach zero and the economy must address its most expensive emissions abatement. This is highlighted by one scenario in which DAC is unavailable, and US abatement places a major constraint on the supply of biofuel for BECCS in 2050. In that scenario, a very high carbon price is required to meet net-zero emissions by 2050. This price is so high that the economic impact is significant. Comparing that scenario's 2050 GDP with others, it becomes clear that the availability of CDR as Canada approaches net-zero emissions is potentially worth hundreds of billions of dollars to the Canadian economy.

These findings reinforce the importance of ensuring that CDR options are available to Canada, especially as we get closer to net-zero emissions. Decision makers can take actions now to increase the likelihood of CDR options being available in the future. A carbon offset credit system is an important first step in ensuring that DAC is deployed. Other steps can potentially be taken to directly invest in the development of DAC. There are also changes in policy that can be taken to ensure that there is enough high-quality arable land that is usable for land-dependent CDR such as BECCS and afforestation and reforestation in the future. Lastly, policy coordination with the United States should they choose to lower their emissions may help in preventing negative outcomes from abatement policy.

6.2 Limitations and Further Research

1. I was unable to fully analyze the relationship between GDP and DAC deployment. The model I used for this study, gTech, is a CGE model. While this model was well-suited for this analysis for the reasons discussed in Section 3, it has its shortcomings. CGE models always return to an equilibrium. This means that when a constraint is placed on the model, it can impact any number of variables. This makes them ill-suited for isolating relationships between variables. In particular, the impact of an emissions price that changes in response to DAC cost made it very difficult to isolate the specific relationship between DAC and GDP. There is room for further research to explore this relationship, which a partial equilibrium energy model would be better suited for.

2. Another limitation is that my study aimed for policy realism with the policies I modeled for Canada, the policies I modelled for the US in USna scenarios are quite unlikely. I put in place essentially no policies at all for the US in these scenarios. In

reality, several US states, such as California, have already started implementing increasingly strong climate legislation. For this scenario to come to pass in the real world, the US federal government would need to oppose all state-level climate action, and successfully do so for the next thirty years. The likelihood of this happening is very small. These scenarios are still very useful for my goal of examining the role of US abatement on Canadian climate policy, but their results are not applicable to the real world.

3. This study closely examines DAC technology, but two important components of DAC are not modelled in gTech. Firstly, there are different DAC methods, which can be loosely defined as high-temperature aqueous solution DAC, and low-temperature solid sorbent DAC. gTech does not distinguish between these, only containing one category for the technology. Secondly, a feature of DAC is that the carbon it sequesters can be used for industrial purposes. One DAC company, Carbon Engineering, has already stated their intent to use carbon sequestered through DAC to create synthetic fuels. gTech is not currently able to model this dynamic. Modelling that includes these features of DAC may have different results.

4. In my discussion, I touched on a study conducted by Rhodium Group on the effectiveness of public investment into DAC. This is the only study of its kind that I am aware of. Although I discussed the possibility of such investment, I did not model it. Future research could examine the impact of public investment into DAC given different assumptions about its cost.

5. The high carbon price seen in scenarios where DAC is unavailable is partially in response to high biofuel prices. Some economists, however, argue that the bioenergy supply curve could remain flat for a long time despite increases in demand. As gTech assumes a fixed supply of land for bioenergy, this possibility was not considered for this study. A more realistic and detailed biomass supply model could further explore this relationship.

