CANADA'S NET ZERO FUTURE

FINDING OUR WAY IN THE GLOBAL TRANSITION

FEBRUARY 2021

CANADIAN INSTITUTE FOR CLIMATE CHOICES
INSTITUT CANADIEN POUR DES CHOIX CLIMATIQUES

Cover and following page:
Traditional territory of the Blackfoot/Niitsítapi, Ktunaxa ?amak?is, Stoney and Tsuu T'ina

CONTENTS

ABOUT THE INSTITUTE

The Canadian Institute for Climate Choices brings together experts from diverse disciplines to undertake rigorous research, conduct insightful analysis, and engage a range of stakeholders and rightsholders to bring clarity to the climate challenges and transformative policy choices ahead for Canada. We are publicly funded, non-partisan, and independently governed. Learn more at climatechoices.ca

1 INTRODUCTION

Canada has committed to reducing its greenhouse gas (GHG) emissions to net zero by 2050. It has proposed new legislation that legally commits the country to that goal and creates a mechanism for defining five-year milestones on the way to achieving it. But what does all of this mean in practical terms? This report seeks to bring clarity to Canada's efforts to achieve its net zero target—examining what it will take to get there and how reaching this goal could shape our shared future.

Put simply to reach net zero Canada would need to take as many emissions out of the atmosphere as it puts in, rather than leaving them there to trap heat and contribute to climate change. That requires 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.

Yet achieving net zero—and understanding what that means for life in Canada between now and 2050—is far from straightforward. Our research demonstrates that a range of very different visions of Canada's net zero future would be consistent with that overarching goal.

In fact, we heard many divergent views regarding which visions were most likely and most desirable when we engaged perspectives from across the country—including experts within the Institute. Opinions differ about the prospects of different net zero technologies and energy systems. And the "net" in net zero is itself open to a wide variety of interpretations. To what extent does net zero mean reducing existing emissions at the source, versus capturing and storing GHGs, whether through nature-based solutions or engineered ones that use technology?

In other words, **the idea of achieving net zero raises as many questions as it answers**. What might a net zero economy look like in this country in more concrete terms? Can Canada get from here to there in 30 years? What are the broader implications of doing so? What choices must Canadians make along the way? And what factors are beyond Canada's control?

Tackling these questions *now* is essential. Though 2050 may seem remote, 30 years is actually a very short timeframe to transform Canada's economy and energy system in ways that sustain or enhance the prosperity and well-being of

Canadians. Achieving net zero by 2050 requires immediate planning and action. Without policy initiatives to drive Canada's progress toward net zero, the country will continue to build long-lived, emissions-intensive infrastructure, making long-term emissions reductions harder and more expensive—even while the impacts of a changing climate intensify and global markets race toward low-carbon solutions.

The economic, social, and environmental costs of climate change impacts are immense and growing, and they underscore the importance of taking decisive action. The Institute is producing a series of reports to identify and quantify these impacts in Canada and show the benefits of prioritizing adaptation and resilience alongside emissions reductions. The first report of the series, *Tip of the Iceberg: Navigating the Known and Unknown Costs of Climate Change for Canada,* was released in December 2020 (Sawyer et al., 2020).

Ultimately, governments in Canada must keep both the short term and the long term in sight to successfully manage a net zero transition. They must respond to the urgent need for action by pursuing a pathway to meaningfully reduce emissions over the coming decade (in order to meet Canada's 2030 target to reduce GHG emissions by 30 per cent below 2005 levels) and set the course for the net zero transition. But at the same time, they must lay the foundations for even more dramatic and disruptive changes to come, keeping a sharp eye on the rapidly changing technologies, markets, and geopolitics that might shape those changes. **Uncertainty and disagreement regarding the future shape of a net zero economy and energy system cannot justify delay**.

In this report, we consider a wide range of potential pathways to net zero, examining the ways they are similar and the ways they are different. Separating these convergences and divergences can better inform Canada's vision of the net zero future while also providing clarity on the policy choices that will take the country there.

First and foremost, we find that **net zero by 2050 is achievable for Canada and many pathways could lead to that goal.** While some of the pathways that we consider could ultimately prove unavailable (depending on domestic and global technology and market and policy outcomes), enough potential routes to net zero exist overall that we conclude that the net zero goal is achievable. Yet, the existence of multiple potential pathways does not mean navigating any single one will be easy. Reaching a net zero goal will be a complex and challenging project regardless of which pathway Canada takes, requiring stringent and effective government policy at a level well beyond any implemented to date.

We find that between now and 2030, the cost-effective solutions to reducing emissions are broadly consistent. **Many solutions—including improving energy efficiency, shifting to non-emitting electricity, adopting heat pumps and electric vehicles—will likely be part of Canada's net zero journey no matter which pathway is taken**. These "safe bets" will contribute a significant portion of the emissions reductions required to get Canada to its 2030 emissions target. In fact, as illustrated in our infographic at the end of this section, these safe bets are central to achieving Canada's 2030 target independent of international market conditions or developments in emerging technologies. Scaling up the stringency of existing policies across Canada, especially building codes, flexible regulations for fuels and vehicles, and carbon pricing—as the federal government has signalled it intends to do through its climate plan released late last year (ECCC, 2020a)—can create incentives for the rapid deployment of these safe bet solutions.

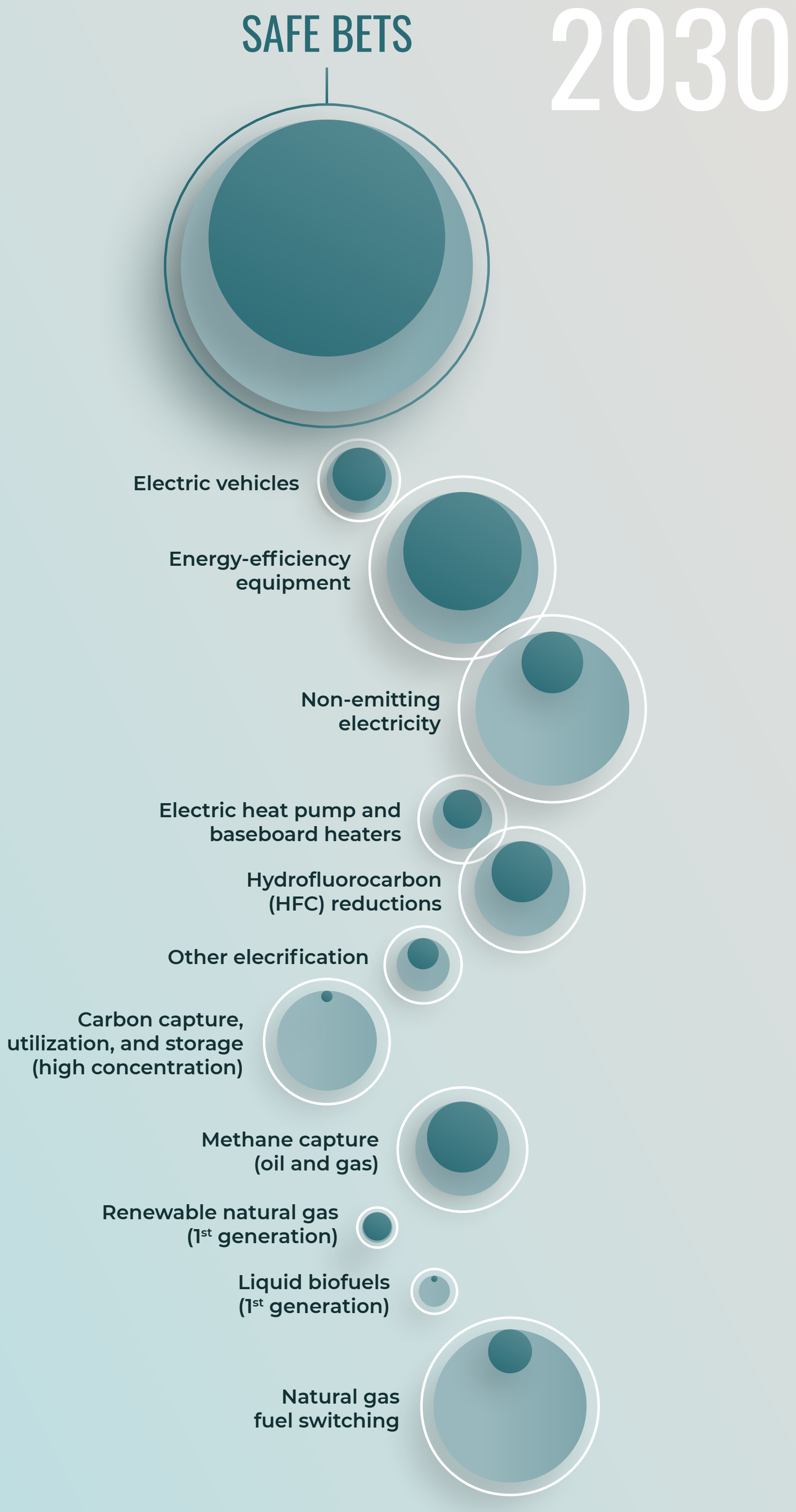
In the longer term, risk and uncertainty make planning for net zero more complicated. Much can and will change between now and 2050. Policy changes around the world will shape market conditions. Technologies will evolve and improve (including both existing early-stage ones and breakthroughs that we can't yet foresee), partly in response to those policy changes. And many of these potential shifts are outside of Canada's control. The transition will certainly come with opportunities for Canada, but it can be difficult to say with certainty where those will be. Given this uncertainty, diversity of opinion on what Canada's net zero future will look like is to be expected—and even welcomed.

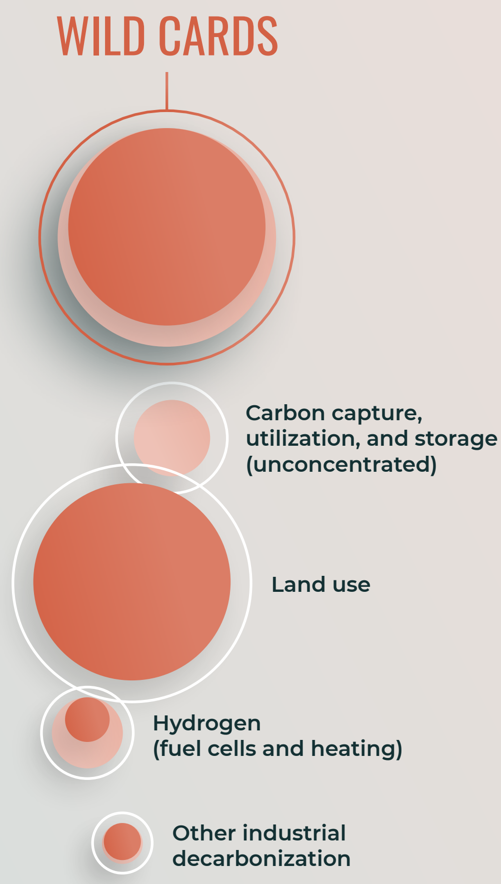
The uncertainty around Canada's longer-term path, however, raises challenging questions and choices for policy makers. For example, should policy remain technology-agnostic or should it aim to accelerate certain early-stage solutions? Should Canada "hedge" against the uncertainty in potential pathways? Should it seek to make specific pathways more likely? And what economic and social trade-offs do these potential pathways entail that might influence government and individual preferences?

This report does not provide a complete answer to these questions. It does, however, provide a strong foundation for engaging Canadians, stakeholders, rightsholders, and policy makers to find answers together. By rigorously exploring credible potential pathways between today and a net zero future in 2050, we are providing a framework for assessing the feasibility of Canada's potential pathways and enabling informed dialogue about the trade-offs involved.

An inclusive transition to net zero will require engaging diverse perspectives now as Canada defines what kind of pathway it will aim to take into the future. In many sectors and regions of the country, these in-depth conversations are well underway. In others, they are only just beginning. Our analysis is intended to help guide and inform these essential conversations.

The remainder of this report is structured as follows. Section 2 defines the challenge and our approach to exploring it, laying out the primary forces that drive uncertainty and risk on the way to 2050. It also describes our approach to exploring Canada's possible net zero pathways, which draws on both modelling and qualitative approaches. Section 3 discusses the overall feasibility of a transition to net zero in Canada, looking at its potential impacts on how Canadians produce and consume energy. Section 4 examines what different pathways would mean for the way Canadians live, work, and move. Section 5 identifies the solutions that together form a winning hand for Canada's net zero transition, grouping them as either safe bets or wild cards; it also considers three possible net zero energy systems for Canada's future, each with its own trade-offs and hurdles. Section 6 summarizes our main findings from the analysis. Finally, Section 7 provides recommendations for all orders of government in Canada to support a transition to net zero, even in the face of uncertainty.



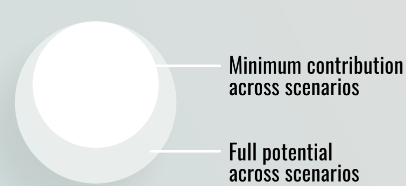


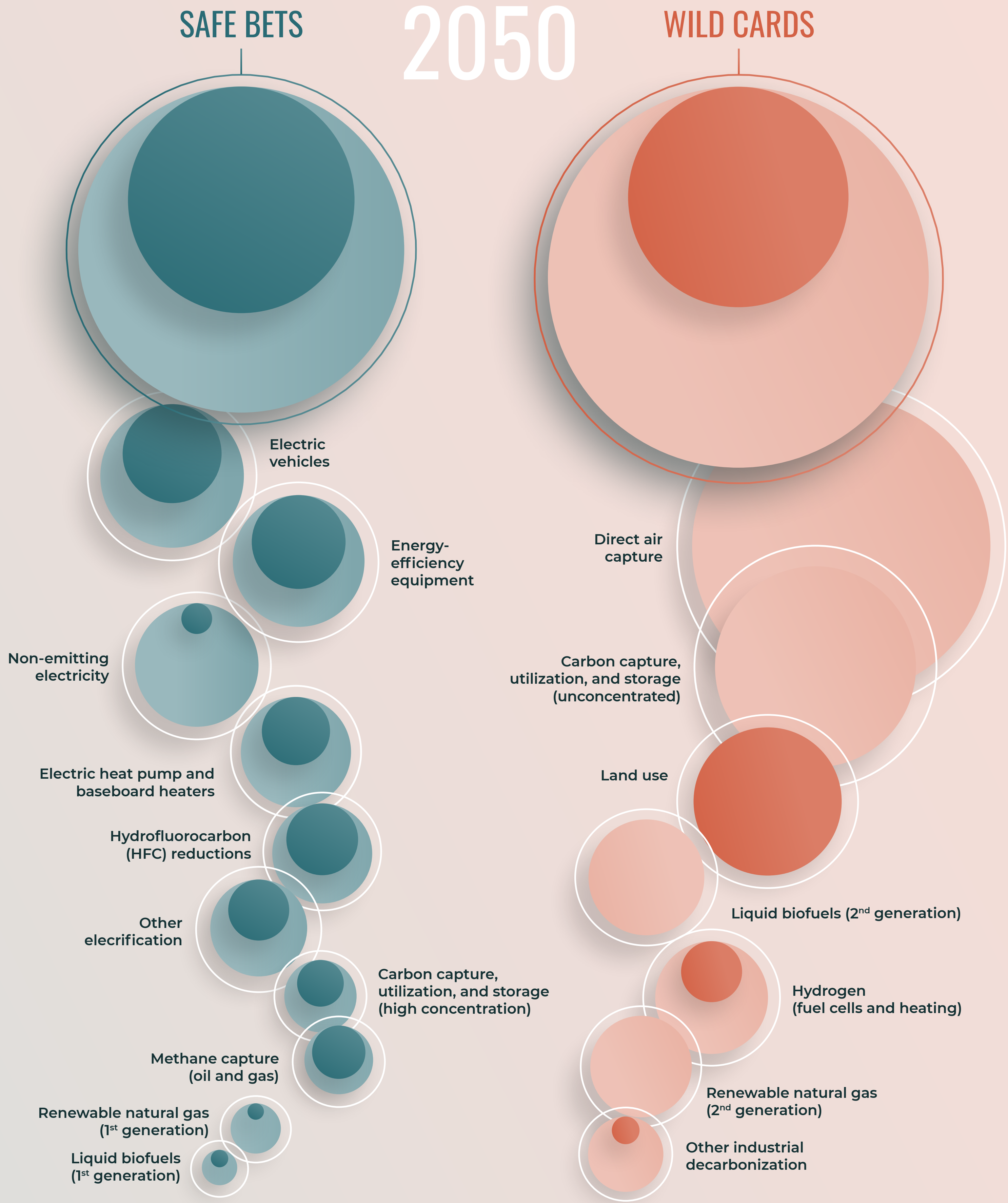
Across all the scenarios we examine, **safe bets** are expected to generate most of the reductions by 2030. **Wild cards** will not be sufficiently developed by then to play more than a supporting role.

By 2050, the contribution of emissions reductions from **safe bets** is more variable, as **wild cards** start to play a bigger part.

Safe bets: Emission-reducing technologies and solutions that are already commercially available and face no major constraints to widespread implementation.

Wild cards: Solutions that may come to play a significant and important role on the path to net zero, but whose ultimate prospects remain uncertain.




SAFE BETS
2050
WILD CARDS
Electric vehicles
Energy-efficiency equipment
Non-emitting electricity
Electric heat pump and baseboard heaters
Hydrofluorocarbon (HFC) reductions
Other elecrification
Carbon capture, utilization, and storage (high concentration)
Methane capture (oil and gas)
Renewable natural gas (1st generation)
Liquid biofuels (1st generation)
Direct air capture
Carbon capture, utilization, and storage (unconcentrated)
Land use
Liquid biofuels (2nd generation)
Hydrogen (fuel cells and heating)
Renewable natural gas (2nd generation)
Other industrial decarbonization

2 DEFINING CANADA'S PATHWAYS TO NET ZERO

This section lays out the context for Canada's net zero challenge and explains our approach to assessing possible pathways to achieve it.

2.1 WHAT DOES CANADA'S NET ZERO GOAL MEAN?

In 2019, the federal government announced a long-term emissions reduction target of "net zero" by 2050 (ECCC, 2019a). This is a relatively new concept in many circles and one that can easily be confused with other aspects of the domestic and global response to climate change. We will begin by clarifying our use of the term and the criteria we are using in our analysis to unpack its implications for Canadians.

How we define net zero

Achieving net zero emissions means that Canada either reduces its emissions to zero or finds ways to pull any emissions it continues to generate out of the atmosphere (and store them permanently), rather than leaving them there to trap heat and contribute to climate change.

Here is a more technical definition of net zero: An energy and economic system in which Canada's total GHG emissions from energy production and consumption, industrial processes, and land use, minus "negative emissions" (or carbon dioxide removal) from nature-based solutions and engineered interventions results in a sum total of zero net emissions.[1]

Reaching Canada's net zero goal is a question of accounting as well as physical science, and the way the federal government (and other governments in Canada) will define that goal remains unclear. For the purposes of this report, however, we defined the term under three clear parameters:

1. A national system boundary;
2. Counting both sides of the ledger, both gross and negative emissions; and
3. Excluding international transfer mechanisms.

How do these three parameters shape our definition of net zero?

1 Other definitions of net zero that focus on net zero emissions of carbon dioxide, but not necessarily other greenhouse gases, are possible. The Paris Agreement goal of limiting global temperature increase to 1.5°C calls for global CO_2 emissions to fall to net zero by 2050, for methane emissions to fall by 50 per cent, for N_2O emissions to fall by one-third, and for black carbon emissions to fall by at least half.

First, a national system boundary means counting only those emissions that occur within Canada's borders. Goods and fuels produced in Canada might well increase global emissions when they are consumed abroad, but in our analysis these external consumption emissions are not included. This is consistent with many other global GHG accounting methodologies. We also exclude "embedded" emissions—those that occur abroad in the production and transportation of goods that are eventually consumed in Canada. This too is consistent with global accounting methodologies.[2] It also reflects the fact these emissions abroad will be accounted for in other countries' climate plans and policies.

Counting both sides of the ledger indicates that negative emissions (emissions sequestered through nature-based or engineered solutions), where genuine and verifiable, are included as a viable method of offsetting gross emissions to achieve a net total of zero. Ensuring these emissions are accounted for credibly, however, will not be straightforward. Concerns include: additionality (whether the emissions would have been sequestered anyway, either naturally or by another process); measurement (ensuring the negative emissions tally corresponds to real amounts of sequestered emissions, especially when the effects of natural processes have to be estimated); and permanence (ensuring that negative emissions from sequestration in geological formations or in biomass remain there more or less permanently).[3]

Excluding international transfer mechanisms means that our net zero pathways do not allow domestic emissions to be offset by international transfers of emissions cuts through trading systems such as those that may be developed under the Paris Agreement's Article 6. We exclude these mechanisms because they are still undefined by the United Nations Framework Convention on Climate Change (UNFCCC).[4] Moreover, there remain strongly divergent views regarding whether these kinds of transfers, once formalized, should be recognized as a legitimate way of reaching individual country targets or only used as a way of increasing total global ambition.

The mounting wave of net zero pledges

Canada's net zero pledge brings its long-term GHG target in line with the recommendations of the United Nations' Intergovernmental Panel on Climate Change (IPCC), which has stated that carbon dioxide emissions would have to fall worldwide to net zero by 2050 in order to limit global warming to 1.5°C and reduce the likelihood of the most catastrophic consequences of climate change. Missing this 1.5°C target will have severe and widespread impacts around the world, from biodiversity loss and extreme weather to costly natural disasters (Hoegh-Guldberg et al., 2018). The federal government's commitment has since been matched by a number of prominent private sector actors, including major oilsands producer Cenovus Energy and the Canadian Steel Producers' Association. A wide range of international businesses and industry groups have also

2 While United Nations Framework Convention on Climate Change (UNFCCC) accounting methodologies exclude these sources of emissions from countries' national emissions inventories, it is nevertheless possible for countries to measure and report them, as the United Kingdom does. Some companies (including BP, Shell, Equinor, and Repsol) have begun to include them in their own internal accounting and reduction targets.

3 UNFCCC accounting has methodologies for quantifying carbon dioxide sequestered in biomass and soil. But there is not yet a mechanism for recognizing sequestration from engineered forms of negative emissions.

4 This does not mean that a bilateral cap-and-trade system link such as that that exists between California and Quebec does not have a credible path to getting recognition under UNFCCC accounting methodologies. Rather, it means that since there is not as of yet any official recognition for these kinds of linkages nor any emerging consensus on what would be required for these them to gain official recognition (e.g., comparable emissions-reduction targets across the two jurisdictions), we have excluded them from our analysis.

Under the 2015 Paris Agreement, nearly every country committed to limit warming to well below 2° C and ideally 1.5° C. The latest science finds that limiting warming to these levels will require reducing emissions to net zero by mid-century.

made net zero pledges, including oil majors BP, Total, and Occidental; companies like Patagonia and the Body Shop; and the Asset Owner Alliance, which includes some of the world's largest pension funds and insurers.

Globally, Canada joins its peers as part of a fast-building wave. More than 100 countries representing over half of global gross domestic product (GDP) have net zero commitments in place or in the works, including European countries such as Germany, Denmark, and the United Kingdom, which are setting the pace in the global energy transition. South Korea and Japan have committed to net zero, as has China, the world's largest emitter (CGTN, 2020). Other prominent members of the net zero movement include some of the largest and most influential U.S. states (California, New York, and Washington), a group of major global cities (among them Paris, Oslo, Stockholm, and Buenos Aires) and several Canadian provinces.[5]

2.2 HOW TO THINK ABOUT PATHWAYS TO NET ZERO

For the purpose of this report, we define pathways to net zero as credible, internally consistent linkages and routes between current conditions and that future state. A net zero scenario for 2050 is only meaningful if a credible pathway exists to achieving it. And that pathway is only credible if it relies on conditions and outcomes that are mutually coherent.

The pathways to net zero we explore in this report are not predictions—the future is far too uncertain for that. Rather they survey the range of possibilities that pursuing Canada's net zero

5 In Canada, Nova Scotia passed legislation in 2019 that commits the province to reach net zero emissions by 2050. In 2020, Newfoundland and Labrador signalled it plans to do the same, as did Quebec and Yukon. At the municipal level, the City of Toronto also endorsed a target of net zero by 2050 as part of its climate emergency declaration.

goal could present, as well as the opportunities and trade-offs of each.

What major drivers define possible paths to net zero?

Canada's available pathways to net zero ultimately depend on a range of drivers—economic, political, cultural, and technological factors that will produce particular outcomes and interact with each other along the way. Some of these are factors that Canada completely controls, some that it has only a partial say in, and some that fall completely outside Canada's control. And many are still uncertain.

One factor certain to play a major role in the journey to net zero is technological innovation. The cost declines stemming from such innovations can be revolutionary. The plunging price of solar power, for example, sent the technology racing from margin to mainstream, as costs of utility-scale solar energy dropped by 82 per cent and total solar installations grew more than 14-fold in a single decade (IRENA, 2020; IRENA, 2019). Such dramatic shifts provide Canada with better and cheaper technology. They also create opportunities to learn to use the equipment more efficiently.

Cleantech costs drop for a number of reasons, including investments in research and development, learning by doing, economies of scale, and knowledge spillovers. Canada can affect cleantech costs through its policy and investment choices. One significant factor in those costs that Canada has little control over, however, is global policy action. Initiatives taken by governments in the rest of the world will have profound effects on which pathways to net zero are available to Canada and on their relative costs. This is both because concerted action in other countries will lower the costs of cleantech (due to global knowledge spillovers and economies of scale) and because it can create opportunities for Canadian companies that produce cleantech goods and services. On the other hand, action abroad could also drive up the costs of some net zero options in cases where it leads to increased competition for vital resources.

In a similar vein, policy choices made outside Canada will determine the global demand for oil, gas, and coal in the years to come, which in turn will affect Canada's net zero path by shaping the market for Canadian fossil fuel exports. Factors such as increasing electric vehicle sales or sustained high production volumes by other global suppliers could continue to depress prices and lead to slower growth or even declines in Canadian oil and gas production, reducing emissions from the sector. If instead oil and gas prices rise significantly in the years to come, Canada's production could remain at current levels or expand, making it harder for Canada's oil and gas sector and the broader economy to reach net zero.

The viability of one category of long-term solution—negative emissions solutions—could have a particularly significant impact on Canada's path to net zero. Canada's huge land mass provides enormous potential for nature-based GHG sequestration. Measures that aim to unlock these solutions' full potential would need to take into account possible implications for Indigenous Peoples' rights, title and traditional territories. They would also raise questions about competing land uses, including food production and protection of biodiversity. Engineered negative emissions solutions such as direct air capture and bioenergy with carbon capture and sequestration could also come to play a substantial role in reaching Canada's net zero target. They may also present significant opportunities for Canada to benefit economically. But these solutions remain at the demonstration stage, and there is a lot of uncertainty regarding which—if any—will prove cost-effective and scalable. (See Box 4 for an explanation of negative emissions solutions.)

Finally, Canada's policy choices at every order of government will play a major role in defining Canada's net zero future. These choices will not only affect which path Canada takes to net zero but also which paths are even available. Federal, provincial, territorial, municipal, and Indigenous initiatives—including regulations, standards, incentive programs, and carbon pricing—set the pace for the nation's adoption of low-carbon solutions, affect the range of technologies developed, and determine which technologies and solutions are on offer for Canadian businesses and households.

What drivers are beyond our analysis?

There are many additional factors that could shape Canada's pathways to net zero in dramatic and unpredictable ways. Our analysis mostly leaves these aside in light of the huge uncertainties surrounding them.

Broader effects of innovation are hard to predict. For example, the speed at which machine learning and artificial intelligence develop could accelerate other technological changes or radically boost efficiency. And then there is the potential for technological leaps—moonshot innovations ranging from small modular nuclear reactors to a radically cheaper electricity storage technology—which are highly unlikely in the short term but still hold the potential to redraw the path to net zero overnight.

Market preferences regarding climate issues are already shifting but could accelerate well beyond their current pace. Investors may come to view climate change risks and opportunities as much more central to everyday business decisions, speeding up the global energy transition (Makortoff, 2020).

Geopolitical shifts are similarly uncertain. Political upheaval internationally could hinder efforts to coordinate climate action, while a stronger climate activist movement would put greater public pressure on policy makers to take faster and more ambitious action. And the entire global financial system could change in ways that alter the course to net zero—a more integrated global system, for example, would likely make the adoption of low-carbon technologies cheaper and more readily available than a siloed retreat into nationalism would.

Global market shifts and geopolitics could shape Canada's pathways to net zero in dramatic and unpredictable ways.

What further factors must be considered in navigating pathways?

The factors above will determine which pathways to net zero exist and which ones never materialize, as well as their costs and broader implications. But a range of other factors matter when comparing and assessing the likely implications and outcomes of those pathways.

Perhaps most critically, the impact of Canada's policy choices extends beyond emissions levels. Addressing social inequality is a key factor in the potential success of Canada's net zero plan. The benefits of the country's emissions-intensive economy are not spread evenly—for example, more than 10 per cent of Canadian households lacked secure, adequate, or affordable housing in 2018 (Statistics Canada, 2020). Issues of social, racial, and environmental justice are key considerations in a net zero transition. Government policy (or lack thereof) will determine how fair and equitable the transition to net zero is, how negative impacts on affected sectors and workers are dealt with, and how the co-benefits of different climate actions (reducing air pollution, for example) are weighed in decision-making.

Canada's regional variation in emissions means that the net zero challenge is very different from province to province and from sector to sector. Alberta and Saskatchewan, for example, face challenges owing to their substantial oil and gas industries that are much different than the ones facing hydroelectric powerhouse provinces like Quebec and British Columbia. And the North, with its existing social and economic difficulties and continued reliance on diesel fuel, has its own unique problems to contend with.[6]

These regional and sectoral differences are amplified by the nature of Canada's governance as a decentralized federation, which obliges the federal government and the provinces and territories to share responsibilities for navigating pathways to net zero on several fronts. Climate policies, for example, are set by both the federal government and the provinces and territories, while other areas crucial to emissions cuts—particularly natural resource development, electricity generation, and intra-provincial electricity transmission—are managed almost exclusively by the provinces.