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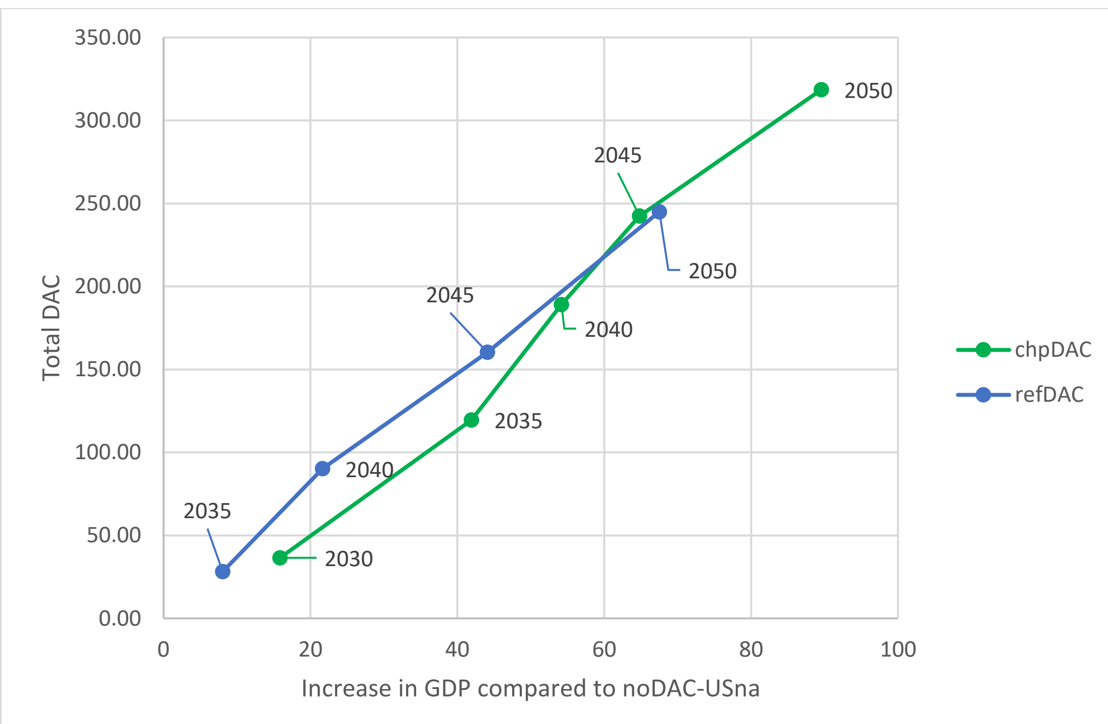
Appendix – GDP and DAC relationship

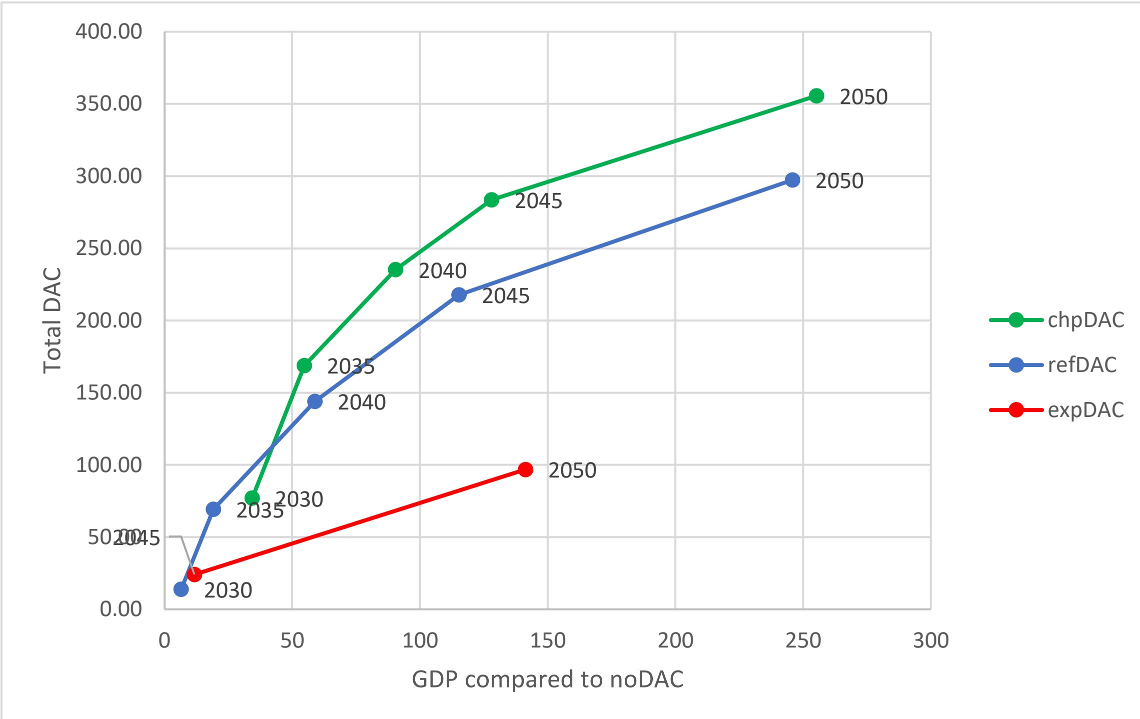
I explore the relationship between DAC uptake and GDP with figure 6. This is an unusual figure so I will take some time here to explain it. The figure depicts two scenarios, chpDAC-USna, and refDAC-USna, which are graphed in green and blue respectively, and compares them to noDAC-USna. The figure graphs the difference in GDP between the scenario being graphed and noDAC-USna as a function of the difference in DAC. Each dot represents one 5-year period; the year shown is compared to the same year in noDAC-USna. Only scenarios with no abatement are shown in figure 6, to isolate for differences in DAC. Note that refDAC-USna does not have a datapoint for 2030 because DAC uptake begins 5 years earlier with cheap DAC than with refence cost DAC. What the graph shows is that the difference between total DAC uptake and GDP difference is fairly linear, with only slight deviations in the relationship between the two.

Figure 6 – Increase in Canadian DAC and Canadian GDP compared to noDAC-USna



I further examine this relationship in figure 7. This graphs the same variables, but uses data from scenarios where the US is abating to net-zero, using noDAC-USnz as the base year. The results from this graph show very different results than figure 6; the more DAC is deployed, the better the Canadian GDP performs. This graph appears to show that the opposite of my hypothesis is true; rather than DAC having diminishing marginal economic utility, it appears to have increasing marginal economic utility. This is misleading however, as there is a confounding variable, which is the price of biofuels in noDAC-USnz driving down Canadian GDP because of a lack of offsets. DAC only appears to have increasing marginal economic utility because the GDP growth of the base year is drastically lower towards 2050 compared to other scenarios. This fact is made clear by looking at the line for expDAC-USnz between 2045 and 2050. The shape of the line between these two years is nearly identical to that for scenarios with cheap and reference DAC, but is set further back because deployment of with expensive DAC starts fifteen years later. The amount of DAC deployed does not result in higher GDP by itself. Rather, the GDP of noDAC-USnz in later years, especially 2050, is hit extremely hard by its lack of offsets, making it look like more DAC results in higher GDP. This result highlights the fact that the availability of CDR is highly important to Canadian GDP. The limitation of one option, BECCS in this case, makes any amount of available DAC much more valuable.

Figure 7 – Increase in DAC (in Mt) and GDP (in billions CAD) compared to noDAC-USnz



In an attempt to further study this variable, I attempted to run another model. This time, I ran everything I had run for other scenarios, but I held the emissions cap constant after 2040. This means that the emissions cap did not reduce past 250Mt in 2045 in 2050 across my scenarios. My reasoning was that a constantly raising emissions cap made the relationship between DAC and GDP difficult to analyze, because gains in GDP from DAC are being partially offset by a raising emissions cap. I thought that if I held the cap constant, that I might find the relationship I was looking for.

In analyzing my results, I quickly realized why this would not work. The tightening emissions cap incentivizes the uptake of DAC. With the cap constant after 2040, the uptake of DAC is nearly constant as well.

I conclude from this experiment that there are too many variables at play to isolate for the relationship between DAC and GDP in my modelling runs. DAC uptake is taking place in response to an increasing carbon price. That carbon price itself is set through a cap, meaning that it also varies in response to the amount of abatement and DAC uptake that has taken place. This makes it very difficult to isolate for the relationship between DAC and GDP, because there are always other variables at play. Although there are many benefits to conducting this analysis using a CGE model, one of the downsides is that placing a single restraint in place forces the model to change any number of variables to come to a new equilibrium. This makes isolating for one or two variables very challenging. I concluded that I am not able to further explore this relationship.