Indigenous Peoples have a critical role in these governance matters. This is both because Canada's net zero pathway must uphold Indigenous rights and because Indigenous communities have vital knowledge and skills for navigating the transition. The Government of Canada has committed to prioritizing reconciliation with Indigenous Peoples after generations of colonization, marginalization, and neglect that continue today. Canada's route to net zero must recognize the inherent rights of Indigenous Peoples (as affirmed by Section 35 of the Canadian Constitution) and reflect the principles of the United Nations Declaration on the Rights of Indigenous Peoples (to which Canada is a signatory). In Box 1, we discuss the essential worldviews, knowledge, and action that Indigenous Peoples can bring to bear in a transition to net zero.

6 Our analysis tries to draw out regional implications where possible, but in many cases the complexity of doing so limits our analysis to a national scale. We expect to roll out regional snapshots as complementary analysis.

BOX 1

The Old Crow solar farm is owned and operated by the Vuntut Gwitchin First Nation.
(Photo: Vuntut Gwitchin Government)

Indigenous worldviews and leadership on climate change

Indigenous worldview is not a uniform concept shared by all communities and cultures—just as there are many Indigenous Peoples, there are also a wide range of Indigenous languages, worldviews, and experiences. These diverse worldviews, however, share a number of central principles that have important implications for Canada's net zero future. In particular, they uphold a holistic understanding of nature, in which all its elements—including people, objects, and the environment—are connected and related. Stemming from this view is a belief that the land is sacred and should not be available for development and extraction for the benefit of humans and that technology should reflect and respect this balanced relationship with the natural world (Little Bear, 2009; Little Bear, 2012). Understanding and respecting differences in worldviews is critical for building meaningful relationships between Indigenous and non-Indigenous people in Canada and for charting a path to net zero based on mutual respect and understanding. Canada's path to net zero provides many opportunities to promote Indigenous agency, sovereignty, and self-determination and to advance social and environmental justice.

Indigenous Peoples are particularly vulnerable to the impacts of climate change, stemming from geographic, economic, and social conditions perpetuated by systemic marginalization and colonialism. But they are also uniquely positioned to prepare for and respond to the impacts of climate change. Across Canada, Indigenous communities are drawing on their traditional and local knowledge alongside technology to take action on climate change, creating local opportunities and benefits at the same time.

Harnessing Indigenous and local knowledge is critical to the management and conservation of ecosystems. Indigenous Peoples are using their in-depth knowledge of their territories—the source of their livelihoods for generations—to protect biodiversity and to safeguard the long-term health of their air, lands, and waters. For several years, the Indigenous-led Guardians Program has empowered communities to manage and protect their ancestral lands and waters according to traditional laws and values. Over 40 Indigenous Nations and communities in Canada have launched Guardians programs (Indigenous Leadership Initiative, 2020). In 2020, one of these communities—the Łutsël K'é Dene First Nation in the Northwest Territories—was awarded the United Nations Development Programme's Equator Prize, an award that celebrates Indigenous Peoples and local communities pioneering nature-based solutions. Łutsël K'é was recognized for its work to establish Thaidene Nëné, an Indigenous protected area spanning 6.5 million acres that was co-established with Parks Canada and the Government of the Northwest Territories (Nature United, 2020).

Many Indigenous communities across Canada are also deploying renewable energy projects in their communities to achieve energy autonomy, establish more reliable energy systems, support community and economic development, and reduce emissions. Communities across Canada (covering all provinces and territories) have implemented thousands of projects, including solar, wind, biomass, hydro, and building retrofits (Indigenous Clean Energy, 2020). For example, the Old Crow solar project, owned and operated by the Vuntut Gwitchin First Nation in the Yukon Territory, is expected to meet 100 per cent of the community's electricity needs during the summer months when the sun is shining and reduce the community's diesel use by 190,000 litres per year (Arctic Council, 2020).

To be effective, Canada's policy choices will also have to be fine-tuned to navigate complex inter-governmental relationships. But Canada's decentralized governance also represents an opportunity to embrace a range of policies in ways that recognize the diverse economies, emissions profiles, and emissions-reduction strategies that exist from one region to another. Indeed, federal, provincial, territorial, municipal, and Indigenous governments across Canada are already acting in their own ways—setting their own climate goals and building frameworks and developing policies to achieve them. Coordinating this work will be aided by the development of a pan-Canadian climate accountability framework that sets milestones for progress based on consultation and expert input, as pledged by the federal government and discussed in our report *Marking the Way* (Beugin et al., 2020).

2.3 OUR ANALYTICAL APPROACH

We used a combination of technical modelling, literature review, and input from experts and knowledge holders to identify and assess more than 60 different potential economy-wide pathways to net zero by 2050. Each pathway represents a specific combination of emissions-reducing solutions being deployed over time, under a range of different conditions and assumptions.

Our overall approach to assessing pathways to net zero is as follows:

First, we **reviewed existing literature** on deep emissions reductions pathways, both in Canada and internationally, to identify key trends, drivers, and implications. This analysis helped identify the drivers described above and also provided comparisons to help us ground in truth the analysis we produced subsequently. Many of these studies focused on Canada, but we also reviewed net zero or "deep decarbonization" studies for the European Union, the United Kingdom, and the United States. (We provide an overview of these analyses and their key findings in Annex 1.)

Second, we used a comprehensive model of Canada's economy, GHG emissions, and energy system to **identify a broad range of economy-wide pathways** to net zero under various assumptions and drivers (see Box 2 for more information). Using this model ensured that the pathways were internally consistent; that is, that assumptions were not at odds with each other and that credible paths existed to connect the current Canadian economy to different types of net zero futures. This modelling also allowed us to determine the conditions necessary to realize various net zero pathways. (Annex 2 describes the full range of scenarios and assumptions we considered.) Taken as a whole, this range of scenarios accounts for the most significant aspects of risk and uncertainty facing Canada's transition.

Notably, these pathways are not linked to specific policy choices—they could be achieved through various combinations of regulatory policy, carbon pricing policies, or even public spending.[7] These policies could be federal, provincial, territorial, municipal, or Indigenous. The modelling does not analyze specific policy choices in order to focus on how other drivers and conditions could affect Canada's available pathways to net zero.

Third, we **assessed the implications of these pathways**. We used the model to explore macro-

7 While our modelling does not make assumptions about which policies would be used to achieve the pathways we consider, it does reflect the existing climate policies implemented in Canada to date. Specifically, it uses the policies found in the "With Additional Measures" scenario in *Canada's fourth Biennial Report to the United Nations Framework Convention on Climate Change (UNFCCC)*, as outlined in the report's Table A2.39. These include policies in place or announced as of September 2019 (ECCC, 2019b).

There are many possible routes to Canada's net zero target.

economic outcomes such as changes in the structure of the economy, as well as microeconomic outcomes such as household energy use and costs. We also assessed the air quality impacts and health benefits of the various pathways using a second, supplementary modelling tool.[8] At the same time, we recognize that regardless of how useful our modelling is, it is limited and incomplete. We therefore also assessed implications qualitatively, drawing on relevant literature and secondary analysis.

Fourth, we **compared across the alternative pathways** revealed by our analysis, paying particular attention to outcomes that were common in multiple scenarios, as well as key factors that drove widely divergent outcomes between scenarios. As a result, most of the results we present in this report are not for individual scenarios but for the range of possible outcomes across the full set of scenarios. Figures in the report therefore represent results across a spread, rather than discrete estimates.

Fifth, we **evaluated three different potential net zero energy systems, each representing substantively different pathways** to net zero: a fossil fuels and negative emissions energy system, a biofuels system, and an electrification and hydrogen system. To make our findings more concrete, we then looked beyond the modelling. For each of these potential net zero energy systems, we explored likely outcomes and implications, drawing on both quantitative and qualitative analysis tools.

We also **evaluated the feasibility of these different energy systems** by considering the barriers to realizing each of them in practice. For each energy system pathway, we assessed the relevant driving factors that can be affected by Canadian policy, the factors that are outside of Canada's policy influence, and key outstanding questions and uncertainties.

Throughout this process, we **consulted with a range of perspectives** to test our assumptions and results and to ensure our findings were representative, credible, and relevant for diverse audiences and decision makers. Our engagement included academic experts, practitioners, individual companies, industry associations, federal and subnational governments, Indigenous Peoples, and labour unions.

8 This modelling uses the CO_2 emissions pathways modelled in gTech as an input (see Box 2). It estimates the emissions of criteria air contaminants associated with the sectoral and provincial emissions found under our different modelling scenarios. It then uses the United States Environmental Protection Agency's Community Multiscale Air Quality (CMAQ) model to attribute national mortality counts associated with chronic exposure to particulate matter air pollution and its monetary valuation to location-specific source impacts. Combined with projections of sectoral emission profiles that are based on historical trends, these impacts are aggregated into estimates of the provincial-level population health burden of air pollution, under various different net zero pathways. For more information, see Soltanzadeh & Hakami (2020).

BOX 2

The gTech modelling tool and how we selected scenarios

In this report, we have used Navius Research's gTech model to explore the regional, sectoral, technological, and economic implications of achieving Canada's target of net zero emissions by 2050. The gTech model is a "recursive dynamic computable general-equilibrium model," combining detailed representations of energy-related technologies with information on consumer behaviour and preferences and Canadian macroeconomic data to generate its results. (For more details, see Navius Research [2021].)

The gTech model provides rich technological detail. A wide range of energy technologies are represented in the model—everything from 41 different vehicle types to various heat production technologies in the crude oil industry. The model is regularly updated to reflect technological and market advancements, providing a clear picture of available technologies, the fuels or other energy sources they use, their energy efficiency, their GHG emissions, and their costs. The model also projects the evolution in the cost and performance of these technologies over time, based on relevant literature and expert input. (The assumptions in these projections can be varied from one modelling scenario to another, providing additional information about their significance.) Emerging or potential technologies are also represented in the model. Timelines for their emergence, their expected cost evolution, and their expected performance are also based on relevant literature and expert input. The availability of these technologies can be switched on or off depending on modelling assumptions, and assumptions about their cost evolution and performance can be varied as well. The overall technological detail of the gTech model allows for rich analysis of the economics of different technologies, their expected uptake under different conditions and assumptions, and their impact on energy use and GHG emissions.

gTech includes a detailed representation of the Canadian economy. The model represents 110 sectors, a labour sector, and a government sector. The goods and services that these various sectors provide act as inputs to other sectors in a way that is consistent with how the actual Canadian economy operates, based on input-output tables from Statistics Canada. The model simulates production levels and prices for goods and services through the interaction of supply and demand for them across sectors. It represents not only the national economy but individual provincial and territorial economies as well. It uses credible projections for national and regional populations, demographics (including the income distribution), and labour force growth. It represents the consumption, personal, and corporate tax system, including differences found across Canadian provinces. It simulates trade with the rest of the world by modelling the sensitivity of exports and imports to changes in prices and costs in Canada's domestic market and by using credible projections of global demand for key goods and commodities. It models the United States economy in greater detail and explicitly simulates the trade relationship between Canada and the United States. And all of these relationships are regularly recalibrated using actual historical data to make sure that the model is accurately representing the Canadian economy.

gTech models behaviour and choice in a realistic way. Rather than assuming that businesses and consumers make technology choices purely on the basis of cost and return on investment, gTech draws on empirical studies to model preferences. For example, it has households weigh up-front costs against future savings in their purchasing decisions by using a behaviourally realistic discount rate, rather than a financial discount rate, which has been shown to overvalue future savings relative to empirical evidence on how consumers actually behave. It models "intangible" costs associated with new technologies that reflect consumers' reluctance to adopt an unfamiliar technology. It also has these intangible costs decline once the technology becomes more widespread, representing the "neighbour effect" that empirical studies have shown to affect technology adoption. And it models business investment decisions using internal rates of return that exceed market interest rates, just as businesses do in real-world decision-making.

Like all models, gTech is not perfect. For example, its results are sensitive to the choice of exogenous (i.e., external) inputs. To ensure that its results are accurate, we commissioned a technical review of many of its key assumptions and inputs. And we also varied a number of them across the scenarios we examined, to ensure that our results were broadly robust across key outcomes and assumptions that could affect our findings.

We used gTech to explore a broad range of possible pathways. We modelled more than 60 distinct scenarios, each with its own combination of drivers and outcomes (see Annex 2 for more detail). None of our scenarios is a prediction of the future; rather, they collectively illustrate the possible economy-wide pathways to net zero under different conditions, assumptions, and choices. We used expert consultation and literature review to identify variables and conditions that could have important effects on Canada's net zero transition and that we could vary across modelling scenarios in gTech. For each scenario, we used the model to identify the most cost-effective economy-wide pathway to net zero under the specific conditions and assumptions used to represent it. We defined scenarios to explore key drivers determined domestically as well as those beyond Canada's control. These included:

- The cost evolution for electric vehicles
- Hydrogen costs and blending rates
- The cost of new non-emitting "firm" electricity generation capacity (see Box 11)
- Climate policy action in other major countries
- The availability of engineered forms of negative emissions solutions (see Box 4)
- The global oil price
- The availability of carbon capture, utilization and sequestration (CCUS) for unconcentrated gas streams
- The availability of second-generation biofuels
- The presence of competitiveness protection measures in Canadian climate policy
- The degree of improvement in the emissions intensity of oil sands production

We limited our scenarios, however, to conditions that were internally consistent (i.e., that did not rely on assumptions that were incoherent with each other). To take one example, we did not evaluate a scenario where other major countries lagged Canada in their climate policy implementation, the global oil price was low, and engineered forms of negative emissions technologies were available. A low global oil price would not be consistent with these other factors, since both would support increased demand (and higher prices) for fossil fuels.

We used this range of scenarios to assess uncertainty. Rather than reporting outcomes from individual scenarios and pathways in this report, we instead considered the range of outcomes we observe when looking across these scenarios. The figures in the report show bands of outcomes to illustrate the range of possibilities. This approach also allowed us to assess similarities and differences across scenarios, under different assumptions and conditions. It also differentiates this study from other Canadian modelling analyses.

We assessed the relative feasibility, not relatively likelihood, of alternative scenarios. We analyzed a wide range of theoretically possible pathways to understand what implications they were likely to have if they occurred. Identifying the assumptions required to realize various scenarios allowed us to identify the barriers that might exist to the emergence of those conditions and the feasibility of overcoming them.

3 CANADA'S MULTIPLE PATHWAYS TO NET ZERO

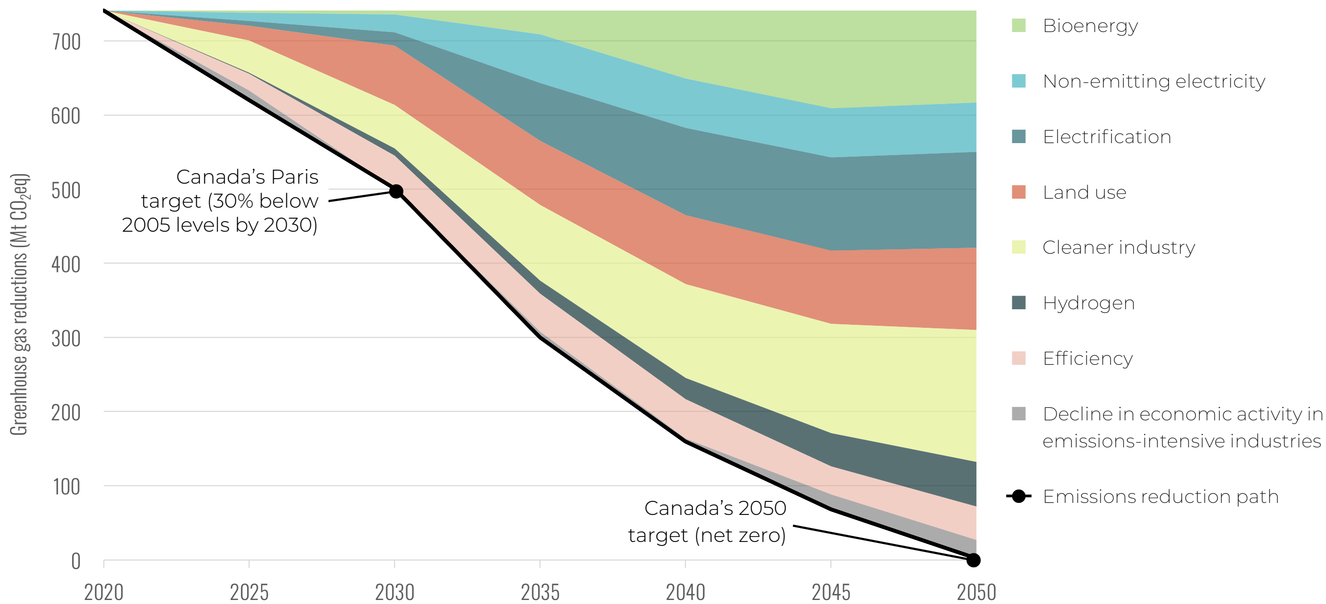
In this section, we begin with some high-level observations about the feasibility of Canada's overall commitment to reach net zero by 2050. We then look at how Canada's net zero transition could affect the way energy is used and the types of energy consumed across the country.

3.1 THE FEASIBILITY OF A NET ZERO TRANSITION IN CANADA

Our analysis clearly shows that Canada can achieve its goal of net zero by 2050 and that many pathways could lead to that goal. The various scenarios we examine—which all result in reaching Canada's 2050 target, though in different ways—see emissions-reducing solutions applied in different combinations and amounts, depending on the specific outcomes, assumptions, and conditions of a given scenario. Some of the solutions rely on technologies that are commercially available today (and that will continue to fall in cost over time). Others require significant advances or commercial scale-up of technologies that are currently in the early stages of development. All of our scenarios use credible projections of the costs and availability of current and potential emissions-reducing solutions and incorporate uncertainties around their prospects where warranted. Therefore, they all represent legitimate potential futures. While the emergence of certain conditions or outcomes could lead to some of them proving non-viable, enough potential routes to net zero exist overall that we can conclude that the net zero goal is achievable.

Figure 1 illustrates just one of the potential economy-wide pathways projected under our modelling that Canada could take to its net zero target. This scenario assumes that some key technologies are at the higher end of their projected cost, that other major countries lag Canada in their progress toward net zero, and that engineered forms of negative emissions do not prove cost-effective and scalable. As seen in the figure, this particular pathway involves a distinct combination of solutions (Sections 4 and 5 discuss specific solutions in detail). All scenarios in our modelling represent different economy-wide pathways that combine potential solutions such as these in different ways, depending on the specific mix of conditions and assumptions specified for a given scenario. In the subsequent figures throughout this section and Sections 4 and 5, we consider the range of outcomes that we find when we look *across* all these scenarios, rather than looking at results for a single one in isolation, as we have done in Figure 1.

Figure 1: One of the many potential pathways that Canada could take to net zero

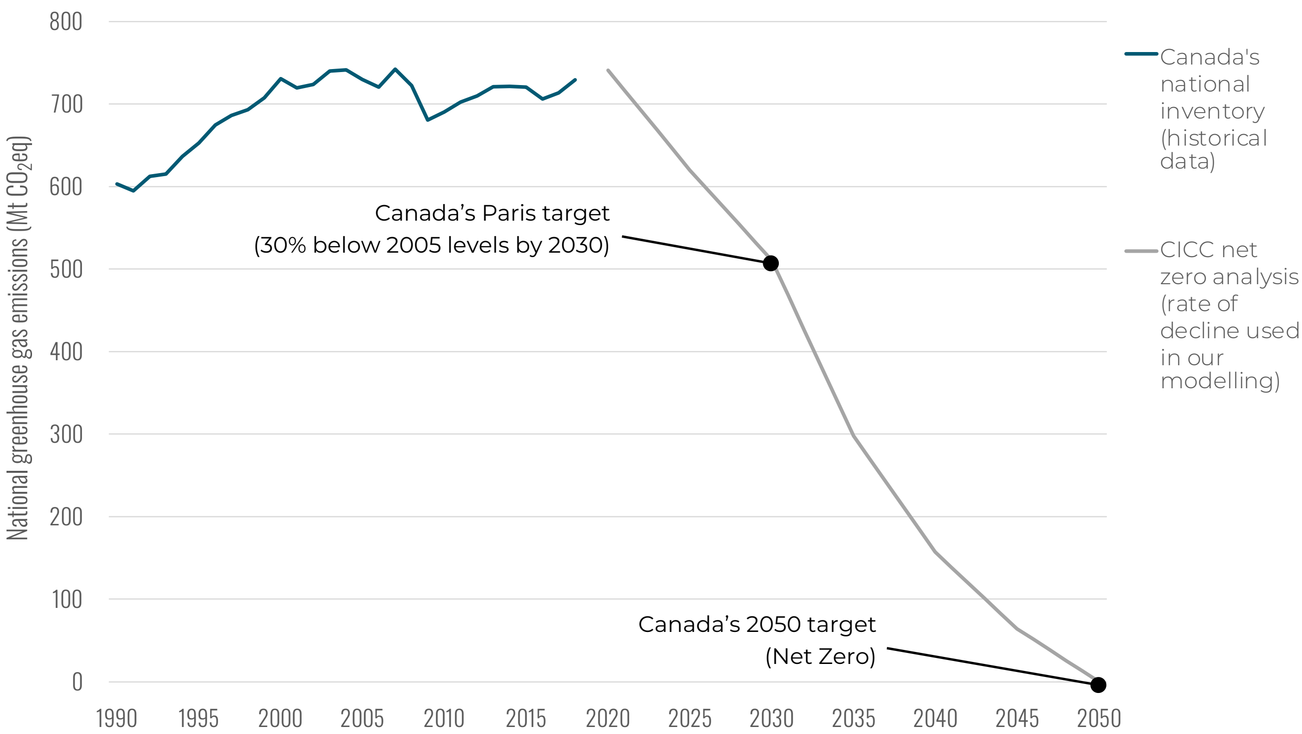


This figure shows only one of the scenarios that we examine in our modelling. As the figure illustrates, Canada's overall emissions decline over time, reaching Canada's Paris Target in 2030 and its net zero target by 2050 (emissions follow this same path under all our scenarios). Different solutions make different degrees of contributions to these overall reductions over time, as seen in the coloured wedges. This combination of solutions represents the most cost-effective pathway to net zero (estimated by our modelling) under the specific conditions, outcomes, and assumptions used to represent this particular scenario. For more on the specific assumptions used for this scenario, see Scenario 14 in Annex 2.

The existence of multiple potential pathways does not mean navigating any single one of them will be easy. Reaching Canada's net zero goal will be a complex and challenging project regardless of which pathway is taken, requiring coordinated and sustained efforts on many fronts. Reducing the costs of important emissions-reducing solutions, improving early-stage technologies, and ensuring mainstream uptake and deployment will be a massive undertaking. Canadian policy makers will surely have help—ongoing private sector innovation, voluntary actions by households and businesses, and efforts in other countries will all enhance the viability of many important solutions. But in the end the success of this transition will rest on stringent and effective government policy at a level well beyond any instituted to date.

Comparing the trajectory of Canada's historical emissions to the path to net zero underscores the challenge ahead. The new federal climate plan can put Canada on track to its 2030 target—if it is successfully implemented. But as outlined in Figure 2, Canada will need to continue driving emissions down after 2030 to get to net zero. Strong policy will be needed to put Canada on course for meeting its 2050 net zero target.

Figure 2: Comparing Canada's historical greenhouse gas emissions and the path to net zero



Canada's historical emissions are based on the latest available national inventory (ECCC, 2019a). The net zero analysis pathway from 2020 to 2050 shows the emissions trajectory that we modelled in our analysis, underscoring the depth of the emissions cuts that will be needed to reach these targets relative to historical reductions.

Getting to net zero requires a growing supply of non-emitting electricity in Canada's energy mix.

3.2 HOW WE USE AND PRODUCE ENERGY IN A NET ZERO CANADA

Energy is essential to everyday life in Canada, and finding ways to make and use energy without generating emissions is naturally the central focus of any net zero goal. Canada's current energy mix—whether used to run vehicles, heat homes, power household or office equipment, or drive industrial operations—is mostly affordable, reliable, and safely generated. But it is also the largest driver of Canada's emissions. The production and use of energy nationwide generates 616 million tonnes (Mt) of CO_2eq, or 83 per cent of total national emissions. This energy is used across many sectors in Canada (for a breakdown of emissions by sector in Canada, see Annex 3). So, Canada's energy path to net zero is of paramount importance.

Our scenario analysis finds that many of the changes to Canada's energy use that would be required to reach our net zero goal are the same down all the economy-wide pathways we examine. Regardless of other factors at play, achieving net zero will require more energy efficiency and conservation and significant changes to how energy is produced and consumed in Canada.

In the discussion below, we focus on "final end-use" energy, meaning the energy ultimately consumed to deliver services such as mobility, heat, or light. Our analysis includes both primary and secondary forms of energy. "Primary" energy refers to an original source of energy (for example, raw natural gas) while "secondary" energy or "energy carriers" refer to forms of energy that are made from primary energy (for example, electricity made from solar or wind energy). Secondary forms of energy are only zero-emissions if they are produced in a way that does not emit greenhouse gases. In a net zero system, any remaining Canadian emissions from either primary or secondary energy end-use would have to be offset. For example, electricity produced using natural gas would have to be equipped with full carbon capture, utilization, and storage (CCUS) or offset elsewhere in the system to be consistent with net zero.

Use of non-emitting energy grows across all of the paths to net zero we examine

Every net zero scenario we analyzed consistently shows non-emitting primary energy sources supplying a growing share of energy on the path to net zero. When it comes to final energy use, we find a growing role for three types of non-emitting energy carriers: electricity,[9] hydrogen,[10] and biofuels[11] (both gaseous and liquid).

Our analysis projects that, barring specific (and uncertain) technological advancements, the contribution to energy use in Canada from fossil fuels would fall dramatically on the path to net zero. We find that *if* engineered forms of negative emissions solutions and advanced types of CCUS technologies were to prove both cost-effective and scalable, fossil fuels could potentially continue to supply a significant share of Canada's end-use energy, and their total use might even grow. But this is a highly uncertain outcome, and the path to achieving it is complicated by numerous barriers, including some that are outside of Canada's control. (We discuss our findings for fossil fuel use in Canada in more detail below.)

> “Every net zero scenario consistently shows a growing role for electricity, hydrogen and biofuels

Figure 3 illustrates the range of projected contributions to final energy demand from different energy carriers and sources on the path to net zero.[12] While the three main types of non-emitting energy carriers make a growing contribution to Canada's energy mix under every net zero pathway we analyze, we find that the mix varies from scenario to scenario, with greater use of one energy type displacing use of another. The differences that we observe stem from different possible cost evolutions for key energy technologies, as well as variation in our assumptions around whether early-stage technologies prove out or not. For some energy carriers, significant growth requires the advancement of technologies that are not commercially viable or scalable today, as identified in the figure. Others—most notably non-emitting electricity—rely mostly on technologies that are commercially available today.

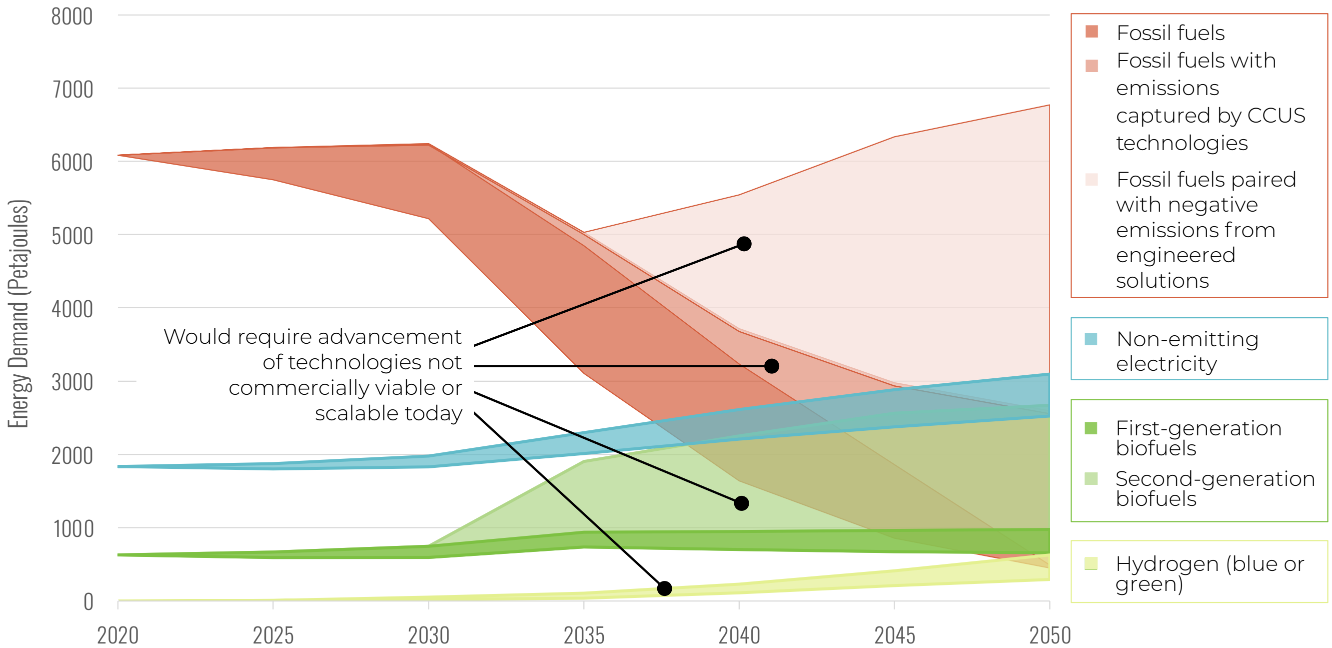
9 Non-emitting electricity can be generated from hydro power, nuclear power, wind, solar power, biofuels, and geothermal energy, as well as early-stage technologies like tidal energy, small modular reactors, and fossil fuel systems equipped with CCUS. Where there are any remaining emissions associated with the production of this electricity (e.g., CCUS may leave up to 10 per cent of emissions uncaptured in some cases), they would need to be offset with negative emissions to be consistent with net zero.

10 Zero-emissions hydrogen is produced from feedstocks such as water and natural gas, using a range of production technologies such as electrolysis using non-emitting electricity ("green" hydrogen), steam methane reforming or autothermal reforming combined with CCUS ("blue" hydrogen), or other emerging technologies that we do not model, such as methane pyrolysis or direct gasification in oil and gas reservoirs.

11 Biofuels include liquid forms of renewable fuels, such as ethanol made from corn and biodiesel made from vegetable oils, as well as gaseous ones, such as renewable natural gas (RNG) made from animal wastes and methane captured from landfills (or from other types of biomass, although these technologies are not yet commercialized). It can also include direct combustion of biomass (e.g., wood burning).

12 Some of the wide ranges observed in the figure are due to differences in the total amount of energy being demanded under different scenarios, which can vary due to differing assumptions regarding costs. Adjusting for this and instead expressing the contribution that energy carriers make to total final energy demand as shares, our modelling projects that by 2050, electricity could supply 28 to 55 per cent of final energy demand, hydrogen three to 10 per cent, and biofuels seven to 44 per cent.

Figure 3: The contribution of different types of energy and energy carriers to Canadian final energy demand on pathways to net zero



This figure (and those that follow) considers results across our 60+ scenarios. The bands in this figure reflect the range of values estimated in our modelling for the contribution that different energy carriers and sources (hydrogen, electricity, biofuels, and fossil fuels) make to final energy demand in Canada under different economy-wide pathways to net zero. The ranges reflect the different possible contributions that we find when looking across our 60+ modelling scenarios. In this way, the ranges illustrate the uncertainty surrounding possible pathways to net zero that our modelling scenarios are themselves selected to reflect (see Box 2).

Any individual scenario will include trends that fall within each of the ranges in the figure. While individual outcomes in a single scenario can be added to express total energy use, the ranges cannot. Using more of one energy type will often mean using less of another. For example, high use of biofuels in a given scenario correlates with lower fossil fuel use.

The use of these full ranges in this graph (and in the graphs that follow) does not imply that the outcomes within them are equally likely. Indeed, some portions of these ranges come with significant uncertainty. For example, the top portion of biofuels and fossil fuel ranges are only found in scenarios where technologies that are not commercially available or scalable today bear out. Growing use of biofuels by 2050, for instance, would require second-generation forms made from feedstocks such as switchgrass or wood wastes to prove commercially viable at scale.

Our modelling is not able to fully capture certain high-demand pathways for electricity and hydrogen, which may mean we have underestimated their potential contribution to final energy demand. For example, the model does not represent the potential role that new interprovincial grid interties could have. Similarly, it allows only for blending of hydrogen into gas pipelines rather than for dedicated hydrogen pipelines. And because the model does not include time-of-use pricing in electricity markets, it cannot capture the complementary relationship that could occur between electricity and hydrogen. In this potential relationship, excess intermittent renewable electricity generation capacity could be used to produce hydrogen, and hydrogen could be used to produce electricity when supply from intermittent generation sources was reduced.

Similar studies have identified a role for electricity and hydrogen in line with the higher end of the range that we project for their 2050 demand in Figure 3. For example, a 2016 study by the Trottier Energy Futures Project found that hydrogen would increase from roughly zero today to 621 petajoules (PJ) by 2050, compared to our finding that hydrogen would increase from roughly zero today to between 294 and 628 PJ by 2050 (Trottier Energy Futures Project, 2016). And the *Pathways to Deep Decarbonization in Canada* report projected that in 2050, electricity could represent almost half (43 per cent) of total final energy consumption, compared to 28 to 55 per cent in our analysis (Bataille et al., 2015). Some studies project even higher shares. For example, the 2018 *Canadian Energy Outlook* projected that electricity would constitute as much as 66 per cent of final energy consumption by 2050 to meet even its least stringent emissions reduction scenarios (Langlois-Bertrand et al., 2018).

Achieving any of the potential energy futures we identify here will not be simple. For every type of non-emitting energy carrier that we evaluate, significant growth would require the implementation of stringent government policy, the deployment of large amounts of capital, and the removal of numerous barriers. We discuss these challenges in detail in Section 5 but provide a few examples here:

- For electricity, building the infrastructure and generation capacity necessary to meet the potential demand we indicate would require large numbers of projects, with new ones developed constantly, and often with complex environmental assessment and consultation processes. And grids, grid operations, and complementary on-demand power would all need to significantly evolve to accommodate this growth (see Box 3).
- For hydrogen, both the costs of hydrogen production and distribution and the costs of end-use technologies such as fuel cells would have to decline. For most industrial uses, hydrogen could be made and stored near where it is needed, but freight vehicles would require a refuelling network along major transportation routes. For wider, more dispersed uses, Canada would have to build pipelines to transport hydrogen and develop standards and retrofits for gas networks and gas-using technologies, such as boilers and home ovens, to accommodate higher hydrogen blends.
- For biofuels, significant growth would require second-generation forms made from alternative feedstocks (e.g., renewable natural gas [RNG] made from gasified wood wastes), which are still at early stages of development, to prove both technically and commercially viable (as seen in Figure 3). It would also require the dedication of large amounts of land for the production of feedstocks, with potential implications for food security, local biodiversity, and Indigenous rights.

BOX 3

How smart grids can prepare Canada's electricity systems for net zero

The transition to net zero poses several challenges to Canada's aging electricity infrastructure. More intermittent sources of electricity, such as wind and solar, can make balancing grid energy flows more difficult. Renewable energy sources also tend to be more distributed and operate at a smaller scale, making future electricity markets more dynamic and local. At the same time, increasing demand for new technologies such as electric vehicles and heat pumps will put added pressure on grid capacity, requiring better demand management and system optimization.

Smart grids can help address these challenges and better position Canada's electricity systems for a net zero economy.

A smart grid is an integrated set of technologies, equipment, and controls that communicate and work together to increase the reliability, security, and efficiency of electricity delivery (U.S. Department of Energy, 2020). Smart technologies that enable grid modernization span the entire supply chain of electricity systems—generation, transmission, distribution, and consumption. Examples include advanced metering infrastructure, enhanced voltage controls, distributed energy resources, energy storage, self-healing grids, and microgrids. Emerging technologies can help build a more intelligent and efficient system based on real-time information and analytics by employing sensors, artificial intelligence, and analytic software (IEA, 2011).

But even though smart grid technologies are critical to keeping pace with an evolving energy system and changing electricity needs, Canada faces several barriers in developing and deploying them.

A rigid and top-down regulatory framework is perhaps the largest barrier. Many provincial electricity systems were designed for the 20th century, where it made sense to have a more centralized system for generating, transmitting, and distributing energy. As a result, they tend to be heavily regulated and operated by a single provider, making limited space for competition, innovation, and entrepreneurial activity. A more effective and efficient regulatory system is needed to create the conditions for utilities to adopt new grid technologies, meet future demand, and adapt to an increasingly complex energy system. In addition, as electricity demand expands and gas demand declines out to 2050, regulatory systems for both networks will need to be revisited.

The cost to modernize the electricity grid will also be substantial. The IEA (2020a) estimates that electricity-related infrastructure will dominate global cumulative capital expenditure on energy infrastructure in a scenario where the world reaches net zero by 2050. In particular, global investment of approximately $13 trillion (CAD) in the upgrade and extension of electric grids and approximately $4.1 trillion (CAD) in energy storage will be required between 2020 and 2070.

These costs will ultimately affect the prices that Canadian households and businesses pay for electricity. On one hand, upgrading grid infrastructure could put increasing pressure on rates. This is a particular concern for lower-income households, which already spend a disproportionate share of their income on electricity. On the other hand, the continued decline in the cost of renewable energy could make it cheaper to generate electricity, while efficiency gains from demand-side management could help utilities reduce expensive peak loads. The ultimate cost of grid modernization—and the distribution of these costs—will depend on the specific context in each region and province. However, our analysis finds that Canadian households would, on average, experience falling energy costs as a share of income under a transition to net zero (see Box 5).

Finally, the transition to a more modernized electricity system will require new skills and knowledge in the labour force. While this will present new opportunities for workers, it may also prove challenging, since the electricity sector will be in competition with other resource sectors to recruit skilled workers.

The potential benefits of smart grid technologies are enormous, but significant challenges stand in the way of their wider adoption. Overcoming them to create more modernized electricity grids would not only facilitate Canada's net zero transition, it could also open up potentially huge export opportunities globally, with Canadian companies becoming suppliers of smart grid technology and knowledge.

Fossil fuel use is likely to fall without substantial technological innovations

In most of the net zero scenarios we examined, fossil fuel use in Canada declines steeply over time. In these scenarios, our modelling projects changes in a range from three per cent growth to 14 per cent decline by 2030 relative to today, and a 57 per cent to 93 per cent decline by 2050 (see Figure 3). (These figures refer to domestic fossil fuel consumption; we discuss the prospects for fossil fuel production in Canada in Section 4.3.)

The steep drop in fossil fuel use we observe is driven at first by improved energy efficiency and later by the replacement of fossil fuels with other types of energy. The limited remaining consumption of fossil fuels that the modelling projects by 2050 is found primarily in sectors where there are no viable alternatives or where valuable capital stock is very long-lived, such as chemicals manufacturing. Emissions from the combustion of these remaining fossil fuels would either have to be captured at source or offset by negative emissions solutions.

Our analysis finds less substantial declines in fossil fuel use only in those scenarios where engineered negative emissions solutions such as direct air capture and advanced types of CCUS technologies prove to be both cost-effective and scalable. (See Box 4 for an explanation of different kinds of negative emissions solutions.) In scenarios where we assume these early-stage and still-uncertain technologies prove viable, our modelling projects that fossil fuel use in Canada could range widely, from a 10 per cent decrease in use by 2050 relative to today to a 22 per cent increase.

There is very high uncertainty surrounding this potential place for fossil fuel use in Canada's net zero future. Currently, engineered negative emissions solutions and advanced types of CCUS are only at the development and demonstration stage. They could become viable with the right mix of technological improvements, economies of scale, and policy changes. But this would still require actions to overcome numerous barriers, particularly for engineered negative emissions solutions. These include achieving significant cost declines; a massive build-out of facilities and infrastructure; the development of a working trading system for negative emissions; recognition in global GHG accounting systems; and the overcoming of potential public opposition. In addition to overcoming these barriers, they must also be deployed in a manner that recognizes and respects Indigenous rights. Canada's policy choices and investments could improve the likelihood of these solutions becoming viable, but the ultimate outcome remains highly uncertain. (There is also a risk, as we will discuss below, that their potential viability would delay other actions and investments that only become more costly to implement later in the event these solutions do not bear out.) And, even if engineered forms of negative emissions could be made viable, whether or not they should be reserved for the significant net negative emissions that are likely to be necessary later this century would remain an open question (IPCC, 2018). We return to these issues and challenges in Section 5.

BOX 4

Carbon Engineering's direct air capture pilot plant in Squamish, B.C. (Skwxwú7mesh-ulh Temíx̱w).

Understanding negative emissions solutions

Broadly speaking, there are two ways to generate "negative emissions." The first way involves harnessing natural processes to store greenhouse gases in the soil or in plants. The second way uses new technologies to remove greenhouse gases from the air before burying them underground or embedding them in new products and materials. Both offer a way of offsetting emissions that physically occur elsewhere, rather than directly reducing these emissions or capturing them at source.

Nature provides a broad range of tools for generating negative emissions. Forests can be induced to hold more carbon by changing forest management practices, boosting conservation practices for existing forests, or planting new trees. Agricultural land can take in more carbon by employing a wide range of farming techniques, including no-till planting, enhancing soils with cover crops, making better use of crop residues, and mixing trees with agricultural land. Grassland and wetland management practices can also sequester carbon, primarily through restoration and avoided conversion for other uses, such as agriculture. And oceans can sequester carbon via seaweed cultivation or restoring coastal ecosystems (including salt marshes). In all of these approaches, however, negative emissions gains are only legitimate when the carbon stays sequestered. Human or natural disturbances—logging or wildfires, for example—can release the trapped carbon and erase the gains.

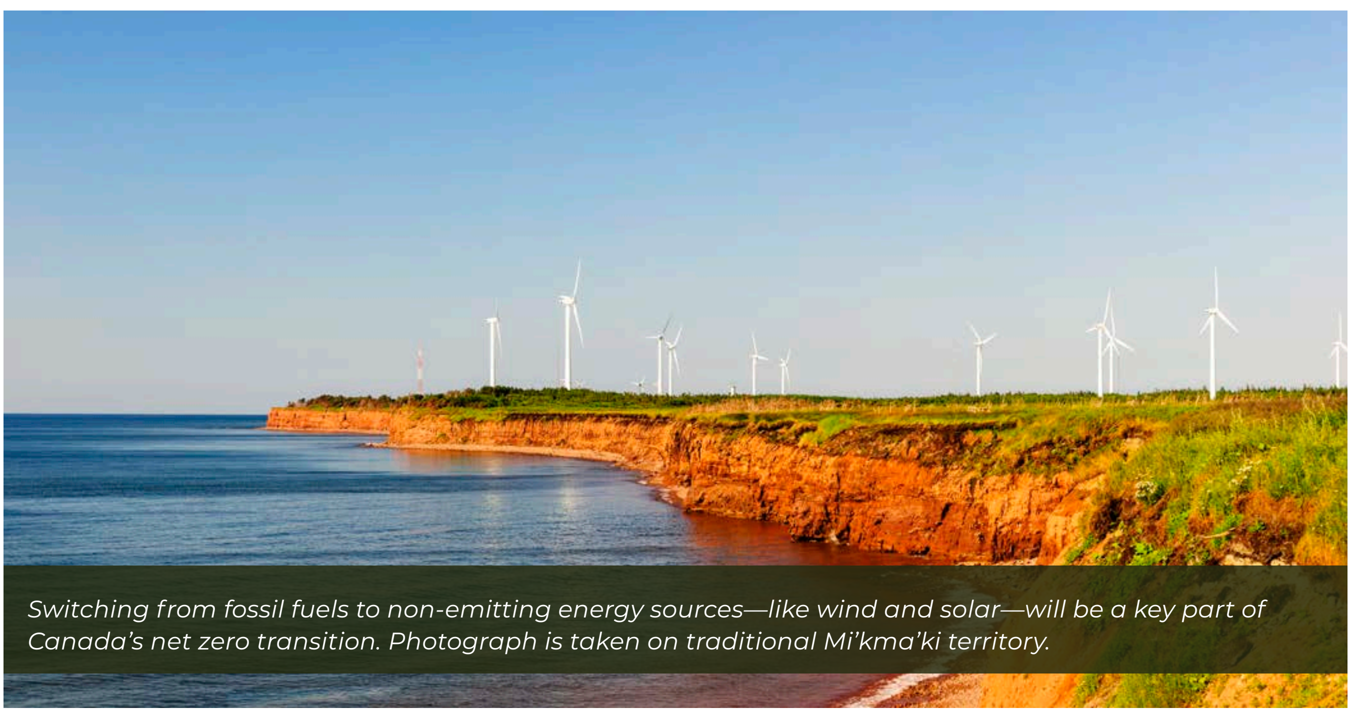
The other path to negative emissions is through technology. New technologies are being developed to capture carbon dioxide from the air and then either sequester it underground or trap it in industrial materials. Direct air capture (whose developers include a Canadian company called Carbon Engineering that operates a pilot project in British Columbia) removes carbon dioxide directly from the air through a series of chemical reactions, expels the carbon-free air, and generates purified carbon dioxide. This can then be pumped underground using carbon capture utilization and sequestration (CCUS) technology or used to produce materials such as carbon fibre and concrete. CCUS pilot projects are already operating in a number of countries, including Shell Canada's Quest facility in Alberta. Another emerging technology is called bioenergy with carbon capture and sequestration (BECCS)—currently being tested at a coal plant in the United Kingdom—which involves burning biomass for energy and capturing and sequestering the resulting emissions underground. BECCS technologies represent a kind of hybrid of natural and engineered negative emissions solutions, taking carbon trapped by plants and trees and recapturing it upon combustion. Other hybrids of nature- and technology-based solutions are also possible. For example, enhanced weathering involves crushing and laying out onto the land certain kinds of minerals (e.g., olivine or used concrete) so that they can absorb carbon dioxide from the air.

Engineered forms of negative emissions have only reached demonstration stage at most, and the role they may one day play in Canada's efforts to achieve net zero remains uncertain. This uncertainty stems both from questions regarding the ultimate cost-effectiveness and scalability of these technologies and from concerns about whether and how they can be recognized in global GHG accounting systems (Vivid Economics, 2020). But if these technologies prove viable, they could come to play a very important role in the global push to net zero, as well as the later push to net negative emissions that most global assessments say will be necessary in the latter part of this century to avoid severe climate change impacts (IPCC, 2018).

Energy efficiency plays a crucial role in all the net zero pathways we examine

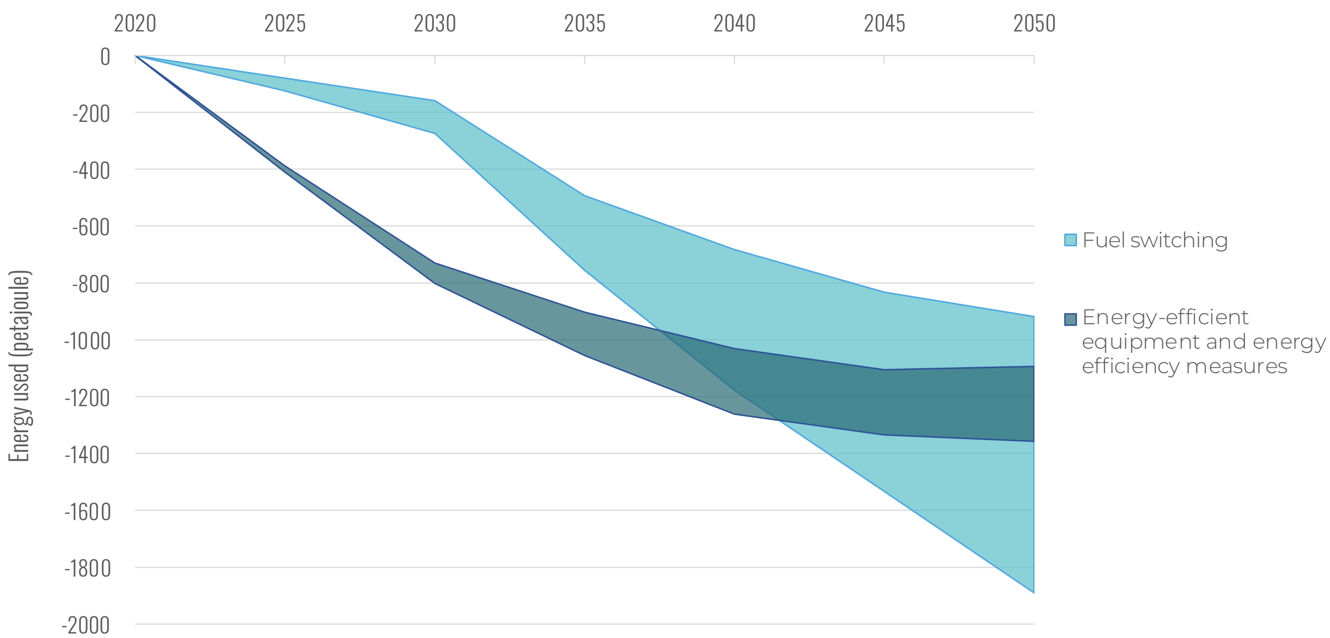
Energy efficiency is often among the least celebrated pieces of a climate plan, but it is always a vital workhorse. In all the scenarios we examine, our modelling indicates that energy efficiency would make a significant and growing contribution to emissions cuts, reducing energy demand by nine per cent to 12 per cent by 2030 relative to today, and 17 per cent to 36 per cent by 2050. The rate of energy efficiency improvement found in our scenarios is broadly consistent with that seen over the past decades (energy efficiency in Canada has improved by 19 per cent between 1990 and 2016 [NRCan, 2020a]). Continued improvement in Canada's energy efficiency on the path to net zero would be economical because the costs of efficiency gains are often much cheaper than adding more zero-emissions energy production. Our analysis indicates these gains would occur in every sector of the economy, from more efficient internal combustion engines to more efficient buildings and industrial processes.

The drivers of these energy efficiency gains will change over time. As we show in Figure 4, energy savings in the next 10 to 15 years from the adoption of more efficient equipment and energy efficiency measures would significantly outweigh those coming from adopting equipment powered by different fuels. Such improvements would drive most of the efficiency gains that occur between now and 2030. But over the longer term, fuel switching—powering end-use equipment with alternative forms of energy such as electricity instead of fossil fuels—would take on a much larger role in reducing both energy consumption and emissions. Fuel switching to lower-emitting fuels tends to improve energy efficiency because equipment powered by liquid and gas fuel is typically more thermodynamically efficient than that using a solid fuel, while electricity-using equipment is even more inherently efficient. However, fuel switching's overall contribution to energy efficiency would also depend on the energy efficiency of the fuel's production.



Switching from fossil fuels to non-emitting energy sources—like wind and solar—will be a key part of Canada's net zero transition. Photograph is taken on traditional Mi'kma'ki territory.

Figure 4: How direct energy efficiency improvements and fuel switching affect energy use on pathways to net zero



This figure shows the effect that different energy efficiency drivers have on projected energy use in our modelling scenarios. The ranges for each reflect the range of estimations that we see for them when we look across all our scenarios, and they therefore reflect the uncertainty associated with Canada's net zero pathway—which the scenarios are themselves selected to reflect (see Box 2).

4 SOLUTIONS ON CANADA'S PATH TO NET ZERO

In this section, we look at how the different possible pathways to net zero and the solutions they rely on could affect the way Canadians live, work, and move. We examine the specific types of technologies and solutions that are most likely to be part of daily life in that future, address the question of why some solutions are more likely than others to play a role, and describe the opportunities and trade-offs that different solutions might present.[13] (For specifics on the size of the emissions reductions that our modelling projects for the various solutions in different sectors, see Annex 4.)

4.1 BUILDINGS: HOW WE HEAT OUR HOMES AND WORKPLACES

KEY PATHWAYS TO NET ZERO

- Canada's built environment can reach net zero by relying on technologies and measures available today.
- Energy efficiency would play an important role, as would switching from higher-emitting heat sources to electric ones. Where electrification was not available or where its costs would be too high, clean gases like renewable natural gas and hydrogen would be involved.
- Overall, this transition can be achieved without increasing energy costs for Canadian households. In fact, households could spend less on energy as a share of income than they do today as Canada moves towards net zero.

13 Our modelling is able to capture a wide range of technological solutions and some non-technological ones. Where it does not consider certain technological solutions (e.g., small modular nuclear reactors or synthetic fuels) or non-technological ones (e.g., changing urban forms or cultural changes that could lead to lower demand for emissions-intensive goods and services), we use literature review and expert input to offer insight on the potential role they could play.

Canada's buildings use energy to maintain comfortable indoor temperatures, to power appliances and everyday devices, and to heat water. At present, 76 per cent of the energy needs of Canada's buildings come from fossil fuels like natural gas or from electricity generated by fossil fuels (NRCan, 2020a), producing 73 million tonnes of GHG emissions or 10 per cent of the nation's emissions. A transition to net zero must continue to meet the energy needs of Canadians while providing a range of energy solutions that work for new and old buildings alike nationwide. Fortunately, the tools to reach net zero in buildings are already commercially available.

Buildings can get to net zero using existing technologies

Our analysis finds that Canada's built environment could reach net zero emissions by relying only on technologies and measures that are commercially available today. While a significant portion of these solutions would still need to clear major hurdles on the path to widespread adoption, many of these could be overcome with sufficiently stringent and coordinated government policies. We find that Canada's buildings sector could reach net zero without relying on negative emissions or technologies still in early-stage development.

While existing emissions-reducing technologies may be more expensive than higher-emitting alternatives at the point of purchase, many are either cost-neutral or cost-saving over their lifetimes. The Canada Green Building Council (2019) estimates that upfront costs for emissions-free buildings are only eight per cent higher than the current standard and, through energy savings, generate a net return (inclusive of capital costs) of one per cent on average over the life of the building. In our analysis, we find that achieving net zero would have minimal effects on the costs of energy for Canadian households—and could even leave households better off. Box 5 discusses these findings in detail.

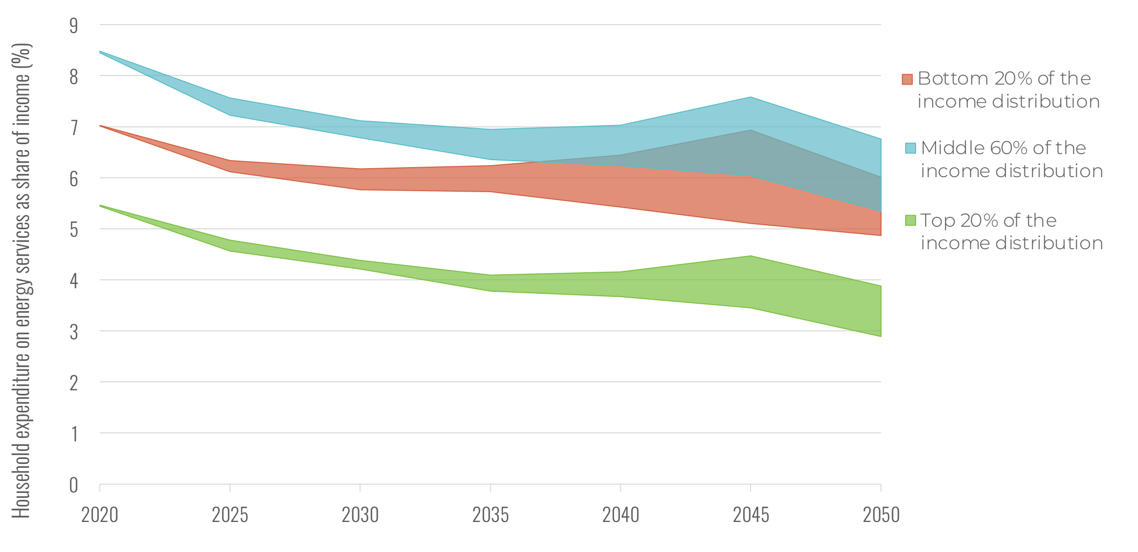
The evolv1 building in Waterloo, Ont. is Canada's first net zero positive commercial office building. Making new buildings emissions-free will not only be a key part of Canada's net zero transition but will offer cost savings over their lifetimes.

BOX 5

Progress toward net zero sees households spending less on energy as a share of income

In every scenario we examined, the proportion of income households spend on energy services—including spending on home heating, electricity, and transportation—declines for all income groups, as seen in Figure 5.

Figure 5: Household energy expenditure as a share of income across pathways to net zero



Energy costs would decline for households in all incomes groups as Canada makes progress toward net zero by 2050. However, their relative levels of expenditures would likely persist. The differences in relative expenditure are explained by the fact that middle-income households actually spend a greater share of their income on energy than lower-income ones, despite their higher incomes, in part because they are more likely to own vehicles and live in larger homes, leading to higher relative energy consumption. The highest-income households, meanwhile, spend the smallest share of their incomes on energy, even though they are often the largest energy consumers (owning multiple cars, living in larger homes, and flying more frequently), owing to their larger incomes. Broader societal shifts in income inequality could alter these differences. Growing inequality, for example, could lead to lower-income households spending an even larger share of their declining earnings on energy, while the highest earners could be spending a smaller portion of their incomes on energy if their incomes increase. But if income inequality instead decreased over the coming decades, energy spending as a share of income could become less divergent across all groups as the income gap narrowed.

According to our analysis, the reduction in household spending on energy services results from several factors:

- Economic growth nationwide from 2020 to 2050 would cause average incomes to rise, meaning even if energy spending holds steady in absolute terms for some households, the share of income spent on energy would decline.
- Energy efficiency would improve throughout the economy, from car engines to home heating, significantly reducing the amount of total energy a household uses and the amount of money it spends. (Behavioural and cultural change will also play a role in shifting energy consumption patterns, as we discuss in Box 12.)
- The additional costs of low-emissions energy equipment would be more than offset by the savings derived from their reduced energy consumption.

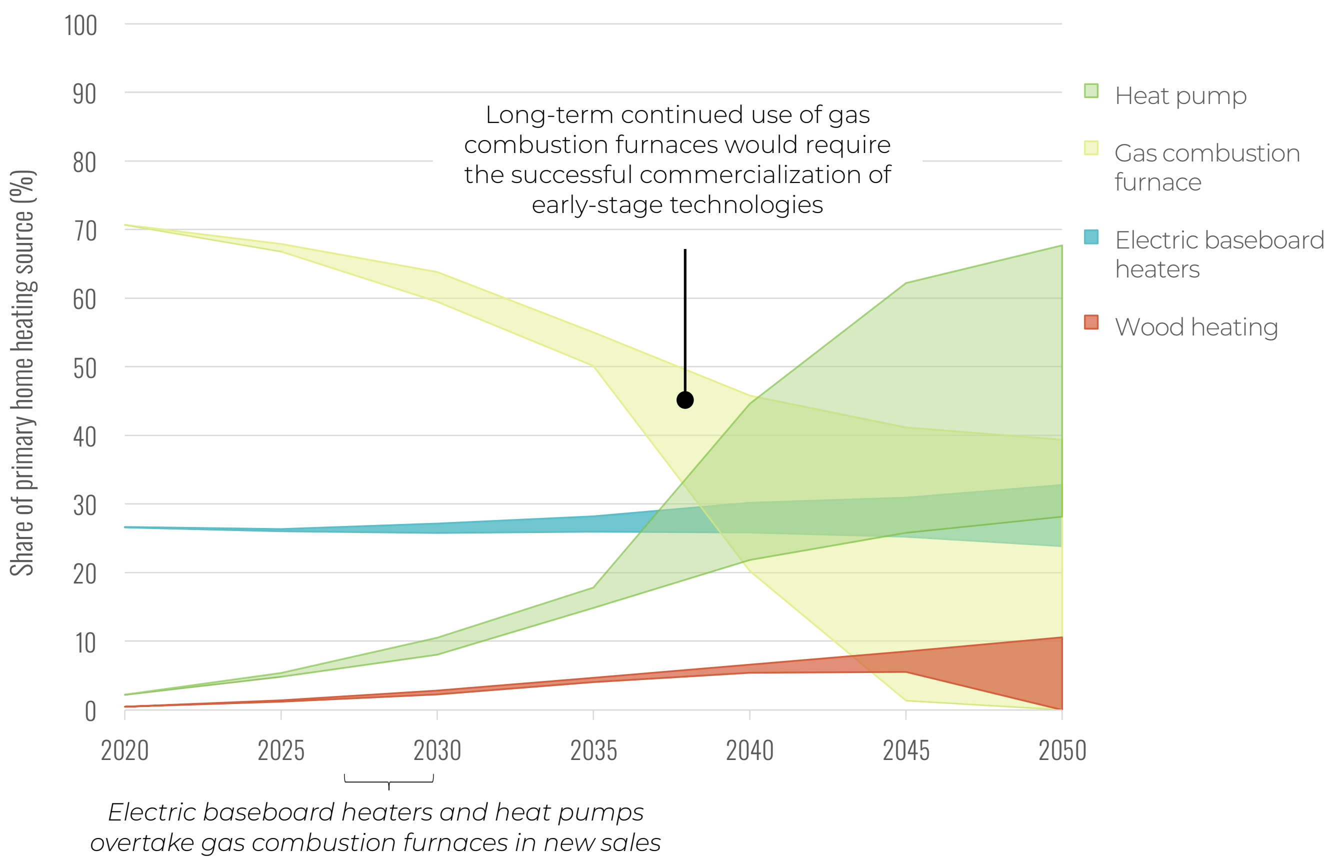
Larger upfront purchase costs, however, remain a significant barrier, especially for lower-income households. Vital net zero energy technologies such as heat pumps, for example, have lower operating costs than current systems but come with much higher purchase prices. One study of deep emissions cuts in British Columbia estimates that average households could save $800 per year in 2030 and nearly $1,000 per year in 2050 from improvements in home and vehicle efficiency, but that this would come with a $4,000 increase in upfront capital costs of new equipment (Navius Research, 2015).

Without policy support, many lower-income households may not have the means to invest in these high-efficiency technologies or may be unable to benefit from their energy-cost savings, especially if the benefits are only available to homeowners and not renters as well. This points to the role of policy measures ensuring that all households are able to participate in the net zero transition, such as equitable financing mechanisms or targeted supports for low-income households to improve their access to energy-saving technologies.

We find that the adoption of energy-efficient equipment and energy-efficiency measures is an important step on the pathway to net zero in the buildings sector. Our modelling projects that better insulation, more efficient windows, and improved building design could reduce the energy intensity of buildings in Canada by 17 to 19 per cent by 2030 relative to today and by 45 to 55 per cent by 2050. These changes would reduce emissions and build on decades' worth of ongoing improvements to the energy efficiency of Canada's built environment, where the average household energy efficiency has improved by 30 per cent over the past 20 years (NRCan, 2019a).

To drive deeper emissions cuts, our modelling suggests that switching from furnaces to electric heat pumps, which are commercially available today, would play an essential and growing role (as shown in Figure 6). Where gas combustion furnaces remain, they would increasingly be powered by clean gases such as hydrogen or RNG, rather than with natural gas. However, any of these clean gas pathways would require the successful commercialization of technologies that are still in the early stages of development. In scenarios where these technologies do not prove viable at scale, we find that combustion furnaces would be fully replaced by heat pumps and electric baseboard heaters by 2050, as well as some wood heating. We further discuss heat pumps and clean gases below.

Figure 6: Share of heating technologies installed as a primary source of home heating across pathways to net zero



Electrification of buildings with heat pumps offers a path to net zero

Our scenarios consistently show electrification of heating as a necessary part of the transition to net zero in Canada's building sector. This will occur either via direct resistance heating (using baseboard heaters, for example) or through the use of heat pumps. Heat pumps—which function like air conditioners in reverse, extracting heat from outside air and transferring it inside—are already becoming common; in the United States, 50 per cent of new, multi-unit residential buildings use heat pumps, and more than 20 million homes globally had a heat pump as of 2019 (IEA, 2019a). Reversible heat pumps (which provide both heating and cooling) have been found to already be cost competitive in many parts of the United States compared to a gas furnace and air conditioner solution (Billimoria et al., 2018).

Buildings that combine high levels of energy efficiency and heat pumps to provide heating suited to the Canadian climate already exist in Canada. For example, a 50-unit passive house in Fort St. John, British Columbia, uses heat pumps that provide comfort in temperatures as low as -20°C (Passive House Canada, 2020).[14] Our modelling projects that heat pumps would expand from two per cent of all household heating systems today to eight to 11 per cent by 2030 and 28 to 68 per cent by 2050, while electric baseboards would hold steady, serving as the primary heating source for 24 to 33 per cent of households by 2050. In total, we estimate that electric heating systems would heat 52 to 100 per cent of households by 2050 (up from 30 per cent today). As a share of new technology sales (i.e., rather than total deployed equipment), this transition would be much quicker. Indeed, our modelling projects that in terms of sales, electric baseboards and heat pumps would overtake gas combustion furnaces between 2027 and 2032.

To make these measures ready for mass adoption in Canada, however, the nation's electrical grids would need to evolve significantly (we discuss this evolution in Box 3). The buildings sector would be both a driver of, and solution to, many of the challenges faced by Canada's electrical grids in pursuit of net zero. For example, the National Renewable Energy Laboratory in the United States has estimated that peak electricity demand would shift from summer to winter months as a result of high heat pump adoption, increasing peak demand by 20 to 33 per cent (Mai et al., 2018). These changes would likely be even more pronounced in Canada's colder climates. However, smart equipment installed in buildings could help to ease the burden of peak demand on the electrical grid. Electric water heaters, for example, can be designed to heat water when electricity prices are low, shifting demand while continuing to supply hot water.

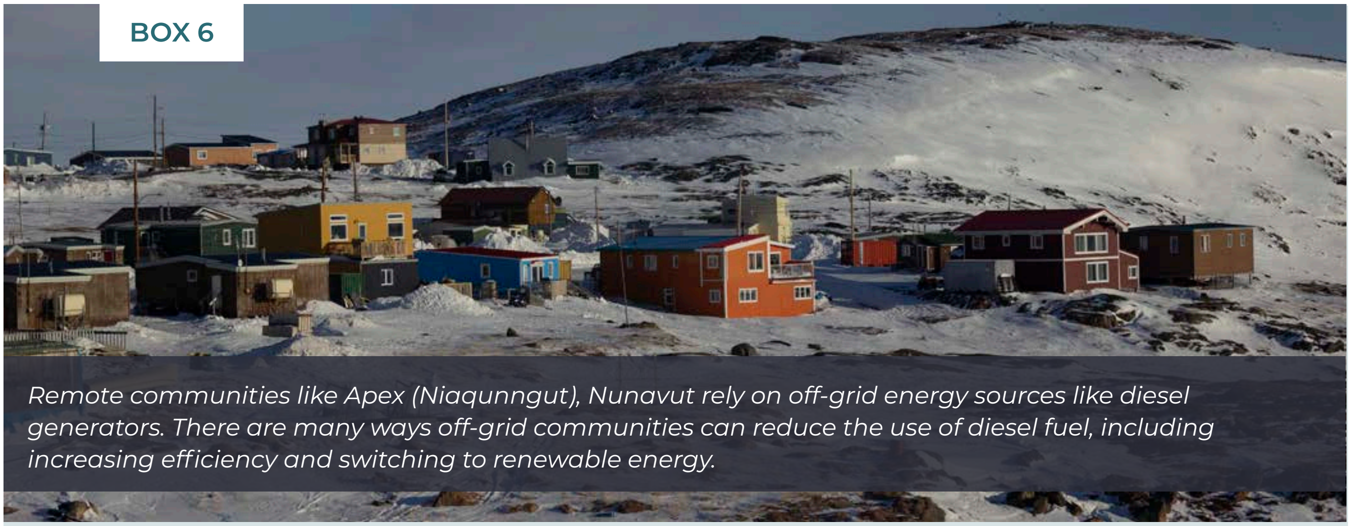
Ensuring wide adoption of heat pumps would also require supportive policy, innovative financing models, or both. In particular, low-income Canadians, including those that rent their homes, may be unable to afford energy efficiency retrofits and heat pumps without targeted support.

Electrifying building heating is likely to be more challenging in some regions than in others. Heat pumps tend to perform better in higher humidity, so their uptake might come faster in regions with more humid climates, such as eastern Canada and western British Columbia. Rural parts of Canada that have access to electricity networks

14 Supplemental natural gas heating is used for temperatures lower than this. However, such units could instead be equipped with supplementary direct resistance heating powered by electricity.

but only limited or costly access to the gas network may make the transition to heat pumps more quickly than some urban ones. In contrast, remote communities connected to neither electrical grids nor gas networks will face unique challenges and solutions, as we discuss in Box 6.

BOX 6



Remote communities like Apex (Niaqunngut), Nunavut rely on off-grid energy sources like diesel generators. There are many ways off-grid communities can reduce the use of diesel fuel, including increasing efficiency and switching to renewable energy.

Reducing diesel reliance in off-grid communities

There are 292 off-grid communities in Canada (NRCan, 2020e), many of which lack access to safe, reliable, affordable supplies of natural gas and electricity—services that most Canadians take for granted. These remote communities, nearly two-thirds of which are Indigenous, must produce their own energy locally, typically using expensive and polluting diesel generators. A recent report by the Pembina Institute estimates that approximately 682 million litres of diesel-equivalent fuel will be consumed in remote communities in 2020, equal to the annual emissions from approximately 500,000 cars (Lovekin et al., 2020).

In addition to the emissions produced by diesel generators, reliance on these systems has a range of negative social and economic implications. Air pollution and environmental leaks and spills from diesel generators harm the health and well-being of local residents (Health Canada, 2019b). Load restrictions of diesel generators limit the ability of communities to build new infrastructure, such as businesses and homes, despite growing populations. And even when subsidized, the costs of electricity in these communities can be more than double the costs for the average Canadian household (Canada Energy Regulator, 2017).

While off-grid communities (along with provincial and federal governments) have several options to reduce and displace their reliance on diesel, there is no one-size-fits-all solution. The energy needs of each community, as well as the challenges and opportunities they face, differ based on their size, climate, and location, among other factors. The solutions available to Northern communities, in particular, are limited due to their remote locations, colder climates, harsher winters, and higher deployment costs.

The path to net zero for remote communities could involve many technologies. Diesel used for heat and electricity could be replaced with clean energy sources, including wind, solar photovoltaic (PV), small hydropower, geothermal, and biomass. Diesel supply could also be reduced or replaced by connecting communities to provincial and territorial electricity grids. Other energy storage and smart grid technologies could also be deployed in remote communities to better manage variable electricity supply from intermittent renewables. At the same time, making community buildings more energy efficient could reduce energy demand and also improve indoor air quality. Other emerging technologies not yet deployed in remote communities may also play a role in reducing diesel reliance (such as tidal energy generators for coastal communities or small modular reactors).

Despite challenges with deploying some of these technologies—including high costs, the intermittency of renewable energy, and difficulty with obtaining adequate financing—a growing number of clean energy projects illustrate significant potential. According to Pembina's report, the use of renewable energy systems nearly doubled in remote communities between 2015 and 2020, with substantial increases in bioheat and solar PV projects. In that five-year period, remote communities deployed 82 diesel reduction projects, increased solar capacity eleven-fold, connected three new communities to provincial or territorial electricity grids, brought over 40,000 new MWh of renewable energy to the mix, and saw a total diesel reduction of over 12 million litres per year. Many more initiatives are in the early stages of development (Lovekin et al., 2020).

Indigenous involvement in renewable energy projects is at the centre of this energy transition, especially in remote communities. According to a 2020 report by Indigenous Clean Energy, there are currently between 2,107 and 2,507 Indigenous clean energy projects operating in Canada, a total that includes power generation, electricity transmission, heat production, and energy efficiency. These range from small systems to medium- and large-scale energy generating projects. Indigenous involvement in clean energy projects can result in significant economic and social benefits, including employment opportunities, and may help build capacity within Indigenous communities to meet their own energy needs.

These projects can do more than provide affordable and reliable energy to communities. They can also help advance Indigenous self-determination and reconciliation, particularly when Indigenous communities have ownership of and control over projects (Hoicka et al., 2020). However, a new study that analyzed 194 renewable energy projects larger than 1 MW in size across Canada that contain some level of Indigenous community involvement found that only 41 of the projects are controlled by Indigenous communities. This raises important questions regarding whether and to what extent renewable energy activities involving Indigenous communities as currently practised contribute to reconciliation and self-determination (Hoicka et al., 2020).

Clean gases could accelerate net zero transition in the buildings sector

Electrifying building heating will be easier in new buildings than in existing ones, which may not need new heating systems for years to come. A promising option for reducing emissions cost-effectively in older buildings is clean gases such as hydrogen or RNG.[15] These fuels could be blended into the natural gas network using existing infrastructure, reducing emissions from any building connected to the network. The Alberta utility ATCO, for example, is planning to add five per cent hydrogen to one of its natural gas networks in 2021, and Fortis blends in RNG from decomposing organic matter like food waste to networks in British Columbia (Canadian Utilities Limited, 2020; Fortis BC, 2020a).

The use of clean gases is likely to vary region to region and building to building, depending on cost, infrastructure investment decisions, and local conditions, among other factors. Overall, our modelling suggests that clean gases could make an important contribution to reducing emissions from buildings with natural gas furnaces. We find that by 2050, clean gases could potentially provide a total amount of energy equivalent to 32 per cent of today's natural gas demand from Canada's buildings.

Clean gases face a number of barriers to significant uptake, however. The costs of hydrogen are high at present, although a recent wave of new investment could reduce the price of hydrogen by 40 to 50 per cent over the next decade, and up to 70 per cent by 2050 (BloombergNEF, 2020). Hydrogen also faces infrastructure challenges and costs, including the modification of existing pipelines and equipment. Without modifications, Canada's gas network can handle an average of five per cent blending, although some parts could handle much higher blends of up to 25 per cent in some instances. Going beyond 25 per cent, which would be necessary to reach net zero, would not only require significant modifications to pipelines and distribution networks but also the replacement of many of the furnaces, water heaters, stoves, and fireplaces that use natural gas today (National Research Council of Canada, 2017).

15 This does not extend to older buildings burning oil for heat, where we find that a switch to electric heat would be more economical than a transition to clean gases.

RNG, on the other hand, can be blended directly into the natural gas network at 100 per cent with no infrastructure modifications (since it is simply bio-sourced methane instead of fossil-sourced methane). But its costs also remain high. Moreover, supplies of its feedstocks are limited, making significant cost declines from economies of scale unlikely. If new technologies that use second-generation feedstocks—gasifying wood wastes, for example—prove viable, cost-effective, and scalable, they could potentially help further drive down costs and increase supply (Fortis BC, 2020b). But the prospects for this remain uncertain.[16]

Maintaining existing natural gas transmission networks would also present significant economic challenges. Under all of our modelling scenarios, we project a significant decline in total gas use—natural gas, hydrogen, RNG, and other gases combined—over time. This holds true even with population growth, primarily due to more efficient homes and competition from heat pumps. However, utilities would still have to maintain their gas networks during this time, even as their customer base declines. This would increase the cost that individual households pay for the delivery of clean gases, raising questions about the long-term economics of clean gases distributed via gas networks. It could also raise equity challenges, since households unable to absorb the cost of switching to electric heat pumps could find themselves stuck with increasingly high fixed costs for their continued use of the gas network.

The viability of clean gases will be affected by policy choices. Will governments require increasing levels of clean gas blending, as British Columbia is planning to do (Government of British Columbia, 2018)? Will Canada see large-scale public investments to make gas networks compatible with hydrogen by replacing piping with plastic, as the United Kingdom did between 1968 and 1976 to move from coal gas to natural gas?[17] Will governments change the economics of clean gas by requiring natural gas and electric utilities to merge or at least to be co-regulated? Will markets recognize the potential value of industrial, commercial, and residential retail gas networks for energy storage?

The future of clean gases in the buildings sector is complex and uncertain. But the gas distribution network looks likely to play a role in helping Canada's built environment reach net zero. At a minimum, it can help to reduce emissions from Canada's older buildings over the medium term by blending in clean gases with natural gas, which can act as a helpful bridge to either eventual electrification or higher rates of blending.

16 Engineered negative emissions solutions offer another potential path to continued gas use in buildings. Instead of reducing emissions from buildings at source by blending in clean gases, they would allow for the offset of those emissions elsewhere. However, these technologies are only in early-stage development, so their ultimate costs and availability are highly uncertain. In any case, our modelling suggests that even if they proved viable, they would only see limited uptake in the buildings sector due to the greater cost-effectiveness of available alternatives. Direct pyrolysis, or separation of methane into hydrogen and carbon residue at point of end-use, is another clean gas possibility for the buildings sector. But its prospects also remain uncertain, and its potential would only be realized over the very long term.

17 The Scottish government and the energy regulator Ofgem have recently launched a four-year pilot project that will see gas use in 300 homes converted entirely to hydrogen. Off-line trials of hydrogen transportation via gas network infrastructure will also be occurring in parallel (Ambrose, 2020).

4.2 TRANSPORTATION: HOW WE MOVE PEOPLE AND THINGS

KEY PATHWAYS TO NET ZERO

- Increased use of public transit and active modes of transport would play a vital role in getting to net zero, driven in part by changes to the design of cities and communities.
- Personal vehicles are not going away, so achieving net zero will ultimately require the adoption of alternative fuel and vehicle technologies.
- For personal vehicles, electrification would play a significant role, with electric vehicles moving from margin to mainstream. But internal combustion engines may have a longer life than many expect—if they become increasingly powered by biofuels.
- The future of heavy freight is more uncertain, with electrification, hydrogen, biofuels, and net zero fossil fuels all potentially playing a role.

Operating an advanced modern economy involves moving an enormous volume of people and goods every day, and all that transportation requires huge amounts of energy. At present, fossil fuels are by far the most used fuel for Canada's transportation sector, supplying 93 per cent of the energy consumed in transportation, which generates 24 per cent of total national emissions (ECCC, 2019b).

The path to net zero for the transportation sector is clear but difficult to navigate: Canada must greatly reduce its use of fossil fuels while retaining the ability to move people and goods efficiently throughout the country. Some parts of the transportation sector's path to net zero are well understood, involving smartly designed cities with ample public transit and the eventual emergence of electric vehicles (EVs) as the dominant type of personal vehicle nationwide. The role of combustion engines and the fuels that will propel heavy- and medium-duty freight vehicles are much less certain.

Smartly designed communities and abundant transit are a key to success

Shifts toward different modes of transportation—especially in urban areas—can complement shifts toward zero emission personal vehicles. Increased use of mass transit and active modes of transportation such as cycling emerge as drivers of emissions reductions in all the scenarios we examined, reducing emissions by a projected seven to eight Mt of CO_2eq by 2030 and up to 15 Mt by 2050, equivalent to taking 2.1 to 2.5 million vehicles off the road by 2030 and up to 4.6 million vehicles by 2050 (NRCan, 2020b). Such a shift in urban transportation also comes with additional benefits, including reduced congestion and air pollution, preservation of green space, and healthier lifestyles (Giles-Corti et al., 2010; Lachapelle & Pinto, 2016; Litman, 2015; Sims et al., 2014; Jaccard et al., 2019).

Electric buses will be critical to reducing transport sector emissions in Canada, and a number of cities are already adopting them.

In many Canadian communities, this transition is already underway. The number of daily public transit users nationwide grew by 60 per cent from 1996 to 2016, while the number of automobile commuters increased by less than 30 per cent (Statistics Canada, 2017). Urban neighbourhoods across Canada are also starting to adopt designs better suited to walking and transit use. The City of Vancouver, for example, invested in 325 kilometres of new cycling routes, changed zoning laws to encourage cycling and transit use, and created a public space and street use platform through its VIVA program. This has boosted transportation by walking, cycling, and transit to 54 per cent of total trips in 2020. In addition, distance driven per person has declined by 28 per cent since 2007 (City of Vancouver, 2020; Transport Canada, 2011).

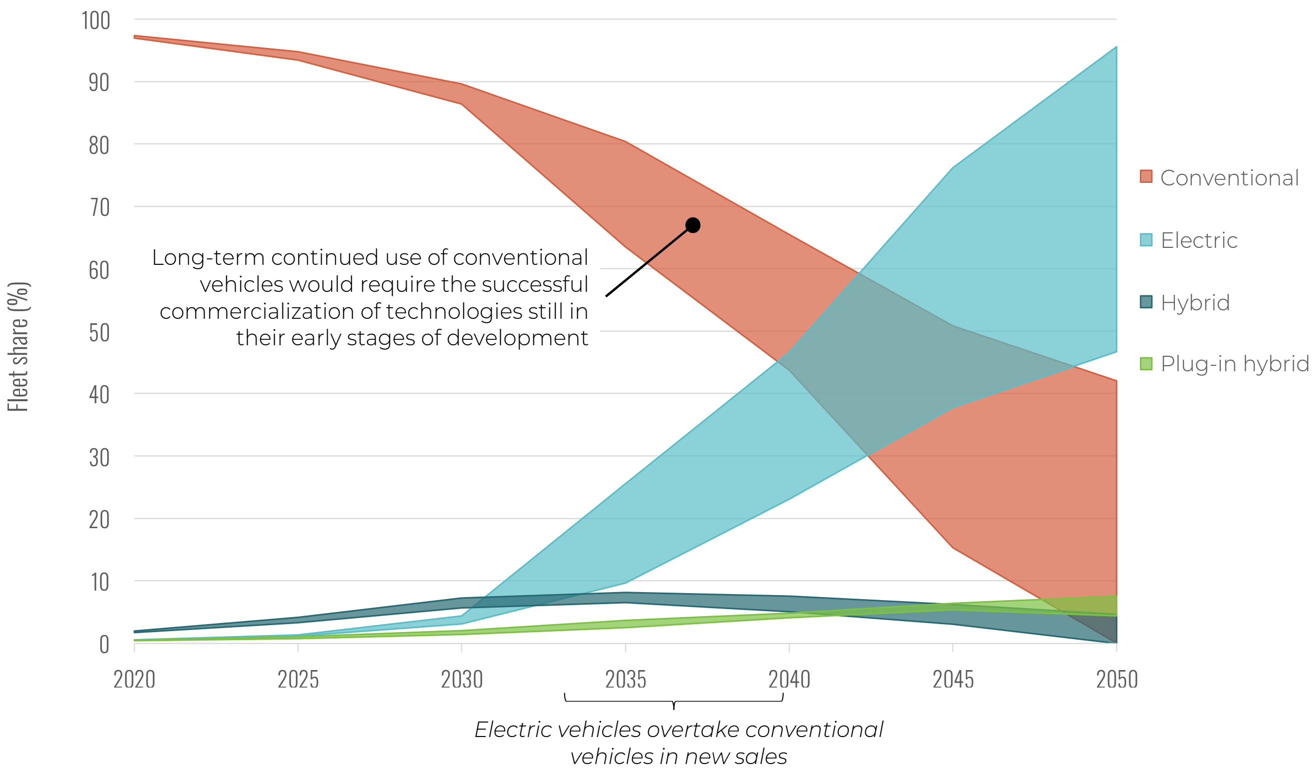
Because the impact of urban design is far harder to measure than transit use, it wasn't included as a specific metric in our analysis. Other studies, however, have found that communities designed to reduce the need for a personal vehicle could reduce emissions by 20 to 50 per cent by 2050, relative to 2010 levels (Sims et al., 2014). And reducing emissions would be only one benefit of smarter community design. Walkable communities with well-integrated transit also see benefits such as reduced air pollution, shorter commute times, less costly transportation, more pleasant living experiences, and easier access to amenities (Devlin et al., 2009; Giles-Corti et al., 2010; Sims et al., 2014; Ewing & Cervero, 2001; Leyden, 2003; Lund, 2002; Frank & Engelke, 2001).

The automobile, however, is not disappearing from Canadian streets for the foreseeable future. Even with efficient community design and more active transportation and transit, there will still be many vehicles on the road, especially in suburban areas of cities, smaller communities, and rural areas—all parts of the country that do not as easily lend themselves to active or public transportation. Shrinking the emissions of vehicles will be an essential part of Canada's net zero transition.

More electric vehicles are essential for making personal transportation net zero

Transitioning to EVs is a crucial part of Canada's net zero path in every scenario we examined. Fossil-powered transportation has been the norm in Canada's transportation sector for decades, but this is already changing fast—over the last decade, EVs have grown from near-zero sales to more than 150,000 vehicles on the road in early 2020 (Electric Mobility Canada, 2020). Our modelling projects that under current and expected market and policy conditions, electric vehicles would make up three per cent to four per cent of all personal vehicles on the road by 2035—a small but important shift. Beyond 2035, EVs would move rapidly from margin to mainstream, comprising 47 to 96 per cent of all vehicles by 2050. Moreover, the lower end of this range emerges only in modelling scenarios where second-generation biofuels prove viable, cost-effective, and scalable enough to compete with EVs (an uncertain prospect that we return to below). As a share of sales, the transition to EVs would occur even faster. Our modelling projects that EVs would overtake conventional vehicles between 2035 and 2040. However, as we discuss below, this transition could occur even sooner as a result of evolving domestic and global EV policies.

Figure 7: The total market share of different vehicle types in Canada's personal transportation fleet across pathways to net zero



As electric vehicles become more affordable over time, sales will increase steeply. In a net zero Canada, EVs are expected to become the personal vehicle of choice.

How could EVs become Canada's primary personal vehicles so quickly? Our analysis projects that by 2033, the cost of a new EV would be the same as conventional cars and trucks, even before accounting for their lower operating costs (this occurs even sooner than 2033 for some vehicle classes). Ongoing development of charging infrastructure, expanded electricity generation, and greater consumer acceptance would also drive the shift to EVs.

The speed of this transition that we see in our modelling may even be an underestimate. Other studies project more rapid cost declines and faster adoption of EVs by mid-century. For example, BloombergNEF (2020) projects that EVs will reach price parity with internal combustion vehicles by the mid-2020s in most segments. Deep decarbonization scenarios from both McKinsey (2020) and Shell (2018) find that internal combustion engines could account for less than half of global sales by 2033 and be completely phased out by mid-century. The *Pathways to Deep Decarbonization in Canada* report projects that by 2050, EVs will account for nearly 100 per cent of all light-duty passenger vehicles in Canada, corresponding to the high end of our projected range (Bataille et al., 2015).

The rise of EVs, however, could vary significantly by region. British Columbia, for example, already leads the country in EV adoption, and our analysis anticipates that this would continue. Northern communities, on the other hand, would take more time to make the switch, in part because of the higher costs of electricity. Rural households may also be slower to adopt electric vehicles, owing to their need to drive longer distances and the likely slower arrival of sufficient charging networks in sparsely populated regions.[18] Then again, uptake across the country could accelerate much more rapidly as a result of domestic and global policy that drives adoption of electric vehicles. And the potential of EVs to reduce harmful air pollution could be a driving force behind this policy push (see Box 7).

18 Some remote regions, especially in Canada's North, may continue to use at least some amount of biofuel-powered conventional or hybrid vehicles over the long term, owing to their vast land mass and cold temperatures that could reduce electric battery ranges. The challenges associated with full adoption in such regions is part of the reason electric vehicle penetration never reaches 100 per cent in our modelling scenarios, as seen in Figure 7.

BOX 7

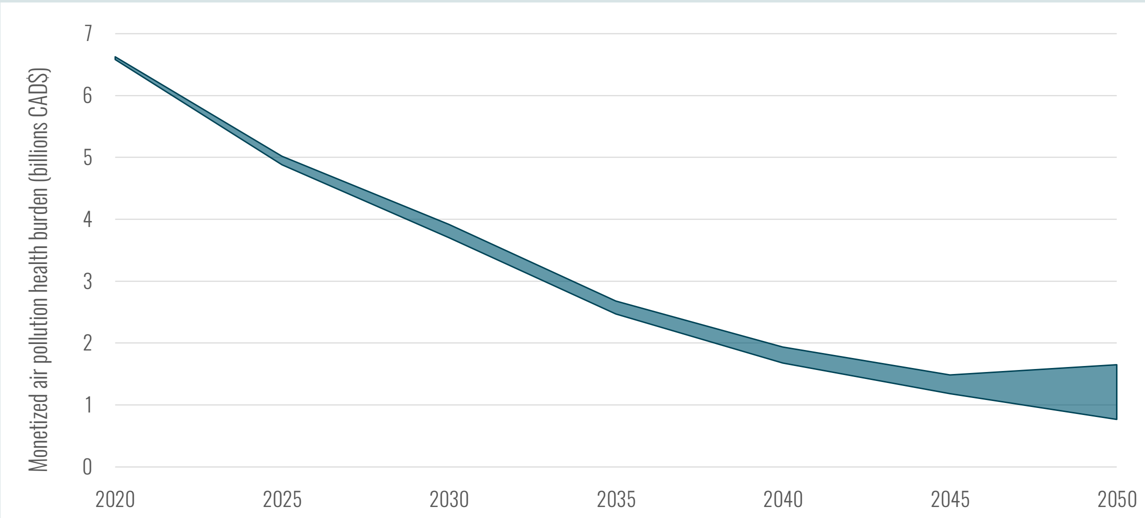
The health benefits of reduced air pollution

Harmful air pollutants that increase the risk of disease and premature death—pollutants such as particulate matter and ground-level ozone—are common by-products of GHG emissions. Globally, air pollution represents the single largest environmental threat to human health, according to the World Health Organization (2016), and it also takes a significant economic toll. In Canada, estimates suggest that air pollution kills around 20,000 Canadians annually, with more than 17,000 of those deaths attributable to fossil fuel use (Lelieveld et al., 2020). The direct welfare costs of fine particulate matter and ground-level ozone in Canada is estimated at as much as $46 billion per year (IISD, 2017), while Health Canada (2019a) estimates the total annual economic damage to public health from air pollution is approximately $114 billion.

A transition to net zero would not only reduce greenhouse gas emissions, it would also reduce the release of air pollutants such as particulate matter, nitrogen oxides, and sulphur dioxide, pollutants that impose a direct health burden on Canada's population. When fossil fuels are combusted, these pollutants are also released. So falling greenhouse gas emissions tends to also be associated with falling levels of air pollution.

Figure 8 shows the projected decrease in monetized air pollution health burden that would be associated with decreased mortality from particulate matter pollution on the path to net zero in Canada. These health benefits would be especially significant in Ontario and Quebec, where high air pollution levels near dense urban population centres would be much improved (Health Canada, 2019a; Manisalidis et al., 2020; IISD, 2017). And the actual benefits would likely be even larger than that shown in Figure 8, since our analysis only considers the health burden of particulate matter emissions. The exact magnitude of the health benefit, however, would depend upon which type (or types) of net zero energy system Canada adopts (we return to this topic in Section 5.2). And benefits would also be driven by ongoing improvement of pollutant control technologies (i.e., independent of Canada's emissions-reduction efforts).

Figure 8: National annual estimated economic burden due to mortality associated with air pollution emissions from energy production and use on pathways to net zero



Source: Soltanzadeh & Hakami, 2020

Falling levels of air pollution from transportation in our scenarios is an especially significant driver of the reduced health impacts seen in Figure 8. Our modelling projects that 73 to 77 per cent of the cumulative health benefits we project between now and 2050 would come from falling emission levels in the transport sector. And falling levels of emissions from heavy-duty vehicles (e.g., freight or public transit) are a particularly significant driver, comprising 45 to 48 per cent of the cumulative health benefits in that time span.

Several other studies have yielded similar findings on the impact of reducing air pollution. One study found that Canada's planned phase-out of coal-fired power by 2030 would avoid more than 1,000 premature deaths and yield an additional $5 billion in health benefits by 2035 (Israël & Flanagan, 2016). And a recent report from the Canadian Association of Physicians for the Environment estimates that more than 110,000 lives would be saved between 2030 and 2050 from air quality improvements alone if Canada met its 2030 and 2050 emissions targets (Edger et al., 2020).

Despite these considerable health benefits, air pollution in Canada would remain a challenge by 2050. Air pollution from climate change impacts such as more frequent and severe wildfires and higher ground-level ozone concentrations from rising temperatures are expected to increase at the same time that air pollution associated with greenhouse gas emissions would be declining.

The long-term future of conventional vehicles depends on significant advancements in biofuels

So how about the gasoline-burning status quo? Our modelling suggests that conventional vehicles would continue to play a role in personal transportation in the near and medium term, but that they would become increasingly efficient. In all the scenarios we examined, the majority of emissions cuts in the transportation sector between now and 2030 come primarily from improved conventional engine efficiency, including greater use of hybrid engines.[19] Blending of biofuels into gasoline would also help to reduce emissions between now and 2030. But over the long term, continued use of conventional vehicles would require that they switch entirely from burning gasoline to burning biofuels.

Our analysis finds significant uncertainty in how large a role conventional vehicles might play in personal transportation over the long term. On the one hand, some of our scenarios see electric vehicles fully dominating the market by 2050, plus a small role for plug-in hybrids. In others, as much as 42 per cent of Canada's personal vehicle fleet could continue to use internal combustion engines, powered by biofuels—despite clear global trends toward the electrification of transportation. So, why would this be the case? And what barriers exist to it coming about?

The possibility of Canada seeing significant amounts of biofuel-powered personal transportation stems from its potential to become a low-cost producer of biofuels compared to the rest of the world, owing to Canada's abundance of feedstocks. But for this future to come about, liquid biofuels would need to be produced differently than they are today. A ten-fold increase in the use of transportation biofuels, as occurs in some of our scenarios, would put significant pressure on feedstocks, including grain crops like wheat and corn and oil crops like soy and canola, raising prices and bringing mounting implications for food security. Biofuels made from second-generation feedstocks such as wastes, residues, and switchgrass would therefore need to prove viable, cost-effective, and scalable, an uncertain prospect at present.

Overall, the future of the internal combustion engine in Canada's net zero future is much less certain than that of EVs, since the biofuels that conventional vehicles would need for fuel still face major barriers and uncertainties around their ultimate viability. EVs are thus much more likely than conventional vehicles to reach the higher end of their potential fleet share range seen in Figure 7 although this would require significant build-out of electricity generation capacity and smart grids (as we discuss in Box 3).

The high relative likelihood of EVs coming to dominate personal transportation is also being reinforced by ongoing domestic and global policy developments. Many countries, cities, and regions have announced bans on the sale of internal combustion engine vehicles, including Quebec by 2035 and British Columbia by 2040; Norway by 2025; Paris, Sweden, and the United Kingdom by 2030; California by 2035; and France by 2040 (Gouvernement du Québec, 2020; Government of British Columbia, 2020; Government of the United Kingdom, 2020; Hampel, 2019; CBC, 2017; Office of Governor Gavin Newsom, 2020). Other governments could

19 Vehicle efficiency would continue to improve beyond 2030. We estimate that conventional vehicles will be 26 per cent to 45 per cent more efficient than they are today by 2050 under a net zero target, continuing a long-established trend—new vehicles today are 24 per cent more fuel-efficient than they were in 2008 (Bigg, 2018).

continue to introduce such bans, particularly as a way of reducing air pollution in urban centres (see Box 7) which, as we discuss in Section 5.2, would not be addressed by a switch from gasoline to biofuels.

Heavy- and medium-duty transportation presents an uncertain picture of four fuels

Daily automotive transportation in Canada, however, is not just about personal vehicles. Where do the myriad freight and delivery trucks and other working vehicles fit in our net zero future?

In some segments of the medium-and heavy-duty transportation sector, our scenario analysis reveals a clear and consistent pathway to net zero. In others, the future is less certain. As with personal vehicles, we find that most urban vehicles, such as buses and local delivery trucks and vans, would be powered by electricity by 2050.[20] This shift is already underway, with electric delivery van and transit bus trials and wider adoption already occurring across Canada. These vehicles have the benefit of being simpler and cheaper to maintain. Charging times and range limits could remain a challenge for some applications, but both are improving.

For long-distance medium- and heavy-duty vehicles, our modelling finds that there are four fuel possibilities in a net zero transition: electricity, hydrogen,[21] biofuels, and fossil fuels offset by negative emissions that occur elsewhere.[22] Each of these approaches could thrive in particular niches or under the right conditions, but each also faces significant challenges and still-uncertain costs that make it difficult to predict which will dominate.

Consider freight vehicles (see Figure 9). In some of the net zero scenarios we examine, hydrogen fuel cell freight trucks command 64 per cent of the market by 2050 but only 36 per cent in others. We find that conventional trucks could comprise as much as 42 per cent of the market by 2050 or as little as 22 per cent—though to be compatible with a net zero target, these trucks would have to be powered increasingly by biofuels (entirely so by 2050) or by fossil fuels offset with negative emissions occurring elsewhere.[23] And while the use of pure battery-electric trucks could be comparatively limited for freight—with an upper limit of only 16 per cent of the market by 2050, largely because fuel-intensive long-haul freight transportation makes relying on batteries difficult—this could also change with unforeseen advances in battery technologies.

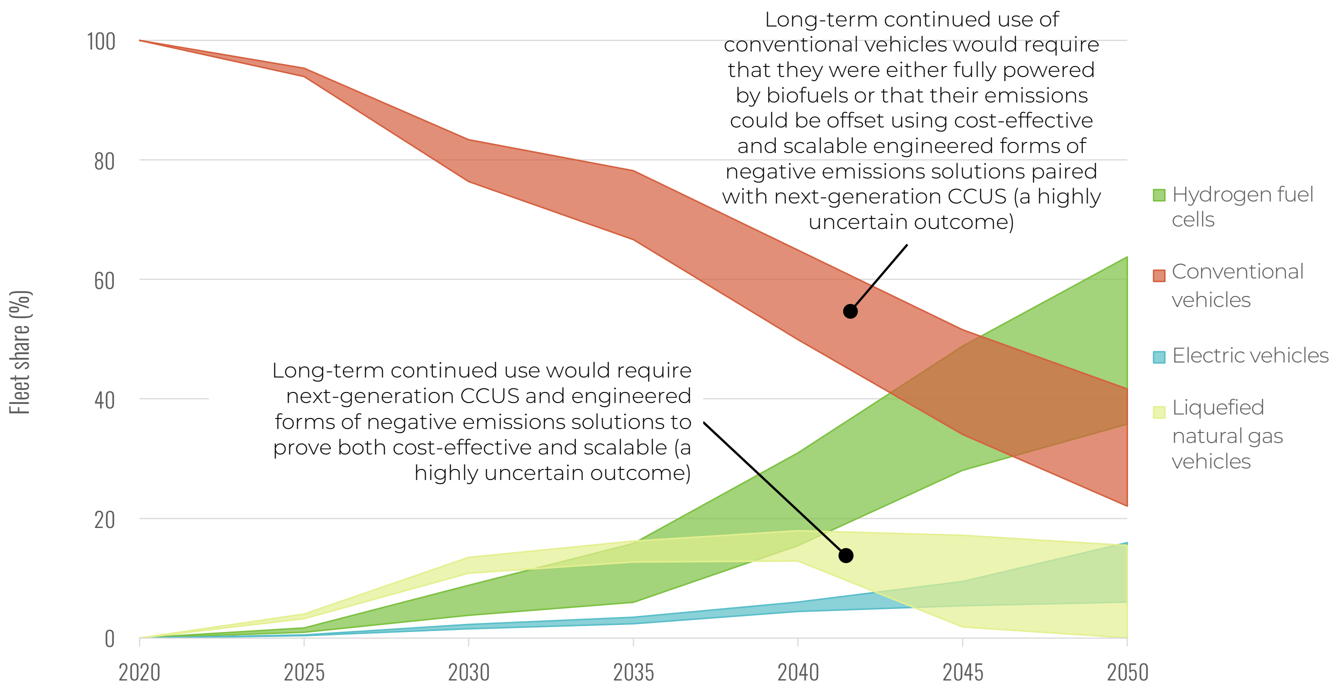
20 Canada is also home to several electric bus manufacturers, including New Flyer in Manitoba, Lion Bus in Quebec, and GreenPower in British Columbia.

21 Specifically, hydrogen freight vehicles would use fuel cells on electric drivetrains with and without batteries. In this sense, they can be considered an alternative type of electric vehicle. Moreover, in some cases, the hydrogen to power these vehicles would itself be produced using electricity.

22 Synthetic net zero fuels produced from carbon dioxide and hydrogen are another possibility for the freight sector (IEA, 2020b). These synthetic fuels are currently costly to produce and not yet commercially available, though the costs to produce them would decline if the costs of hydrogen and renewable electricity also fell. They come with benefits that would make them very attractive for Canada, including the ability to be refined and distributed using existing infrastructure and the significantly lower impacts on land use and natural ecosystems compared to biofuels. However, their ultimate commercial viability is still uncertain.

23 Long-term use of freight vehicles powered by liquefied natural gas would similarly require offsetting via negative emissions.

Figure 9: The total market share of different vehicle types in Canada's freight transportation fleet across pathways to net zero



The uncertainty around the future of vehicle freight extends to other types of freight as well. For freight travelling by rail, Canada achieves net zero in some of our scenarios by transitioning to more-efficient conventional locomotives, powered either by biofuels or by fossil fuels with engineered negative emission offsets. In others, hydrogen fuel cells are a major factor, powering up to 64 per cent of rail freight. Hydrogen- or biofuel-powered trains might also be made into hybrids. Diesel trains already run on electric drives, because they are more efficient and reliable with very heavy loads than mechanical drives. Such trains are commonly equipped with overhead electric wires in many parts of the world, and the same could be done with hydrogen fuel cell or biofuel-powered trains here in Canada.

The uncertainty we observe in the rail sector also extends to the net zero shift in the aviation and shipping sectors (as we discuss in Box 8).

BOX 8

Marine shipping and air travel

Reducing GHG emissions from Canada's shipping and aviation sectors is a critical component of achieving net zero emissions by 2050. Domestic aviation and shipping accounted for approximately 12 Mt of emissions in 2018, or less than two per cent of total emissions (ECCC, 2020b). However, this figure does not capture Canada's share of international shipping and air travel.

The two sectors have already made progress on reducing emissions, and proposed policies should help drive further gains. For example, the energy intensity of commercial airplanes has declined by more than 70 per cent per passenger-kilometre since the 1960s (IEA, 2020c), though emissions overall have risen steadily as commercial air travel has increased (EESI, 2019). At the same time, the Government of Canada (2016) estimates that incoming regulations and other measures to increase the use of low-carbon fuels for shipping and aviation (as well as rail) could reduce emissions by between one and two Mt of CO_2eq by 2030. A shift to virtual workspaces due to the COVID-19 pandemic could also weaken long-term demand for air travel, reversing a historical trend of steady growth.

The shipping sector in particular can reduce emissions by adopting existing technologies, especially by improving energy efficiency and switching to renewable and alternative fuels (Bows-Larkin, 2015; Gould et al., 2009; IRENA, 2015). These improvements can be integrated by retrofitting existing fleets or incorporating them into new shipbuilding and design. Recently, the International Maritime Organization implemented a number of key steps to reduce the carbon intensity of the sector, including new rules limiting the sulphur content of fuels (IMO, 2020). Large-scale freight vessels powered by zero-carbon ammonia are also being tested, with the ammonia made from hydrogen and nitrogen and stored as a liquid on ships.

But even with the adoption of available technologies, getting the shipping sector onto a net zero pathway remains a challenge. Energy efficiency and fuel-switching technologies tend to be expensive. They are also insufficient to get the shipping sector all the way to net zero. At an international level, the uncertainty regarding how to reduce the sector's emissions has encouraged some major shipping companies to put off investing in new ship construction (The Economist, 2020).

Cost barriers are even more formidable in the aviation industry, where solutions have not yet reached an equivalent state of readiness (Bows-Larkin, 2015). Alternative fuels for aviation are being explored, including sustainable aviation fuels, electric and hybrid-electric technology, solar-powered aircraft, and hydrogen. However, these options may only be cost-effective in the long term. The cost of producing alternative fuels is also much higher than jet fuel and would therefore require strong policy support and high capital investment to enable deployment (ICAO, 2019). In the nearer term, operational and technological options can help improve fuel-use and service efficiency (IEA, 2020c).

The significant challenges to making deep cuts in aviation and shipping emissions may push these sectors to offset a certain portion of their emissions. The limited technical and operational opportunities in aviation in particular has led the global industry to look to emissions trading systems to provide net emissions reductions (Bows-Larkin, 2015). Negative emissions solutions, if they prove scalable and cost-effective, could offer the sector another path to net zero.

Hydrogen, biofuels, electric vehicles, and net zero fossil fuels all hold considerable promise for the freight sector, but each would also require the advancement of early-stage technologies and in some cases the development of dedicated infrastructure. Hydrogen offers range and power, but it requires new fuelling infrastructure and is still expensive.[24] Biofuels are already in use for heavy-duty transportation today, but there remain concerns about scaling up their production due to feedstock limitations. Electric freight vehicles are not yet well-suited to long-haul transportation. And net-zero fossil fuels could play a significant role, but only if negative emission technologies prove cost-effective and scalable—a highly uncertain prospect.

Which of these fuel technologies becomes an industry standard in the freight sector will be determined by both policy and market developments. Significant public investment in production or fuelling infrastructure for a particular solution could drive investment toward it, supporting economies of scale. A decision by a major freight operator to transition its entire fleet to a particular solution could cause other operators to follow suit. And technology breakthroughs or policy decisions in other countries could dramatically affect the relative costs of the key technologies.

24 A demonstration project underway in Alberta has begun exploring hydrogen's potential for freight vehicles, including development of a corridor with refuelling infrastructure (Emissions Reduction Alberta, 2020).

4.3 INDUSTRY: WHAT WE MAKE

KEY PATHWAYS TO NET ZERO

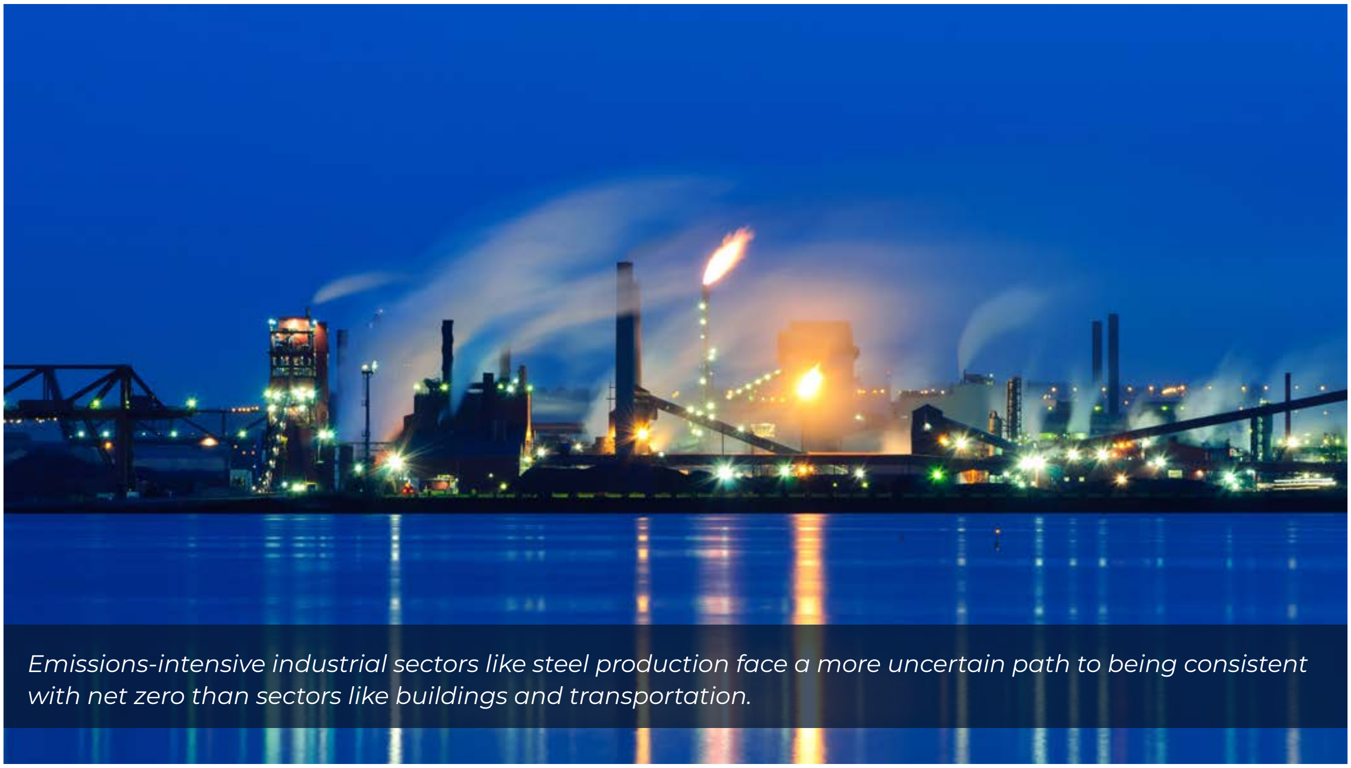
- There is no one-size-fits-all approach for transitioning Canada's industries to be compatible with a net zero future—their emissions reduction pathways are much more uncertain and diverse than those for buildings and transportation.
- In all the scenarios we examine, the sector uses some amount of negative emissions to reach net zero due to the high cost of reducing some types of industrial emissions at source, but the amount varies depending on the extent to which negative emissions solutions prove viable.
- Canada would continue to be a resource producer and manufacturer on the path to net zero, but the mix of products it produces and sells to the world would evolve.
- We find that Canadian oil and gas production can only be consistent with net zero if a very specific (and uncertain) combination of outcomes and conditions comes to pass.

Canadian industries supply the essentials of our daily lives—from energy to raw materials to consumer goods—and drive the international trade that propels our economy. They also employ people across the country, providing income and jobs. At present, this industrial base is heavily reliant on fossil fuels for the bulk of its energy, producing half of the entire country's emissions (362 Mt CO_2eq per year) through fuel use and industrial processes. The oil and gas, petroleum refining, metals, and chemical production sectors are particularly large emitters.

Transitioning Canada's industries to be compatible with a net zero future is a major challenge. Each industry will need to find its own path consistent with global technological and market dynamics and policy in their sector,[25] and even similar industrial operations may require separate paths in different parts of the country. Overall, our analysis finds that industry's path is much more difficult to predict than other sectors of the economy.

Regardless of how exactly Canada's net zero transition plays out, our modelling finds that the country would remain a major resource producer, manufacturer, and high-tech service provider. The exception is Canada's oil and gas sector. We find that Canadian oil and gas production can only be consistent with net zero if a very specific (and uncertain) combination of outcomes and conditions comes to pass – many of which are highly uncertain, not to mention outside of Canada's control. At the same time, growing markets for cleaner energy, materials, chemicals, and services will provide new oppor-

25 In industries that produce globally traded commodities and services, global market and policy developments may even prove to be a more important determinant of their net zero pathway than domestic policy action and market developments.



Emissions-intensive industrial sectors like steel production face a more uncertain path to being consistent with net zero than sectors like buildings and transportation.

tunities for Canadian businesses and workers in emerging and existing sectors to thrive in supplying their products and know-how to Canada and the world.

Reducing industrial emissions is less clear-cut than for buildings or transport

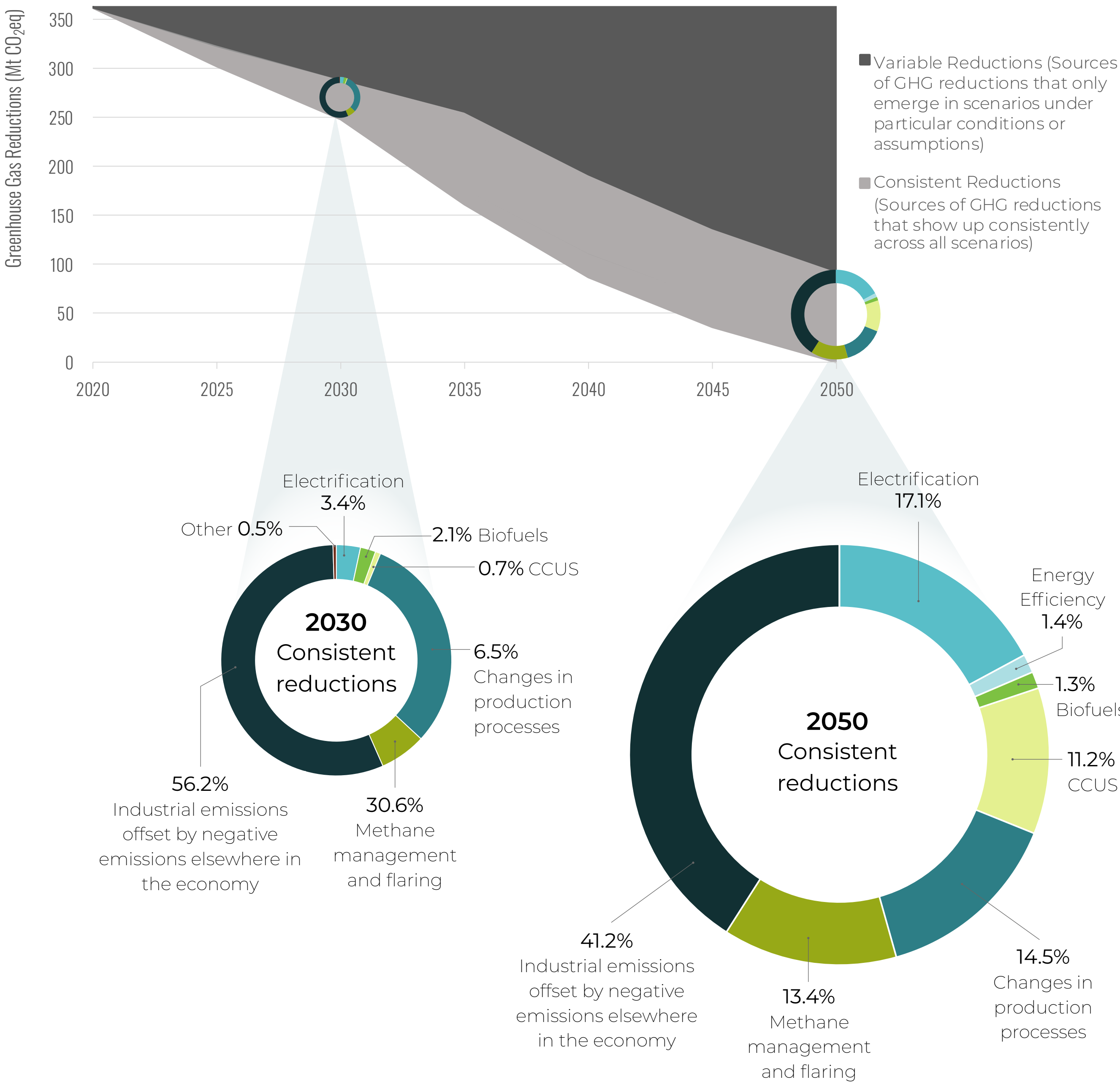
There is definitely no one-size-fits-all solution for Canadian industry.[26] In all the scenarios we examined, only 36 per cent of industry's emissions cuts by 2030 are delivered by the same group of technologies and interventions, and only 26 per cent by 2050 (see Figure 10). The solutions that show up consistently in all of our scenarios include methane management, CCUS, electrification, energy efficiency, and production process changes such as using electricity to recycle steel.

Our analysis suggests that reducing heavy industry to net zero on its own is likely to be expensive. Net zero for Canada does not necessarily imply net zero for any one sector. Because all our scenarios assume that at least some negative emissions are available, some "gross" emissions can continue (we return to the challenges in this assumption in Section 4.4). Across our scenarios, 20 per cent of heavy industry's emissions remain in 2030 and around 11 per cent by 2050.[27] The high costs associated with fully decarbonizing certain industrial production processes (cement production, for example) and with early retirement of some emissions-intensive production facilities are key factors.

26 We define Canadian industry broadly to include agriculture, forestry, mining, oil and gas, auto manufacturing, chemicals, hydrogen, biofuels, metals, paper, and other manufacturing sectors.

27 The sector may also generate some amount of negative emissions itself by combusting RNG for energy at industrial facilities and then sequestering the emissions via CCUS technologies. When the emissions from combusting RNG with net zero lifecycle emissions are captured, its overall emissions become net negative, opening the possibility of offsetting other parts of a facility's emissions or even selling credits to other facilities or operations.

Figure 10: Comparing consistent and variable emission-reduction pathways for industry to reach net zero



Blue or green hydrogen may come to offer industry a cost-effective source of zero-emissions heat.

The extent to which heavy industry emissions that are especially costly to reduce or capture at source can persist in a net zero world depends on the availability of negative emission solutions to offset them. We assume that some amount of nature-based negative emissions will be available in all our scenarios. However, some scenarios also assume that engineered forms of negative emissions solutions will prove cost-effective and scalable.

In scenarios where those technologies do not prove cost-effective and scalable, the remaining industrial emissions are eliminated by a range of technologies, including wider use of solutions like electrification of production processes, CCUS, much greater deployment of otherwise marginal solutions such as biofuels, and structural changes in the industrial base that shift more production to less emissions-intensive sub-sectors.

On the other hand, in scenarios where engineered negative emissions solutions do prove cost-effective and scalable, they tend to play a very large role, leaving only a minority of the remaining industrial emissions to be reduced at source. In these scenarios, engineered negative emissions solutions also allow for continued use of existing production methods in emissions-intensive industrial sub-sectors, avoiding deep and costly changes to production processes. But there remains significant uncertainty regarding whether engineered negative emissions solutions will prove an available tool for industry in this way and, if so, at what cost.

Uncertainty regarding industrial sector pathways is amplified by the unknown future cost of certain technologies. For example, in a scenario in which CCUS becomes relatively high-cost, biofuels tend to play a larger role in providing high-grade heat for industries. And when biofuels become relatively high-cost, CCUS applied to fossil fuel combustion tends to play a larger role.[28]

28 When both technologies are relatively cost-effective, they might often be deployed in combination to generate negative emissions.

Canada will remain a resource producer and manufacturer

Although industries will be required to significantly cut their emissions on the path to net zero and the composition of Canada's industrial production may well see big changes, Canada and the rest of the world will continue to need many of the resources and products produced here. In all the scenarios we examined, resource sectors such as agriculture, forestry, and mining see continued growth, as do manufacturing sectors like vehicles, chemicals, steel, cement, hydrogen, biofuels, metals, and paper (see Figure 11 and Figure 12). The modelling tells a different story for oil and gas, which we discuss below.

Figure 11: Resource output across pathways to net zero*

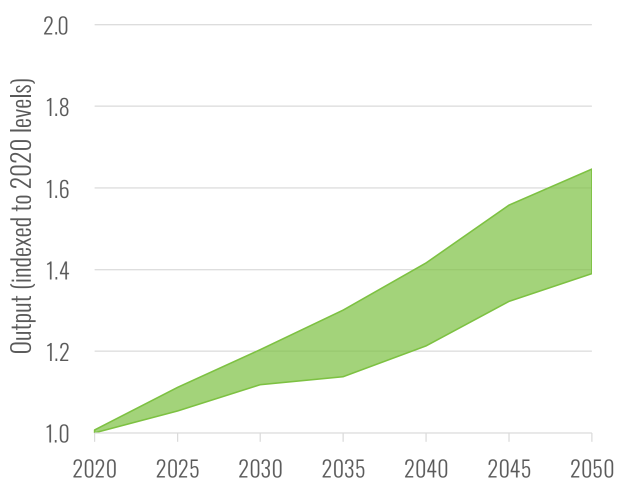
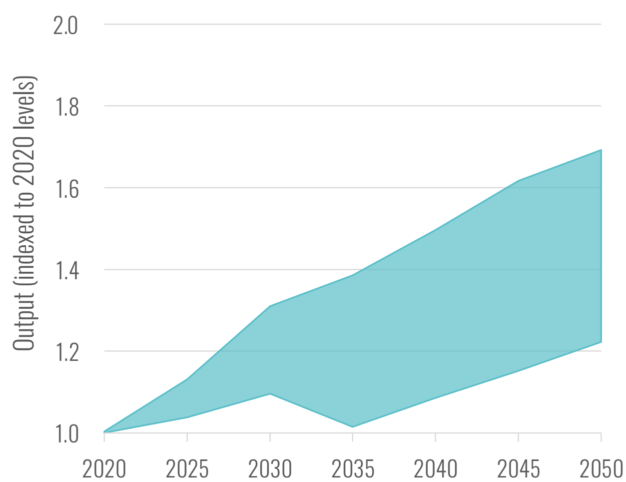


Figure 12: Manufacturing output across pathways to net zero**



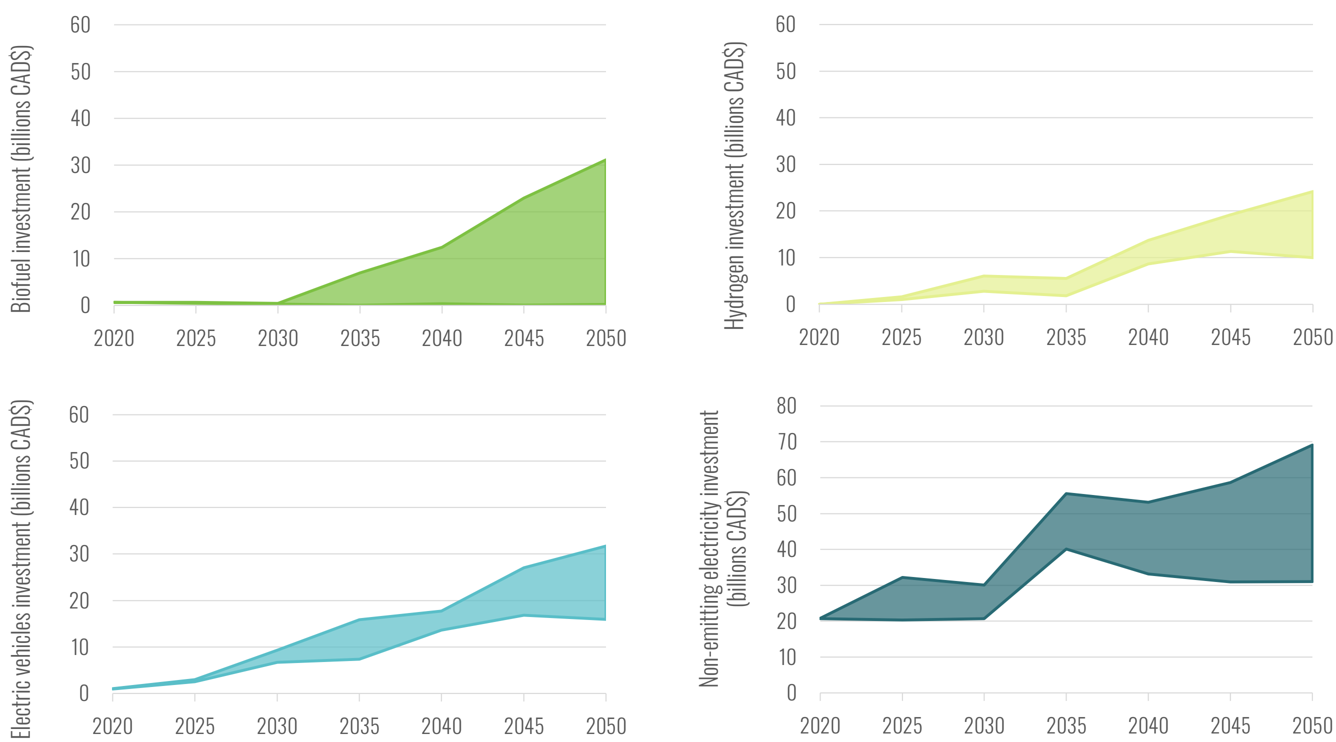
**Resource sector figures combine output in the agriculture, forestry, and mining sectors (Canada's oil and gas sector, which we discuss below, is not included in this figure).*

***Manufacturing sector figures combine output in the vehicles, chemicals, steel, cement, hydrogen, biofuels, metals, paper, and other manufacturing sectors.*

Some industrial sub-sectors would see especially significant growth on the path to net zero. Our modelling finds that the technologies and products that play central roles in the net zero transition would become important industrial growth areas in and of themselves, as illustrated by the investment pathways for hydrogen, EVs, biofuels, and non-emitting electricity shown in Figure 13.

In scenarios where the rest of the world takes increasingly decisive action on climate change, some parts of Canada's industrial sector would see especially significant expansion. For example, our analysis finds that investment in biofuels would be highest when other countries also act decisively on climate change, boosting global demand, increasing prices, and making domestic production more competitive. And significant global climate action would drive growth not only in emerging cleantech sectors but in existing Canadian industrial sub-sectors as well. For example, Canada is a major producer of many of the minerals required to manufacture technologies that are vital to the low-carbon economy, such as EVs, solar panels, and wind turbines. Canada is also well positioned to supply lead, zinc, copper, and gold, all required by the solar industry; the cobalt, graphite, and nickel essential for battery manufacture; and low-emissions aluminum essential to the automotive, transportation, and construction industries, among others (NRCan, 2017; NRCan, 2019b; IEA, 2020d). And as the world decarbonizes, there may also be opportunities for Canada to export its technical knowledge and services to other countries, including in the buildings, transportation, and electricity sectors (see Box 3).

Figure 13: National investment in clean technology sectors across pathways to net zero*



In these figures, investment includes expenditures on goods that will be used to produce other goods and services in the future as well as household expenditures on clean energy technologies.

Clean technology exports, such as biofuels, are already showing promising trends. Between 2014 and 2019 clean technology exports grew by a rate of 9.7% annually.

The global clean technology market is expected to exceed $2.5 trillion by 2022 (Clean Technology Table, 2019). Canada has an opportunity to thrive in this booming marketplace, since its clean technology sector is already generating $17 billion in annual revenues and scoring well on international rankings (fourth out of 40 countries on the 2017 Global Cleantech Innovation Index). China and the E.U. have already shown particularly strong appetites for Canadian cleantech (EDC, 2020).

Canada's clean technology exports are already showing promising trends. For example, between 2014 and 2019, clean technology exports grew by an annual rate of 9.7 per cent (triple the rate of all Canadian exports in that same period). Notable sectors include clean fuels, rare earth minerals, clean electricity, clean power technologies, technologies for industrial decarbonization, clean transportation technologies, and energy-efficient equipment (Sawyer, 2020).

Canadian oil and gas faces a precarious future

The production of oil and gas (much of which is exported[29]) is Canada's largest source of emissions, at 26 per cent of Canada's current national total (ECCC, 2019b). While improvements to the emissions intensity of production can drive reductions, overall emissions rise and fall predominantly with changes in production levels.

Our analysis finds that, independent of domestic climate policy choices, production in the Canadian oil and gas sector will be determined first and foremost by global forces. Factors such as increasing EV sales or sustained high production volumes by other global suppliers could continue to depress prices and lead to slower growth or even declines in Canadian production. Climate policy action abroad could reduce global demand for fossil fuels and, by extension, prices. And because all of these drivers are fully outside of Canada's control, Canada's oil and gas sector could face significant challenges independent of any domestic choices.

Our modelling suggests that in scenarios where global oil and gas prices drop significantly due to changing market conditions or global climate policy (or both), Canadian production (and emissions) would drop significantly. We find that in a low-oil-price scenario—where global oil prices decline to US$38 a barrel by 2030 and drop slightly further to US$36 by 2050[30]—oil production in Canada would fall by 89 to 96 per cent by 2050 relative to today and natural gas production by between 56 and 74 per cent (see Figure 14 and Figure 15).

29 81 per cent of Canadian crude oil production and 45 per cent of Canadian natural gas production is exported (NRCan, 2020c; NRCan, 2020d).

30 For context, oil prices have been trading at roughly $40 per barrel in 2020.

Figure 14: Canadian oil production under low and high global price scenarios for oil across pathways to net zero

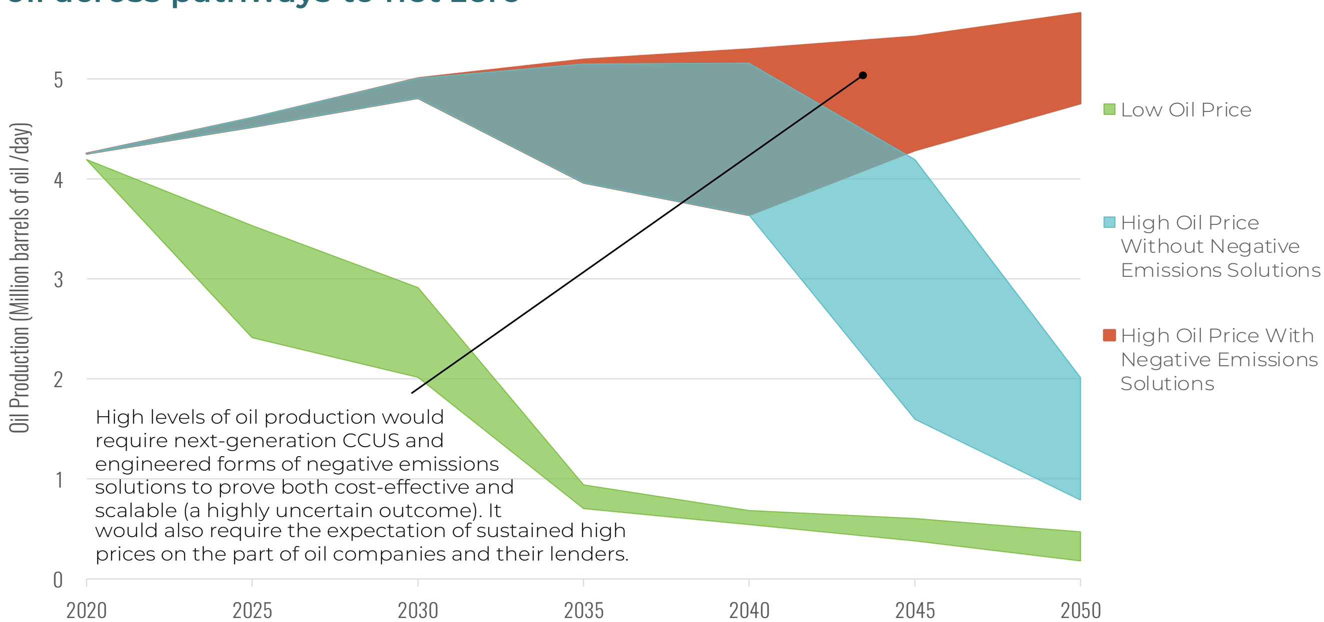
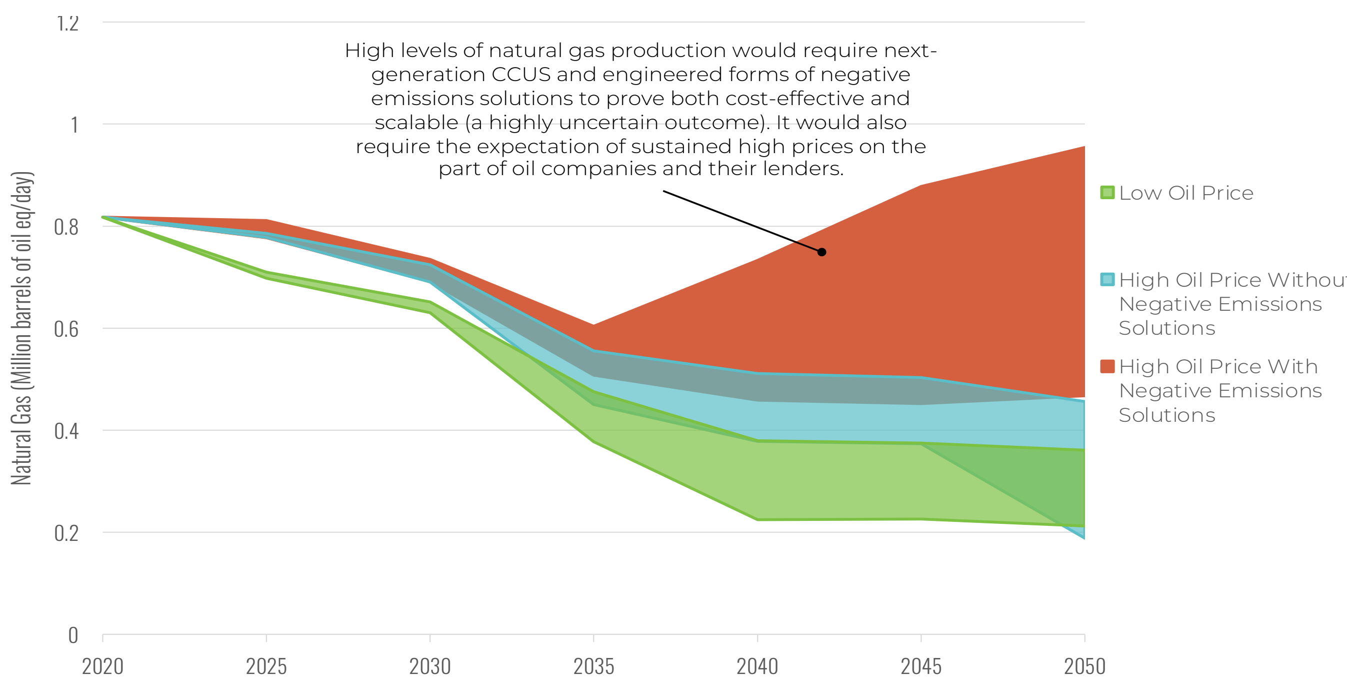


Figure 15: Canadian natural gas production under low and high global price scenarios for oil across pathways to net zero*



*Our modelling uses global oil prices as a proxy for global natural gas prices, since the two tend to correlate.

Canadian oil production (and emissions) would fall significantly under any scenario where global oil prices stay low. While the low variable cost of Canadian oil production can allow producers to weather periods of low prices, its high fixed costs mean that significant levels of production cannot be sustained if prices stay low over the medium or long term. These difficulties would also be exacerbated if global climate policy drives low prices, since policies in other countries favouring oil produced with low emissions intensity would put significant portions of Canada's oil production at a competitive disadvantage. Emissions intensity improvements aimed at improving this competitiveness would also be made more difficult in such an environment, since thin margins for producers would reduce the capital on hand to make the necessary investments and financing would be more difficult to obtain (Jaccard et al., 2018).

Looking at the full range of scenarios we examined, we find that Canadian oil and gas production levels would only stay steady or grow on the path to net zero under a set of very specific conditions. Global prices would have to rise above their current levels and remain high (the high-price scenarios that we model have oil prices rising to US$63 a barrel by 2030 and US$87 by 2050). There would also have to be an expectation that prices would behave this way.[31] At the same time, oil and gas producers would have to make significant investments to reduce the emissions intensity of production, both by implementing existing technologies and developing better ones.[32] And demonstration-stage technologies such as CCUS for non-concentrated flue gas streams and engineered forms of negative emissions would need to prove both cost-effective and scalable, which is a highly uncertain outcome.

In other words, for sustained Canadian oil and gas production to be consistent with a net zero goal, both net zero production emissions and continued international demand (as well as the expectation of it) would be required. The former depends on successfully and cost-effectively scaling engineered negative emissions solutions and next-generation CCUS domestically (a highly uncertain prospect, as we discuss in Section 4.4).[33] The latter can only occur if engineered negative emissions scale globally[34] or if international efforts at addressing climate change fail, leading to potentially dramatic climate change impacts both in Canada and internationally.

31 Canadian oil producers and their lenders would need confidence that capital expenditure on measures that reduce their emissions intensity of production and that maintain or increase Canada's overall productive capacity (by building new projects or expanding operations in ones where output was declining) would offer a long-term return on investment.

32 Our modelling scenarios vary in the assumptions they use for the degree of emissions intensity reductions that could occur over the long term in Canada's oil sands. We use both reference case assumptions found in the gTech model as well as projections from the Canadian Association of Petroleum Producers. We find that even when deeper cuts in emissions intensity occur in the sector, they do not affect our main findings regarding Canadian oil and gas production's compatibility with net zero.

33 If, on the other hand, engineered forms of negative emissions do not prove out but second-generation forms of CCUS do, Canadian oil production could remain competitive in Canada's net zero transition and potentially still find a market abroad—but only if prices were high enough, if they were expected to be so, and if sufficient emissions intensity improvements were made. This would happen only in a scenario in which other major countries significantly lagged Canada in their climate policy implementation. Other countries could not be adopting CCUS to offset their continued fossil fuel combustion, since our analysis indicates this would only be economical in some parts of the industrial sector. Significant sustained global demand for oil and gas in this scenario would therefore require continued consumption in the global buildings and personal transportation sectors, indicating weak climate action abroad and that the world was likely to exceed its target of limiting global temperature rise to 1.5°C. If, on the other hand, neither engineered forms of negative emissions solutions nor second-generation CCUS proved out but nature-based solutions were available in Canada at sufficient scale and cost-effectiveness, then Canada's oil and gas production could potentially find a market abroad—but again, only if prices were high enough, if they were expected to be so, and if sufficient emissions intensity improvements were made. However, this would also require other countries to be lagging Canada in their climate policy implementation. According to our analysis, using nature-based negative emissions solutions to offset emissions from buildings and personal transportation would not be cost-effective. Therefore, in this scenario continued global demand would have to lag global climate policy and the world would likely fail to meet the target of limiting global temperature rise to 1.5°C.

34 Only a select number of countries have the geological potential for large-scale sequestration of CO_2. Therefore, a scenario in which other countries offset their fossil fuel consumption with negative emissions would require not only that they opted to do so but that they were able to as a result of a global trading regime being developed under the UNFCCC that included negative emissions.

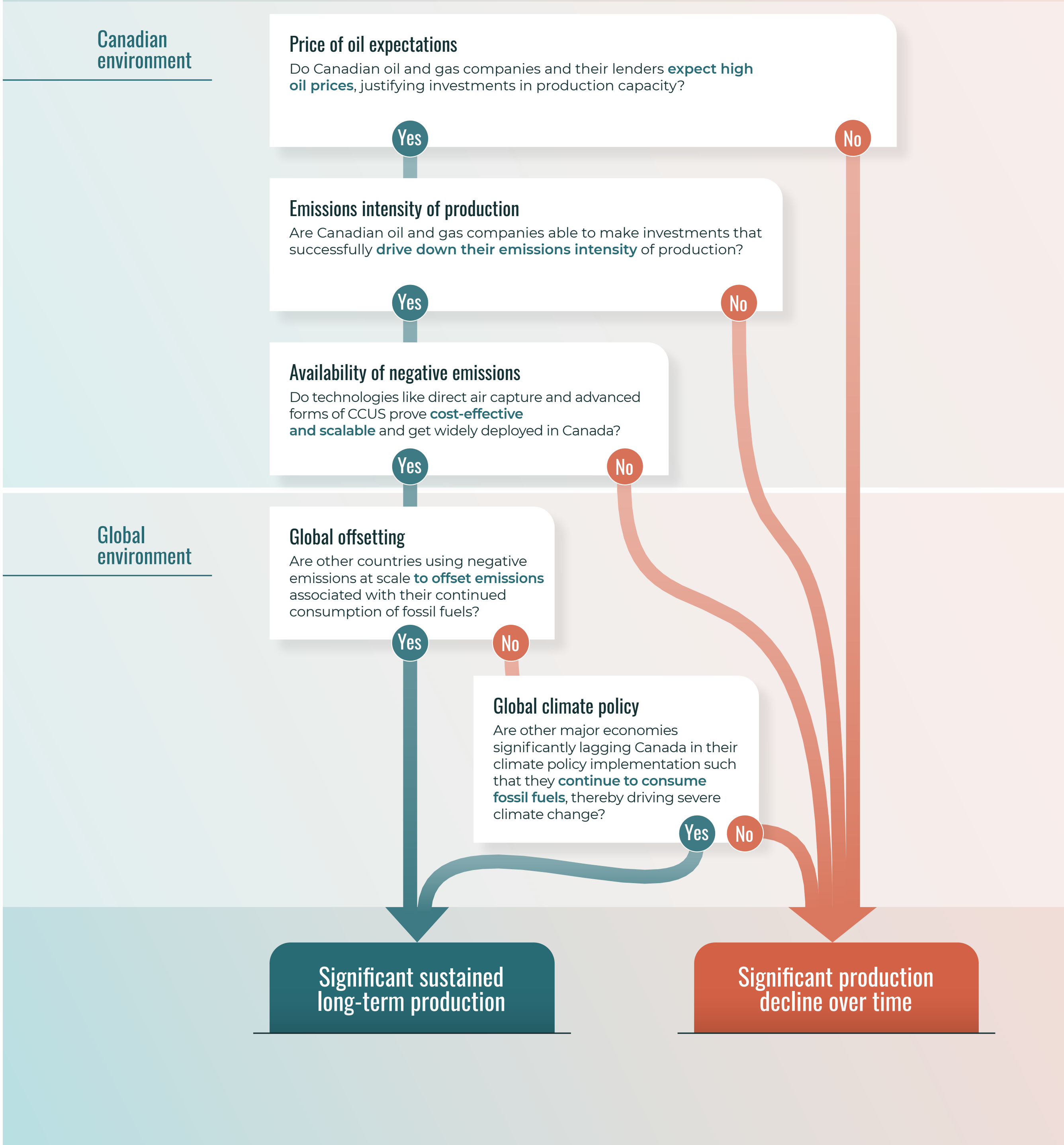
In the event that those conditions were to come about, there is a potential pathway in which the Canadian oil and gas sector could reduce its production emissions to net zero while remaining competitive. If these conditions emerge, our modelling projects that demand for Canadian oil would boost production 30 per cent higher by 2050 relative to today (as seen in Figure 14). Natural gas production would follow a different path (as seen in Figure 15), initially declining by 26 per cent by 2035 before rebounding by 2050 to a level 17 per cent higher than today's projection levels, as CCUS and engineered forms of negative emissions were increasingly deployed by the sector.

But these outcomes are far from guaranteed and depend on a number of factors that Canada does not and cannot control. And while there may be scenarios in which Canadian fossil fuel reserves serve as a feedstock for the production of petrochemicals or other new materials and products, these are not guaranteed either at any dependable scale.

The vulnerability of Canada's oil and gas sector to larger global and market forces underscores the importance of economic diversification to ensure the continued prosperity of Canada's oil-producing provinces. Box 9 explores some of the economic opportunities that could exist for oil-producing regions in a transition to net zero.

Both net zero production emissions and significant long-term global demand for fossil fuels (as well as the expectation of it) would be required for sustained Canadian oil and gas production to be consistent with a net zero goal.

Factors affecting Canadian oil and gas production on the path to net zero



BOX 9

Economic diversification in Canada's oil-producing provinces

The pathways we examined vary significantly in terms of the amount of structural change each would create in the Canadian economy (further discussed in Section 5.2) and their associated regional impacts. But in general, the economic move from carbon-intensive sectors to low-carbon ones would have the strongest impacts in Canada's oil-producing regions. And a decline in carbon-intensive sectors may occur regardless of Canadian climate policy.

A number of the sectors that are expected to grow under a net zero transition, however, align well with the infrastructure, resources, and know-how found in Canada's oil-producing provinces. Sectors such as hydrogen, biofuels, and electricity are all potential growth areas for such regions.

Hydrogen production is one of the most promising new sectors for Alberta and Saskatchewan in the net zero transition. In all scenarios we examined, our modelling estimates that investment in the hydrogen sector would rise steadily in both provinces between 2020 and 2050. And because our modelling likely does not capture hydrogen's full potential, the opportunity could be even larger than we estimate. What's more, this new industry will require skills that many oil and gas workers already possess—for example, building steam-methane reforming facilities with CCUS to produce blue hydrogen, building CO_2 pipelines, and converting oilfield operations and orphaned wells to CO_2 disposal or to hydrogen production facilities. Hydrogen could also represent an important export opportunity for these regions. Canada's oil and gas industry is already making important strides as the country's largest hydrogen producer, with companies like Shell producing hydrogen with CCUS to reduce emissions.

Oil-producing regions can also seize the growing biofuels opportunities that we project in our modelling by re-tooling to support biofuel production. Refineries can be converted to biofuel facilities, as Phillips 66 is planning to do in the United States, or oil production companies can build and operate new biofuel facilities, as Suncor and Husky do today (Phillips 66, 2020; Suncor, 2020; Husky Energy, 2020).

Other potential growth sectors include lithium and uranium mining, battery production, small modular reactors, and geothermal energy. And negative emissions solutions may themselves present economic opportunities, as we discuss in Section 4.4.

Jobs and skills, however, are not readily interchangeable from sector to sector. Many workers may lack the specialized training in science, engineering, and operations management needed in some emerging low-carbon sectors (Thirgood et al., 2017). Hydrogen, biofuels, and electricity production, for example, see growing employment in all the scenarios we examined, but some of this employment requires particular skill sets. Careful attention to education and retraining is essential to dealing with these kinds of potential skill set mismatches.

The transition to net zero bears the risk of generating or amplifying significant economic, social, and cultural disruption for workers and communities, particularly those dependent on emissions-intensive sectors. But it will also not be the only driver of challenges. Even net zero transitions that create the least amounts of structural change could still see significant changes in the employment picture, owing to larger global trends such as shifting demand and automation. Government policy that mitigates impacts on displaced workers and communities and that creates opportunities for them to participate in and even lead the transition will be essential (Phanord-Cadet et al., 2018).

4.4 NEGATIVE EMISSIONS: PUTTING THE "NET" IN NET ZERO

KEY PATHWAYS TO NET ZERO

- Negative emission solutions, whether nature-based or engineered, would complement other solutions such as energy efficiency, renewables, and electrification. Should they prove viable, they could drastically change Canada's net zero path and future energy system.
- Nature-based solutions could play an important role but conflict with other land-use priorities. And they would have to involve Indigenous Peoples, who have inherent rights to the lands the solutions would be deployed on. But there are concerns about how additional and permanent these kinds of negative emissions can be in reality.
- Engineered forms of negative emissions have enormous potential, but whether (and to what extent) they will contribute to Canada's net zero target remains highly uncertain.

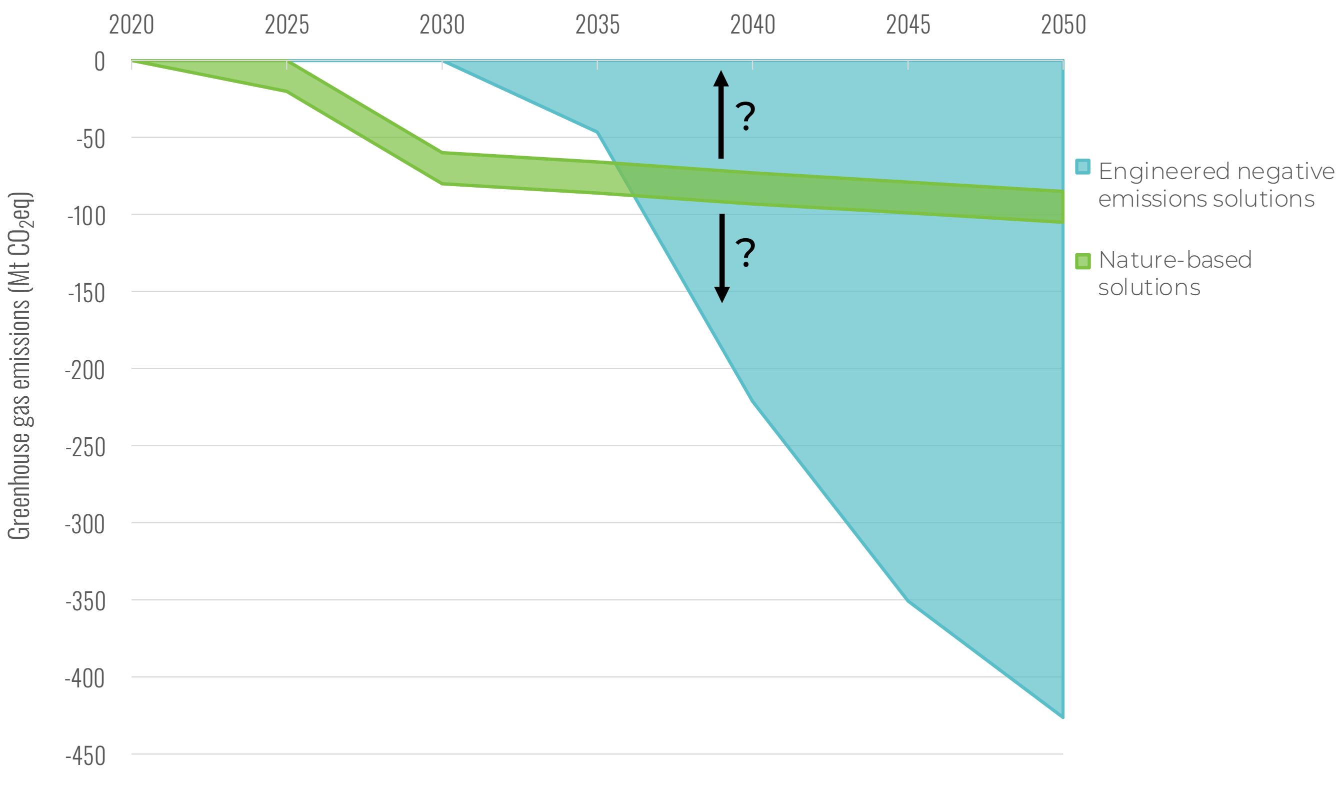
Negative emissions are a necessity, not a luxury, on the global path to addressing climate change. The IPCC's special report on the impacts of a 1.5°C temperature rise calls for not just net zero emissions of CO_2 by 2050 but net negative emissions by 2100, depending on how fast global emissions fall to net zero (Hoegh-Guldberg et al., 2018). And most global assessments of the path to the 1.5°C goal indicate that net negative emissions will become part of the mix by the 2030s.

Negative emissions may also be necessary for Canada to hit net zero by 2050. Some aspects of Canada's emissions can be extremely difficult or costly to reduce because existing capital stock (infrastructure, factories, buildings, large vehicles) is so long-lived or because near-zero emissions alternatives will not be available for some time, if at all. Negative emissions could potentially help to neutralize some of these sources of continued emissions, helping Canada achieve its target.

As we discuss in Box 4, these negative emissions could come from nature-based solutions, such as planting trees, adjusting agricultural practices, or letting marginal agricultural land return to wilderness. They could also come from engineered solutions, such as biomass combustion or direct air capture of CO_2 combined with CCUS.

In the scenarios we examine, there is substantial variation in the potential contributions from negative emissions. As seen in Figure 16, our modelling projects a very wide range for the uptake of engineered forms of negative emissions solutions, owing to the uncertainty that still surrounds their ultimate cost-effectiveness and scalability. In contrast, the narrower band seen for nature-based solutions is more of a function of the limited availability of credible estimates of its potential than it is this level of uptake being a stable and consistent outcome across the scenarios we consider. We discuss nature-based and engineered forms of negative emissions solutions below.

Figure 16: The high uncertainty surrounding the potential of negative emissions from nature-based and engineered solutions across pathways to net zero



Modelling inputs for the technical potential of GHG sequestration from nature-based solutions are drawn from pending analysis by Nature United. The potential seen in the figure may be an underestimate, owing to the fact that Nature United's analysis only considers the effects of nature-based interventions that would occur between now and 2030 (some of which would continue to sequester GHGs after that, as biomass continued to grow and sequester carbon). Or it may be an overestimate, owing to the difficulty and barriers associated with realizing nature-based interventions on this scale and challenges around credibly establishing their additionality and permanence (see Box 10).

Nature-based solutions could play a significant role in offsetting emissions in areas where they are very difficult or costly to reduce directly.

There is opportunity for nature-based solutions but implementation may be challenging

Nature-based solutions have enormous potential for the low-cost sequestration of GHGs in forests, grasslands, wetlands, and agricultural lands.[35] Canada's large land mass offers significant potential for such interventions. In our analysis, we project that nature-based solutions would contribute to offsetting GHG emissions in areas where they are very difficult or costly to reduce, such as particularly emissions-intensive industrial processes for vital materials like cement.

Realizing this potential, however, would be far from straightforward. First, there is the issue of crediting for the GHG sequestration that would occur. Canada has some experience with this: national GHG inventories already include these kinds of estimates for interventions in the agriculture and forestry sectors. However, Canada would also need to extend these estimates to cover grasslands and wetlands (as Australia, for example, has done) using UNFCCC-recognized accounting protocols. And, despite there being a pathway to getting credit for nature-based solutions in Canada's emission inventory, difficult questions would remain about the level and permanence of the sequestration that these solutions would provide (as we discuss in Box 10).

35 The potential also exists for ocean-based forms of sequestration. However, we exclude these from our analysis because there is little literature available on their quantitative potential in Canada and because such interventions are not yet recognized in the UNFCCC emissions accounting system (unlike terrestrial sequestration, which can be included in countries' GHG inventories).

BOX 10

Challenges of carbon sequestration through nature-based solutions

There are significant challenges in ensuring that the carbon sequestration attributed to nature-based solutions is genuine and credible. While globally agreed methodologies exist for the inclusion of land-based carbon sequestration in emissions inventories, there is enough potential for inaccurate estimates or attribution that concerns remain around how and whether countries should rely on this kind of sequestration as a way of reaching their emissions targets. Some of these concerns stem from the fact that while carbon sequestration using CCUS technologies can be measured, sequestration from nature-based solutions can often only be estimated.

Permanence is another concern. Credible estimates of sequestration must ensure that the carbon is stored permanently (defined as 100 years or more) and that any leakage is accounted for (Thamo & Pannell, 2016). Nature-based solutions can be particularly prone to leakage of their stored carbon compared to engineered solutions that sequester it underground, which has been found to be a more reliably permanent means of long-term storage (Kampman et al., 2016). Carbon sequestered in biomass can "leak" when, for example, the biomass dies off due to drought or is combusted by wildfire (drivers which are both expected to increase due to climate change). It can also be affected by future land use conversion, such as urban development. Accurately estimating the permanence of carbon sequestered in soil can be particularly difficult, due to the variability of soil carbon content, the need to measure small incremental changes in it, and the high costs of soil carbon measurement procedures (Garcia-Oliva & Masera, 2004). And while the leakage of stored carbon from land is addressed under UNFCCC accounting methodologies, the leaks have to be correctly observed and their effects credibly estimated for them to be accurately reflected in a country's emissions inventory.

Second, crediting mechanisms would need to be in place to offer the private purchase of nature-based emissions offsets.[36] Offset protocols exist today that provide the building blocks for this type of mechanism, but their size and scope would need to be expanded significantly to enable significant deployment of nature-based solutions.

Third, the physical footprint of nature-based solutions would raise difficult questions, since the sheer amount of land needed for some solutions such as afforestation would likely conflict with competing land uses (such as food production) and have impacts on surrounding ecosystems (Fuhrman et al., 2020).

Most critically, nature-based solutions would need to respect the inherent, treaty, and constitutionally protected rights of Indigenous Peoples, given that these solutions would often be deployed on their traditional lands. The recognition and implementation of Indigenous rights is central to Canada's relationship with First Nations, Inuit, and Métis for the advancement of reconciliation and recognition of self-determination. But the current framing of nature-based solutions tends to conflict with Indigenous worldviews by commodifying nature in terms of offsets and by viewing the land as empty and open for development, effectively erasing the presence of Indigenous Peoples (Indigenous Caucus Statement, 2020; Carton et al., 2020).

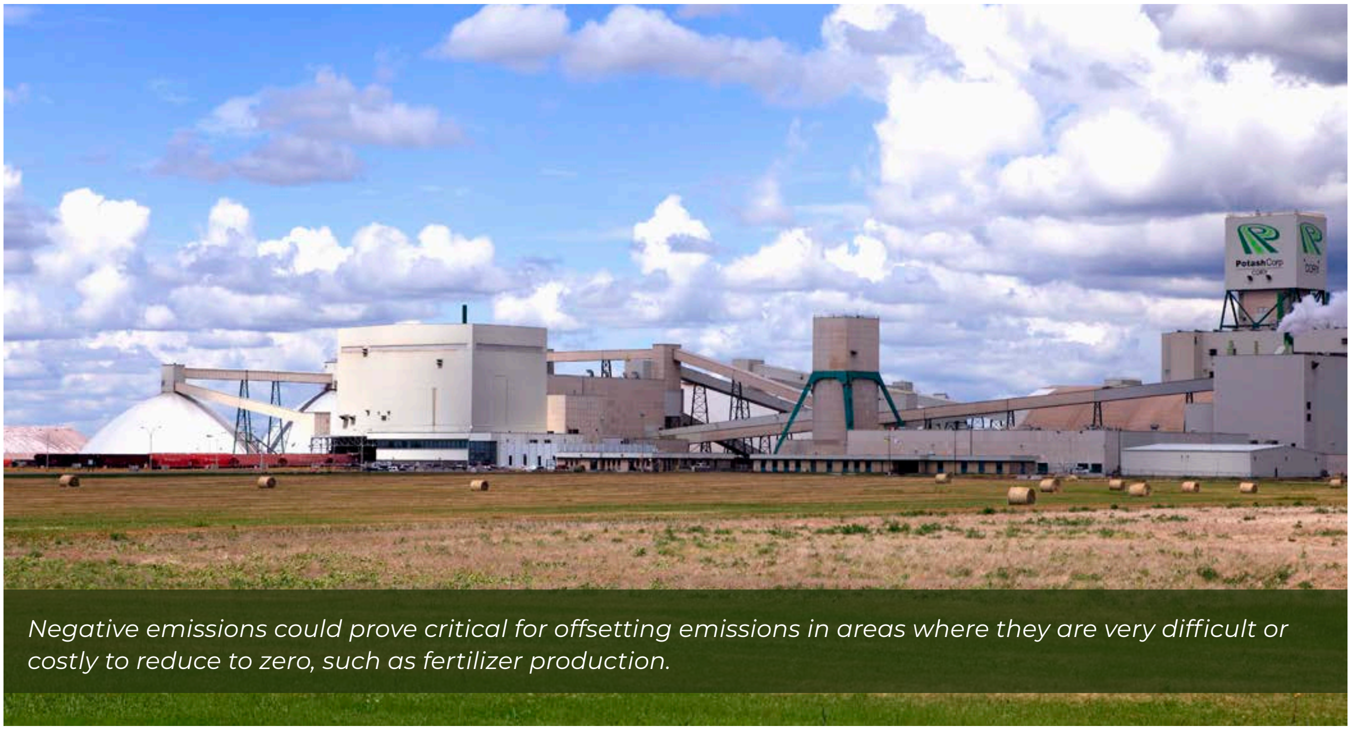
An alternative approach to nature-based solutions building on Indigenous perspectives and values could offer a path forward. Past experience will provide critical lessons. Plans to increase sequestration in lands that are deemed underused and therefore suitable to use as carbon sinks have often ignored the complex land-use practices of local and Indigenous communities (Carton et al., 2020). In contrast, Indigenous-led land management initiatives such as the Indigenous Protected and Conserved Areas not only sequester GHGs by maintaining a range of ecosystem services, they also conserve biodiversity and empower Indigenous Peoples to do so using Indigenous knowledge, governance, and value systems (Townsend et al., 2020). By working closely with Indigenous partners, nature-based solutions projects could be proposed in a way that both supports a renewed nation-to-nation relationship between Canada and Indigenous Peoples and enhances the net zero transition by drawing on the knowledge of people who have been living on and caring for the land for thousands of years.

The role engineered forms of negative emissions will play in Canada's transition is uncertain

In our analysis, engineered types of negative solutions such as direct air capture paired with CCUS vary widely in the degree of negative emissions we estimate they could supply, from a high of 426 million tonnes (Mt) annually by 2050 (over half of Canada's current emissions) to a low of zero.

We find that in the event that these engineered types of negative emissions solutions proved cost-effective and scalable, they could open up significant possibilities for Canada. Not only would they make continued use of fossil fuels possible, but they could in fact potentially support increased fossil fuel use (providing 56 to 62 per cent of Canada's final energy demand

36 Alternatively, governments could instead purchase these offsets and allocate them against large sources of remaining emissions. But to do so they would need to make decisions regarding what sorts of remaining emissions would be entitled to such allocations.



Negative emissions could prove critical for offsetting emissions in areas where they are very difficult or costly to reduce to zero, such as fertilizer production.

by 2050).[37] In such a scenario, our modelling suggests that energy use in Canada would take a very different path (see Figure 17), with overall energy use rising by 2050 rather than falling over time as it does under economy-wide pathways where these technologies do not prove viable. If sufficiently cost-effective, engineered negative emissions could help to avoid the full elimination of emissions in some parts of the economy that can be very costly, as well as much of the structural change in the economy that our modelling suggests would occur under most alternative economy-wide pathways.

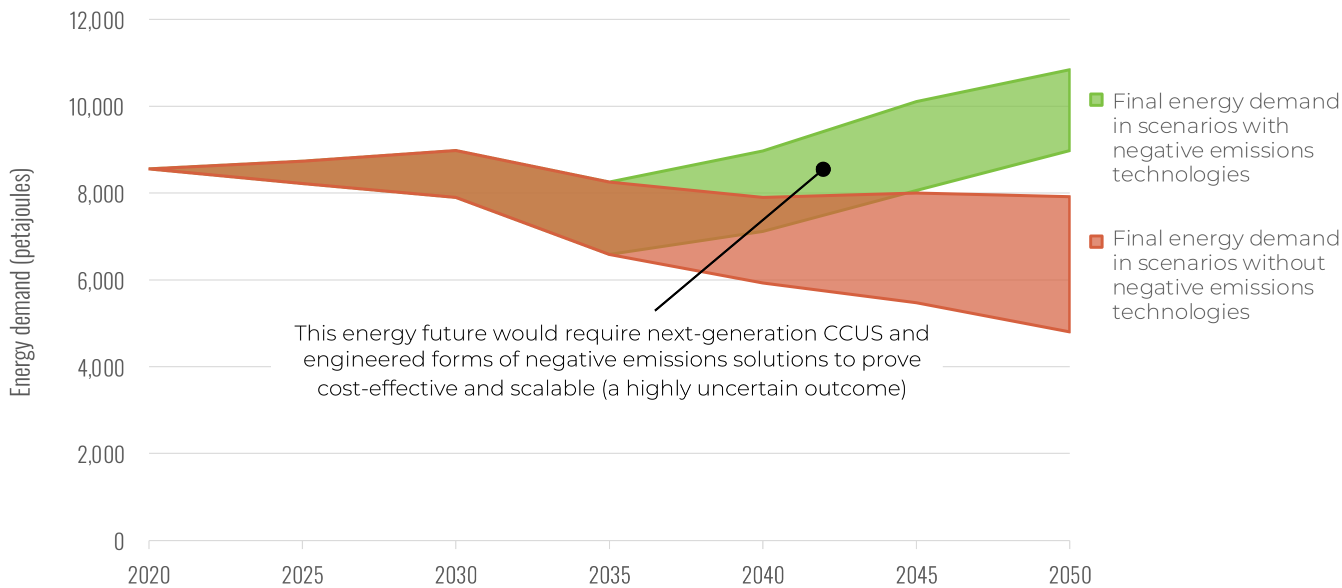
Engineered forms of negative emissions solutions, if they prove cost-effective and scalable, could also offer valuable economic development opportunities for Western Canada. This is owing to both the region's potential for relatively cheap clean electricity and the huge geological potential for carbon sequestration that underlies northeastern British Columbia and most of Alberta and Saskatchewan.[38] Development of a negative emissions industry would engage many of the skills and capacities already abundant in Western Canada's workforce and leverage existing infrastructure. Notably, in the scenarios we examined in which negative emissions technologies prove viable, the return on investment is high enough to justify repurposing significant parts of Western Canada's pipeline network to carry CO_2 destined for sequestration, instead of fossil fuels. There may even be the opportunity to use captured carbon as a feedstock for products and as an input for other sectors.[39]

37 Some of this fossil fuel use would go toward the operation of the engineered negative emission solutions themselves. (The energy demands of such solutions and systems is considered in our modelling.)

38 There is also potential for sequestration in British Columbia's offshore marine basalts.

39 CarbonCure, a Canadian cleantech company founded in Nova Scotia, has designed a technology that injects captured CO_2 permanently into concrete. CarbonCure is already working with approximately 300 concrete producers to inject captured CO_2 into their products (Milman, 2020). Fixing captured CO_2 in materials in this way could offer opportunities both in Western Canada and outside it, since it does not require local geology suited to CCUS.

Figure 17: Domestic final energy demand (for all energy types) under different net zero scenarios



But engineered forms of negative emissions solutions would also have their limits. Even at their highest levels of uptake, our analysis projects that they would only drive a minority of the total emissions reductions required between now and 2050. And that work would not be expected to start until at least the next decade.

The opportunities that engineered negative emissions could present would also require them to prove cost-effective and scalable. These outcomes remain far from certain today. Realizing their potential would also require a nearly unprecedented level of facility construction and infrastructure development. It would require the development of recognized and rigorous accounting protocols for engineered negative emissions solutions under the UNFCCC emissions accounting system. And, as with nature-based solutions, crediting and trading mechanisms would need to be developed to facilitate this expansion, using clear accounting, financing, and institutional mechanisms. There could also be challenges associated with gaining Indigenous support, as well as buy-in from the general public, which tends to view these solutions with skepticism. (We return to the barriers and conditions for widespread uptake of engineered negative emissions solutions in Section 5.)

Given this range of necessary conditions, the path for engineered negative emissions to play a significant role in Canada's net zero transition is far less certain than many of the other pathways we have examined in this report.

Fortunately, we find that Canada can reach net zero by 2050 without having to rely on engineered negative emissions. In the event that such solutions are not available, our modelling finds that other solutions would step in to play a larger role (as shown in Figure 1 in Section 3.1). We also find that across all the pathways to net zero we examined, emissions in the building and personal transportation sectors would be reduced at source without any reliance on negative emissions solutions.

In many ways, the largest risk created by negative emissions solutions may be that an excessive focus on the potential role they could play distracts governments and businesses from critical near-term action and investments. This has already led some to call for a separation of negative and gross emissions targets (McLaren et al., 2019). We explore this potential tension further in our discussion of safe bet versus wild card solutions in Section 5.

Projects like Carbon Engineering's direct air capture pilot in Squamish, B.C. (Skwxwú7mesh-ulh Temíx̱w) could come to play a significant role in Canada's net zero transition. But whether or not they will remains uncertain.

5 SAFE BETS AND WILD CARDS

This section reviews many of the solutions we discussed in Section 4, grouping them into two categories: "safe bet" solutions and "wild card" solutions. We discuss the roles that each of these types of solutions can play in achieving Canada's net zero goal by 2050 and its interim 2030 emissions target. We then outline the ways different types of wild card solutions could combine to deliver a net zero energy system (or systems) for Canada, and we consider the trade-offs and hurdles associated with each.

5.1 SHAPING CANADA'S NET ZERO PATHWAYS

As our analysis shows, the technologies and solutions that we expect to guide Canada down the path to net zero in energy, buildings, transportation, and industry are at varying states of readiness.

Some of the emissions-reducing solutions we explore in section 4 can be considered safe bets—relatively low-risk pathways to net zero. We define safe bet solutions as those that show up consistently across all of the scenarios we examine, that rely on commercially available technologies that are already being used in some places and applications, that face no major barriers to scaling, and that have a reasonable expectation of continued cost declines. Examples of safe bets include energy efficiency measures and equipment, non-emitting electricity, heat pumps, electric vehicles, and CCUS for concentrated gas streams.

Calling a solution a safe bet does not imply that its widespread uptake is inevitable or that its implementation would be straightforward. All of the safe bets we identify would face barriers and challenges. Stringent and coordinated policies would be needed to drive their adoption and the knowledge spillovers, learning by doing, and economies of scale necessary to drive down costs. Regulatory or policy barriers that are currently inhibiting their deployment would have to be addressed. And meanwhile, equity and access would remain important concerns that would often require dedicated policy. Still, our analysis finds that the safe bets represent a set of solutions that, with the right supports and incentives in place, can be expected to play a significant and growing role in Canada's transition to net zero—regardless of how that transition plays out.

Carbon capture, utilization and storage may come to play a significant role on the path to net zero, particularly if its wild card version (applied to unconcentrated gas streams) proves to be cost-effective and scalable.

Wild card solutions are those that may come to play a significant and important role on the path to net zero but whose ultimate prospects are still uncertain. We define wild card solutions as those that rely on technologies that are still only in early stages of development, that face potential barriers to scalability, or that only play a role in a subset of Canada's possible pathways to net zero. Examples of wild card solutions include hydrogen, CCUS for non-concentrated gas streams, biofuels made from second-generation feedstocks, and negative emissions solutions.

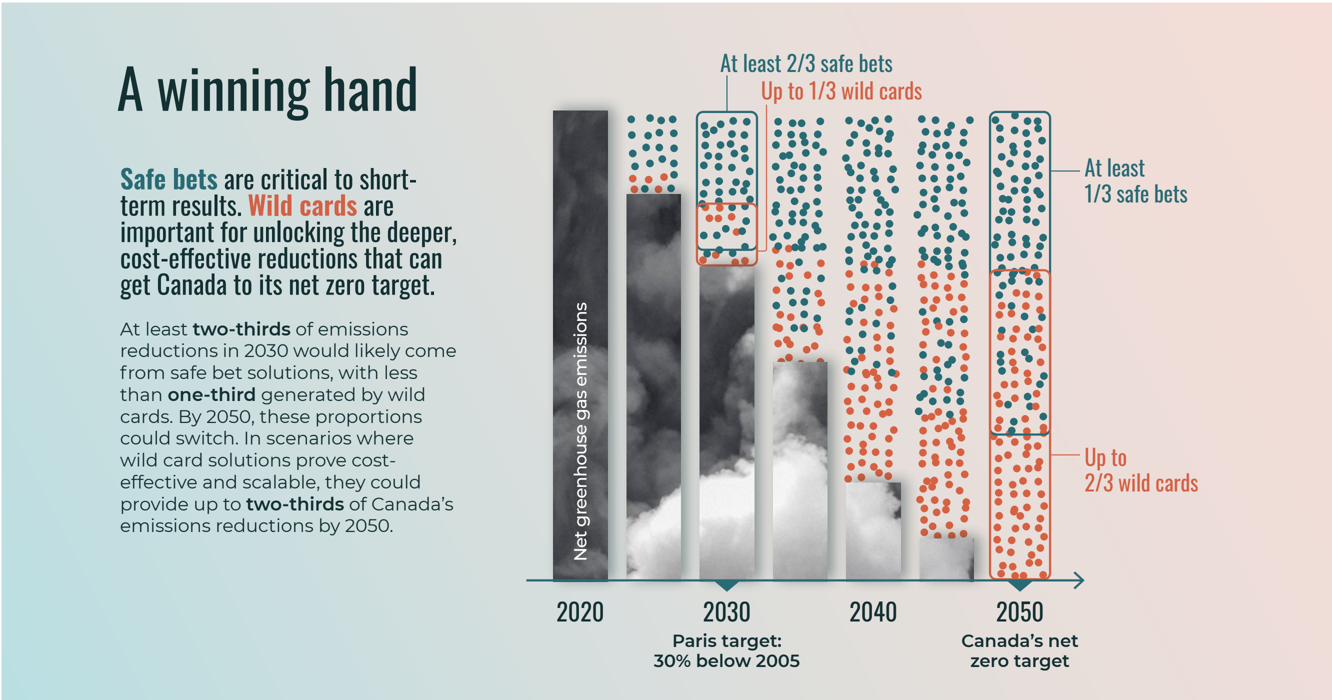
Unlocking the potential of wild cards to drive cost-effective emissions reductions would require particular conditions and outcomes to arise—ones that cannot currently be predicted with certainty. For instance, the costs of zero-emissions hydrogen production would need to come down significantly for it to out-compete potential substitutes for it. Renewable natural gas (RNG) produced from second-generation feedstocks would need to prove technically viable and scalable before it could play a large role. And negative emissions solutions that store carbon in land would need to overcome concerns about their land-use, its trade-offs and implications, and potential conflicts with Indigenous rights and worldviews.

Canada can rely mostly on safe bets to get to 2030

Safe bet solutions are critical on the path to net zero and even more so for reaching Canada's 2030 emissions target. In all of the scenarios we examine, our modelling finds that safe bet solutions would drive most of the GHG reductions required to meet Canada's 2030 emissions target. Looking further out, the size of their contribution tends to be more variable, as wild card solutions start to play more significant roles in some scenarios.

Figure 18 illustrates this shift, showing how safe bets contribute at least two-thirds of the reductions required to hit the 2030 target across all our scenarios, but only about one-third of the reductions required to hit the 2050 target. This is only their minimum contribution, however. In scenarios where numerous wild cards do not prove to be sufficiently cost-effective and scalable, safe bets take on much greater significance—driving as much as 89 per cent of reductions by 2030 and 66 per cent by 2050.

Figure 18: Contribution of safe bets to emissions reductions across pathways to net zero

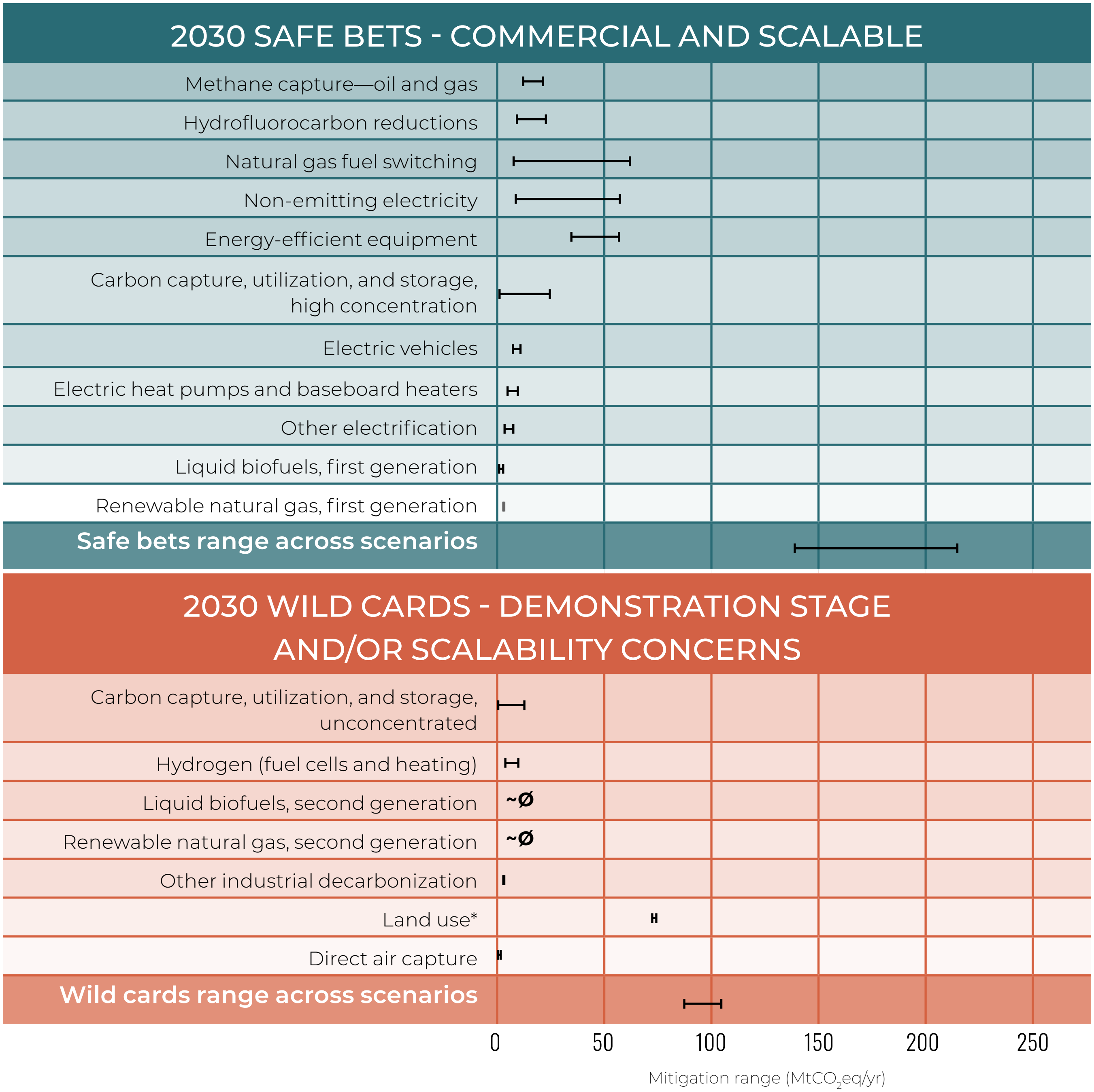


Safe bets consistently take on the most substantial share of the work in reaching Canada's 2030 target even when wild card solutions prove viable. Even under best-case scenarios, the time and high costs required to advance early-stage wild card solutions relative to safe bets mean that the latter can usually offer the more cost-effective path for near-term reductions. In this sense, **safe bet solutions provide Canada with "no-regrets" pathways to its 2030 target that are likely to make sense no matter how wild card solutions (or any other key factors) might play out.**

So which specific safe bet solutions play a significant role on the path to 2030? And how large and variable does that role tend to be? In Figure 19, we provide an overview of a number of key safe bet solutions and the range of emissions reductions that they provide by 2030 across the full range of scenarios that we consider. We also show the smaller potential role that a number of important wild card solutions might play by 2030. Negative emissions from nature-based solutions represent the most significant wild card from now till 2030. However, the significant contribution and narrow range that we attribute to these solutions in our modelling is mostly due to the limited capacity at present to credibly estimate their potential.

> "Safe bet solutions provide Canada with "no-regrets" pathways to its 2030 target that are likely to make sense no matter how wild card solutions (or any other key factors) might play out.

Figure 19: Projected contributions to 2030 emissions reductions by different solutions across pathways to net zero.



Our grouping of solutions into safe bets versus wild cards draws on our modelling analysis, our literature review and expert consultation, and our process for identifying potential pathways to net zero (see Box 2).

**Nature-based solutions are categorized as a wild card because of the difficulties associated with ensuring their additionality and permanence, as well as questions surrounding their scalability, due to competing land-use priorities as well as their potential conflict with Indigenous rights and worldviews. The narrow range seen for the GHG reduction potential of this kind of solution is more a function of the limited availability of credible estimates of its potential than it is this level of uptake being a stable and consistent finding across our scenarios. The range that we show could be an underestimate or an overestimate.*

The roles of non-emitting electricity and natural-gas fuel switching merit further discussion. Using natural gas to generate electricity rather than coal reduces emissions per unit of electricity by about two-thirds (federal and provincial regulations will phase out coal-fired electricity by 2030). Yet the remaining emissions from natural-gas-fired electricity mean that it only provides an interim solution on the path to net zero; eventually, it would have to be phased out in favour of non-emitting electricity (risking stranded assets) or equipped with CCUS. Given these long-term challenges, it may be more economical in some cases to "leapfrog" electricity generation technologies by moving directly to non-emitting types of generation that are commercially available today, such as hydroelectricity, wind, or solar PV. These generation technologies can be considered safe bets. Other non-emitting types of electricity generation that we classify as wild cards have less promise by 2030. Still, we find that there are enough available and potential technologies that non-emitting electricity is, as a whole, considered a safe bet solution. (For further detail, see Box 11.)

Non-emitting electricity generation technologies like wind and solar represent "safe bets"—commercially available technologies that Canada can push forward with confidence starting today.

BOX 11

Non-emitting electricity as a safe bet solution

One of the most important safe bet solutions identified in our analysis is non-emitting electricity generation. Some individual types of non-emitting electricity are considered wild cards because they are not yet commercially available or face potential barriers to significant scale-up. But there is such a variety of both existing and potential sources of non-emitting forms of electricity generation that, viewed as a whole, these power sources can be deemed a safe bet. If any one technology does not work out, there will be others to lean on.

Non-emitting forms of electricity generation can be broken down into two main types: intermittent and firm. Intermittent sources of generation such as solar PV and wind have output that varies with the weather. Firm sources of generation such as reservoir hydroelectricity, on the other hand, have output that can be readily controlled.

Many of the most prominent sources of non-emitting power are intermittent generation technologies, including onshore and offshore wind and utility-scale solar PV—these have dropped enormously in cost over the last decade (solar PV in particular). While each still faces challenges (especially when they form a significant share of total generation, as we discuss below), deployment experience has evolved and costs have declined to a point where they can now be considered safe bet technologies. In fact, they are already playing a significant and growing role in electricity production across Canada. Alberta-based Greengate Power Corp., for example, is expected to begin generating power at Canada's largest solar plant—a 400-MW facility—next year (Hall, 2019).

As the share of these intermittent sources of generation increases on a power grid, the challenge of integrating their variability mounts as well, though only when they reach shares of 60 per cent or more. There is a range of options for overcoming this challenge. Storage solutions can directly shift power from periods of excess supply to times of high demand (indeed, Canada's largest battery storage facility was recently installed by TransAlta in Alberta [Crider, 2020]). Demand responses can incentivize flexible consumers to shift their needs to coincide with shifting supply. And transmission can help with variability by exploiting geographic differences in supply availability. But even with these types of solutions, firm non-emitting sources of generation will likely be needed on most grids to ensure a reliable power supply.

There are numerous options available for non-emitting firm power. Some rely on technologies that are common today, such as hydroelectric and nuclear generation. Other firm technologies, such as geothermal power, are commercially available now but remain expensive. And some are only in the early stages of development or commercialization, such as coal-fired or natural gas-fired generation equipped with CCUS, small modular nuclear reactors; and stored blue or green hydrogen, run through either a turbine or fuel cell to produce electricity (Sepulveda et al., 2018; Jenkins et al., 2018; Dowling et al., 2020).

Each of these firm power sources faces challenges to its widespread deployment. Hydroelectricity and nuclear are proven technologies, but new projects often face local opposition and create risks for local ecosystems and biodiversity. Early-stage technologies like geothermal and small modular reactors still face significant technical and economic hurdles. And CCUS technologies would need to come down in cost substantially before they could see widespread uptake (IEA, 2019b).

In the scenarios we consider, our assumptions about the evolving costs of non-emitting firm power were varied to reflect the uncertainty surrounding them. When it comes to estimating the roles that specific non-emitting electricity generation technologies might play, our ability to accurately represent electricity sector futures was constrained by the gTech model's inability to simulate time-of-use pricing for electricity, which can have important implications for the economics of different generation sources. We therefore do not provide detailed projections of which generation sources would be likely to dominate. Instead, we focus on the higher-level role that non-emitting electricity could be expected to play.

The various challenges and uncertainties facing particular technologies that we discuss above should not be seen as a barrier to the uptake of non-emitting power in general. An approach to electricity generation policy that treats all non-emitting power equally on a portfolio basis for intermittent and firm sources (with the balance depending on needs across the two) can help balance the individual performance risk of any one technology, while also allowing the most cost-effective options to emerge through market forces. The mix of generation sources that a given region chooses to adopt, however, will depend on more than just their economics and local physical potential (for example, the amount of wind energy available for harvesting in a particular location). Those choices will also be shaped by the characteristics of the existing system, the governance systems in place, and local political and cultural preferences. Germany, for example, has chosen not to deploy CCUS or nuclear technologies to meet its electricity needs, which has led to large-scale purchases of solar PV under its Energiewende program.

Wild card solutions are important for driving the deeper emissions reductions required to hit Canada's 2050 target

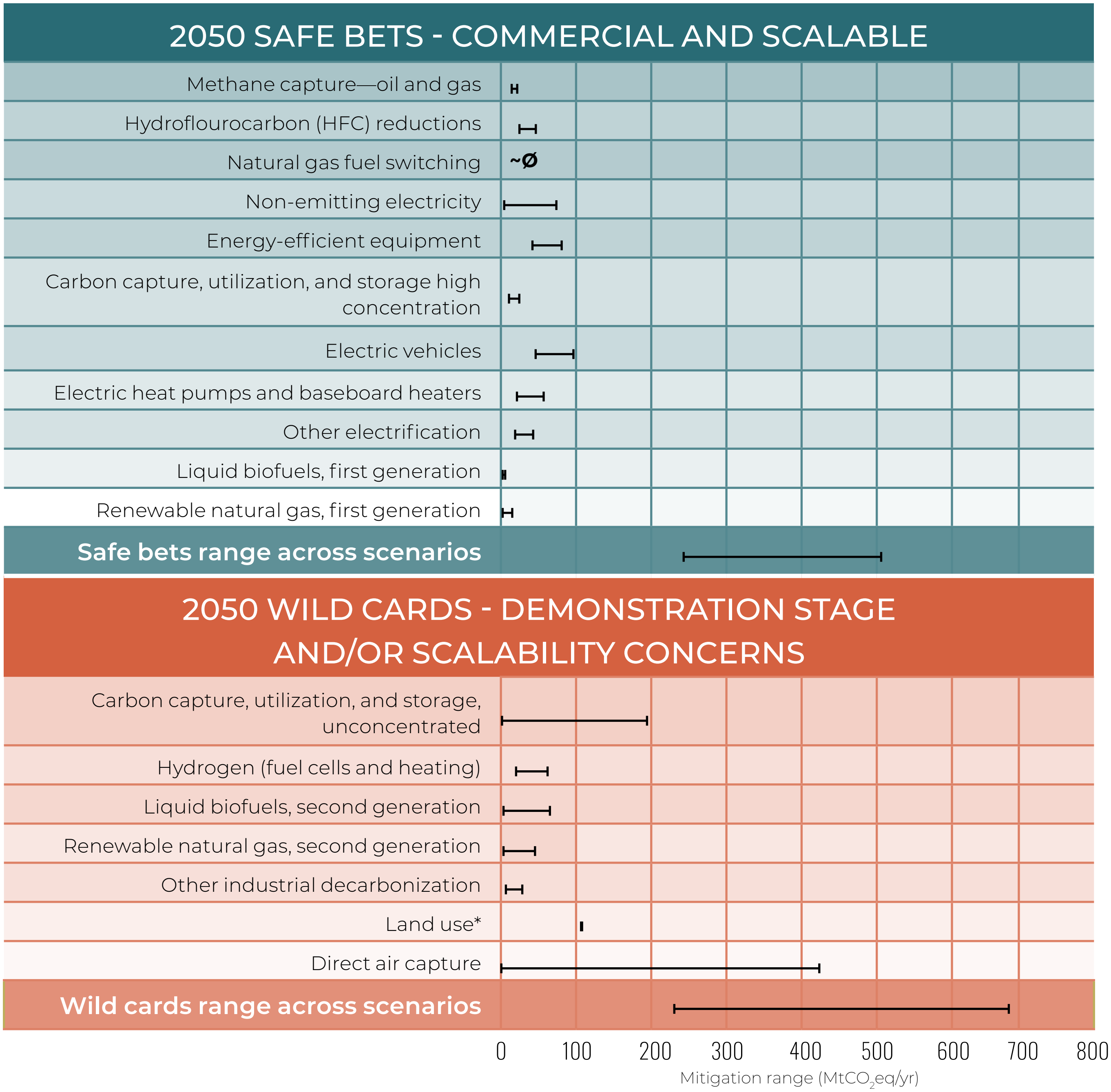
Wild card solutions could come to play a very important part in reaching Canada's net zero target, but there is considerable uncertainty regarding how they will fit into the overall picture. Our modelling finds that the uptake of wild card solutions by 2050 varies widely from one scenario to another, depending on different assumptions about which early-stage technologies become viable, what their relative costs are, and how scalable they prove to be. Figure 20 looks at the range of contributions that different solutions make to emissions reductions across our scenarios by 2050. Notably, our analysis suggests that many of the individual wild card solutions we identify could range from playing a very significant role in GHG reductions by 2050 to none at all.

One wild card solution that stands out is direct air capture, a type of engineered negative emissions solution. The range for this solution is massive in scale, potentially accounting for a volume of negative emissions equivalent to over half of Canada's current total inventory. In many ways, engineered negative emissions represent the ultimate wild card. They could potentially play an especially large role in Canada's net zero transition, but the uncertainties surrounding them mean they do not yet represent a reliable pathway to Canada's net zero target.

Harnessing the potential of any of the wild cards we identify will require coordinated and sustained effort on many fronts. Even those wild cards that show up consistently across our scenarios (for example, hydrogen fuel cells) would require considerable advancement before they could be expected to take on a significant role. And the wild cards that prove technically and economically viable would still have to overcome a number of significant barriers to their large-scale deployment (as we discuss in Section 5.2).

At the same time, technological development alone won't set the pace of Canada's net zero transition. In Box 12, we discuss the role that behavioural and cultural changes could play.

Figure 20: Projected contributions to 2050 emissions reductions by different solutions across pathways to net zero



Our grouping of solutions into safe bets versus wild cards draws on our modelling analysis, our literature review and expert consultation, and our process for identifying potential pathways to net zero (see Box 2).

**Nature-based solutions are categorized as a wild card because of the difficulties associated with ensuring their additionality and permanence, as well as questions surrounding their scalability, due to competing land-use priorities as well as their potential conflict with Indigenous rights and worldviews. The narrow range seen for the GHG reduction potential of this kind of solution is more a function of the limited availability of credible estimates of its potential than it is this level of uptake being a stable and consistent finding across our scenarios. The range that we show could be an underestimate or an overestimate.*

BOX 12

How behavioural and cultural change can reduce emissions

Changes in behaviour—including what Canadians eat, how they travel, how they consume energy, and what they purchase—will play an important role in reaching Canada's net zero goal. These types of changes may arise from voluntary actions by individuals, policy incentives, a broader shift in cultural norms, or some combination of these.

Adopting a more sustainable diet represents a significant opportunity for emissions reduction in Canada. For example, a significant decrease in overall meat and dairy consumption could reduce Canada's total GHG emissions by one to three per cent by 2030 (Frenette et al., 2017) However, diets that reduce the consumption of animal products are not the only path to sustainability and may also not be culturally relevant. For example, other studies identify reducing processed foods as key to improving sustainability (Fardet and Rock, 2020; Hyland et al., 2017). And while a number of policy tools exist to encourage consumers to adopt more sustainable diets—from taxation, product labelling, and waste reduction efforts—changing people's diets is far from easy (Hyland et al., 2017).

Shifts in travel behaviour—including walking, cycling, transit, carpooling, car-sharing, reduced car ownership, and more efficient driving—can also reduce emissions.

Research finds that driving more efficiently could reduce vehicle fuel use by up to 25 per cent (NRCan, 2020f). Reduced air travel could lead to particularly sizable emissions reductions, especially as part of a larger global trend. For example, shifting 140 million business trips from in-person meetings involving air travel to online meetings could result in a reduction of between two and 17 Gt of CO_2eq by 2050 globally—which is between 1.5 and 22 times Canada's current entire GHG inventory (Hawken, 2017).

But changing travel behaviour comes with challenges. For example, negative perceptions associated with public transit may inhibit transformational shifts away from car use and ownership (Thomas et al., 2014; St-Louis et al., 2014). Changes in travel behaviour can also have unintended negative consequences, such as increased overall car travel when non-car users join car-shares (Namazu et al., 2018) or use ride-hailing services (Coulombel et al., 2019; Axsen & Wolinetz, 2019). And air travel has long been viewed as essential for many business functions, though this may be changing as business travel practices evolve following the COVID-19 pandemic.

Changes to household energy and material use patterns, such as reducing heating demand in winter months and cooling demand in summer months, installing energy-efficient upgrades, and increasing recycling and composting can also contribute to Canada's net zero target. However, some initiatives to encourage behaviour change may have unintended consequences. Low-consumption energy users may increase their consumption if they realize their peers are less efficient (Wynes & Nicholas, 2018), and individuals may consume more if they know that products will be recycled rather than disposed of (Catlin & Wang, 2013). Meanwhile, there may be a lack of motivation in cases where energy-saving activities are falsely perceived as being inconsequential (NRCan, 2016).

Finally, emissions can be reduced through **changes to purchasing patterns**, such as consuming more locally produced goods, a shift to less materially intensive consumption and greater focus on services, or even voluntary reductions in overall consumption. Here again, though, there are challenges. Locally produced goods may not necessarily be less emissions-intensive depending on how they are produced and how their longer-distance alternatives are transported. And any effort to drive larger shifts in purchasing patterns must contend with a consumer culture accustomed to cheap and plentiful material goods and a tendency to prize certain material goods as status symbols.

For both safe bets and wild cards, delay drives up costs

Putting off emissions reductions only increases the costs of meeting an emissions target (NRTEE, 2011; Furman et al., 2015; Sanderson & O'Neill, 2020). This is true of both safe bets and wild card solutions. Delayed action on either of these fronts will increase the costs of an eventual transition to net zero. However, the mechanism is different for each category of solution.

Delaying the implementation and deployment of safe bet solutions will drive up the costs of Canada's transition to net zero. Failing to enact policies that are stringent enough to increase the near-term adoption of these solutions will cause households and businesses to purchase more emissions-intensive cars, furnaces, and other types of equipment as existing stock reaches the end of its useful life. Keeping Canada on track to net zero would then require either the early retirement of some of this new capital stock (which raises costs by stranding assets) or costlier emissions reductions in other parts of the economy.

For wild card solutions, delays to the development of solutions which either don't exist yet or are too expensive (or both) will increase costs. To unlock the potential of these solutions to drive cost-effective emissions reductions in the medium and long term, Canada will need to invest in their advancement immediately. As we discuss below, steps to accelerate this advancement could include research and development, demonstration and pilot projects, incentives, international cooperation and coordination, or even direct public investment.

But which wild card solutions should policy makers and industry work to advance? All of the wild cards have considerable potential, but which ones are complements, and which are substitutes? How would they work together, or not? What kinds of infrastructure would they require? To make the possibilities that wild cards could create more concrete, in the next section we discuss how different existing and potential solutions could fit together under three different types of net zero energy systems. We outline some of the opportunities and challenges associated with each, and we begin to pose questions about the feasibility and desirability of these different systems.

5.2 THREE POSSIBLE NET ZERO ENERGY SYSTEMS FOR CANADA

The myriad pathways and solutions that we discuss above provide a clear sense of the range of possibilities for Canada's net zero future. But what are the implications when we look for common traits and consistent patterns in terms of how Canadians will use and consume energy when the goal is reached?

We have found that between now and 2030, energy efficiency will be a central driver of emissions reductions. Fuel switching will ramp up in some places and for some applications, but Canada will still have an energy system based mainly on fossil fuels. Looking beyond 2030, however, Canada would transition to a net zero energy system, and our analysis has identified several distinct possibilities for that second phase.

Three possible net zero energy systems emerge from our aggregate analysis of the scenarios: a fossil fuels and negative emissions energy system; a biofuels system; and an electrification and hydrogen energy system.[40] Each of these energy systems leverages a different set of wild card and safe bet solutions, and each presents its own opportunities and challenges, as well as significant barriers to widespread deployment. (Of course, there is more to reaching net zero than reducing emissions from the energy sector. While energy decarbonization will be the largest source of reductions, other initiatives such as adopting new agricultural practices could further assist by reducing Canada's methane emissions, as we discuss in Box 13.)

We examine each of these three potential energy systems in detail below, highlighting some of the main opportunities and challenges associated with each one becoming the dominant pathway to net zero.

Though we focus on what it would mean for one of these systems to dominate, Canada's path to net zero could also ultimately employ a mix of these systems, with different ones operating in particular sectors or regions or employed for specific energy needs (Tsiropoulos et al., 2020; Davis et al., 2018; Bataille, 2020). Indeed, our modelling scenarios often combine elements of multiple energy systems. In particular, the electrification and hydrogen energy system experiences significant growth even when other energy systems also see significant uptake. In those scenarios where negative emissions technologies see widespread use, for example, our modelling projects that there would still be an expansion of 65 to 92 per cent in the use of electricity relative to today.

Alternately, one of these systems could come to dominate in time, owing both to its economic advantages and to policy choices aimed at realizing the economies of scale and integration potential that moving to a single system could offer. But the final result will also not be an entirely domestic decision. Canada's net zero energy system (or mix of systems) will ultimately be determined by factors both within the country's control (domestic policy choices and public support, for example) and well outside it (including investment decisions and political conditions around the world).

40 We focus primarily on the contribution these types of energy could make to final energy demand. As we note in Section 3.2, either primary energy sources such as natural gas or secondary ones such as electricity, hydrogen, and gasoline can be consumed as final energy. All of the energy systems we discuss in this section would use net zero final energy—that is, energy whose consumption and production generated net zero emissions in Canada.

BOX 13

Mitigation of agricultural methane

Methane is a potent air pollutant and the second most common greenhouse gas in Canada, accounting for approximately 15 per cent of total emissions (Government of Canada, 2019). The oil and gas sector is Canada's largest source of methane, but the agricultural sector is also a significant contributor, and its efforts to reduce methane emissions will be crucial to reaching Canada's net zero goal.

Canada's agricultural methane emissions come primarily from livestock production, with additional emissions from agricultural soils and waterlogged lands. There are many options for reducing these emissions, including land management (such as soil management and revegetation), livestock strategies (such as feeding and dietary changes, breeding management, grazing strategies, and manure management), and shifting consumer demand to methane-free food sources.

One study found that methane inhibitors and vaccines have the greatest potential to reduce emissions from the agricultural sector, though these solutions are not yet commercially available (Reisinger et al., 2018). Another recent study looking at dairy farms determined that combined changes in livestock diet and manure management would be necessary to reduce their emissions (Jayasundara et al., 2016). However, there are significant barriers to widespread uptake of all of these options, including technological development, concerns over food security, costs to farmers, and perceived challenges to industry competitiveness.

To be consistent with net zero, an energy system reliant on fossil fuels would require extensive use of negative emissions solutions.

A fossil fuels and negative emissions energy system

In one of the three possible energy systems in Canada's net zero future, fossil fuels would remain the dominant source of energy, but their emissions would be offset to net zero through extensive use of negative emissions solutions. Our analysis indicates that nature-based forms of negative emissions could support some continued fossil fuel use in industries where alternatives are very expensive. But widespread uptake of this energy system would ultimately require significant reliance on both nature-based and engineered forms of negative emissions, which would have to prove cost-effective and scalable in order for it to be viable. This would likely include a large role for direct air capture paired with CCUS, which would mainly sequester captured emissions underground (something that Canada possesses the geology for but many other countries do not), though emissions could also be fixed into materials. In this system, negative emissions technologies would themselves often be powered by fossil fuels whose emissions were also offset.

In this energy system, offsetting fossil fuel use with negative emissions would increase the costs of fossil fuel consumption such that other emissions-reducing solutions would still be more cost-effective in some areas. For example, electric vehicles would still likely become the vehicle of choice for light-duty transportation, and buildings would mostly use some combination of energy efficiency, electric power and clean gases to get to net zero. But fossil fuels would continue to dominate in many other sectors, including heavy industry and medium- and heavy-duty transportation.

This energy system has the following implications for Canada's economy and population:

- A fossil fuels and negative emissions energy system would require less structural change in the economy by mid-century compared to other net zero energy systems. It would enable continued (or even growing) use of fossil fuels throughout the economy. Emissions-intensive sectors whose mitigation costs would be high could continue to use their existing production processes, offsetting their emissions with negative emissions that would occur elsewhere instead of reducing or capturing them at source. This system would also require less capital stock turnover, extending the life of productive assets. But the level of fossil fuel production in Canada under this energy system would still be determined primarily by global demand for oil and the stringency of global climate policies.
- This type of energy system could also present economic opportunities for Western Canada, which has both the know-how and the geology for engineered negative emissions solutions. One study found that Alberta has the capacity to sequester more than 1,100 Mt of CO^2 over a period of 30 to 40 years (Alberta Carbon Capture and Storage Development Council, 2009). It might even be possible to export negative emissions to other countries, if a mechanism for doing so emerges under Article 6 of the Paris Agreement.
- While air quality and health outcomes associated with energy production and consumption would improve under this energy system, the changes would be mostly due to ongoing improvements in pollution control technologies. Our modelling analysis suggests that under this kind of energy system, the annual air pollution health burden associated with energy production and consumption would be 75 per cent lower by 2050 than it is today. But these gains would be smaller than those under other systems, due to the continued (or growing) use of fossil fuels (Soltanzadeh & Hakami, 2020).
- This energy system would likely create less labour disruption relative to other systems that result in a sharper transition away from fossil fuels. But fossil fuel production levels would remain dependent on global market forces, and increasing automation and other labour sector trends would still pose challenges, meaning significant job losses or workforce shifts would not necessarily be avoided.
- This system may pose challenges and concerns for some Indigenous communities. Widespread use of negative emissions would likely conflict with Indigenous worldviews. Both the conception of nature as a commodity and the continuation of fossil fuel extraction perpetuate a relationship with the environment that can be at odds with Indigenous worldviews, in particular the principles of reciprocity, balance, and interconnectedness. Nature-based negative emissions solutions often require the use of large swaths of land, which could have implications for Indigenous Peoples' rights, especially if done without their ongoing leadership and/or participation. In addition, local environmental impacts from ongoing fossil fuel extraction could exacerbate existing threats to the health, well-being, and sovereignty of some Indigenous communities.
- The large land use requirements of nature-based solutions could lead to competition with agricultural land, potentially driving

up food prices and threatening food security, especially for already food-insecure populations such as low-income households and remote communities (Fuhrman et al., 2020).

- This energy system would risk perpetuating a number of non-climate environmental problems created by Canada's current system, particularly if the total level of domestic fossil fuel consumption were to increase. These include air pollution, soil degradation, water contamination, water shortages, biodiversity loss, and ecosystem damage. The continued use of current production processes in heavy industries that would be enabled by negative emissions solutions would also pose risks of further ecosystem damage and threatened water security. The extensive use of nature-based systems could also incentivize land use change and monoculture practices that are harmful to local ecosystems.

The fossil fuels and negative emissions energy system faces a number of significant challenges to its wide-scale deployment.

First, the technologies required for engineered negative emissions are only at demonstration stage. They would still need to prove cost-effective and scalable. Even then, they would require the construction of infrastructure for emissions capture and sequestration at unprecedented scale and speed. Global investment and deployment of these solutions is a significant but highly uncertain factor in overcoming challenges to the successful commercialization and scaling of these technologies. Global economies of scale and knowledge spillovers could help to drive costs down. However, the level of global commitment to engineered forms of negative emissions that Canada can expect remains highly uncertain.

There are also major non-technical barriers to this system's development. Global GHG accounting systems would need to recognize engineered negative emissions, and a trading mechanism would need to be developed that could establish prices, allocate credits, and match sellers of negative emissions with buyers. Moreover, proponents of negative emissions solutions, both engineered and nature-based, would need to work closely with Indigenous peoples to understand and address potential implications for Indigenous rights and worldviews, since the land footprint of these solutions—nature-based ones in particular—would almost inevitably require them to be deployed widely across Indigenous peoples' traditional territories. Public opposition would also likely be a factor, since the public tends to view negative emissions as high-risk and inferior to reducing emissions at source. A recent study in the United States and the United Kingdom found that people are generally skeptical that negative emissions technologies will be ready in time to address the climate crisis and that these solutions did not align with public desires for a transition to a more sustainable future (Cox et al., 2020).

Finally, this energy system raises difficult questions about whether the kind of negative emissions capacity that it would rely on should be reserved for the significant net negative emissions that are likely to be necessary later this century. Using negative emissions to enable continued fossil fuel combustion in the interim may only delay rather than avoid a transition to one of the other possible systems.

A biofuels system

A second possible net zero energy system our analysis identified as a possibility for Canada is a biofuels system. This energy system would require extensive fuel switching to renewable fuels in the buildings, transportation, electricity, and industrial sectors. It would rely primarily on "second-generation" types of renewable gaseous and liquid fuels, such as RNG made from wood wastes and liquid biofuels made from switchgrass. It would also require huge amounts of land to be devoted to the production of feedstocks. Canada's expansive land mass and resource abundance make it one of the few nations in the world for which this pathway might be viable at scale.

This energy system would have the advantage of being able to leverage much of the fossil fuel infrastructure already in place, including refineries, pipelines, fuel storage systems, and distribution networks. It would also have the potential to generate negative emissions by capturing the combustion emissions from biofuels. This would enable some amount of ongoing emissions in sectors of the economy where direct emissions reductions are extremely costly.

This energy system has the following implications for Canada's economy and population:

- In terms of changes to **economic structure,** widespread domestic use of biofuels would drive significant growth in the sectors that produce both the fuels and the feedstocks those fuels require. This energy system would create new local economic and employment opportunities in the production and refining of biofuels, especially in provinces with large biomass capacity such as British Columbia, Alberta, Ontario, Quebec, and New Brunswick. It could also create new opportunities for regions with large agricultural and refining sectors. Biofuel feedstock prices could sometimes be highly variable, however, risking disruptive boom/bust cycles for these regions, with associated fluctuations in employment, mental health, and well-being.
- The **export potential for biofuel production technologies and services would likely be limited**, because this energy system would only be viable at large scale in other countries with large land masses and low population densities (Russia, Australia, and Brazil, for example). And the export potential for Canadian biofuel feedstocks to those countries that do not have plentiful domestic supplies would be even more limited, since the majority of Canadian feedstocks would be needed to produce the biofuels consumed domestically.
- A biofuels system would provide **greater health benefits compared to a fossil fuels and negative emissions system but fewer benefits than an electrification system** (discussed below). On the one hand, combustion of biofuels in place of fossil fuels does little to improve air quality and may even increase the emissions of harmful pollutants (Delucchi, 2006; Hill et al., 2009; Health Canada, 2012). A biofuels system would, however, likely come with a decrease in overall energy use, which would create more air quality and health benefits than a fossil fuel and negative emissions energy system. Our modelling analysis suggests that under this kind of energy system, annual economic costs due to mortality associated with air pollution from energy production and consumption would be 88 per cent lower by 2050 than they are today (compared to only 75 per cent under a fossil fuel and negative emissions energy system) (Soltanzadeh & Hakami, 2020).

- The substantial land requirements of this system would create **social equity and justice challenges**. Turning over such a massive amount of land to fuel production would likely require some existing cropland to switch to producing biomass feedstocks (unless the abandoned marginal farmlands common in eastern Canada could deliver the required supply), with implications for domestic food production and agricultural exports. This land conversion could also reduce food security and sovereignty if it led to rising food prices or declining availability. Although these changes would have implications for all Canadians, they would pose the greatest challenges for Canada's most food-insecure populations, such as low-income households and remote communities.
- These changes in land use would also have **important implications for Indigenous rights,** since this energy system's vast land footprint would inevitably require use of land found on Indigenous Peoples' traditional territories. This could present local economic opportunities for Indigenous communities but may also be inconsistent with Indigenous worldviews and traditional activities.
- A biofuels system's land conversion requirements would also have **significant environmental impacts**, particularly if feedstocks were produced using monocropping, which would damage ecosystems and hinder biodiversity. The water used for feedstock production could also lead to increased opportunity costs or even scarcity, depending on the type of feedstock crop and the availability of water nearby. The increased use of fertilizer for biofuel crops could also lead to increased runoff into water resources (Fuhrman et al., 2020). This energy system could also be vulnerable to climate change, which will increase the risk of droughts, floods, and severe weather that could destroy feedstock crops and reduce energy security.

A biofuels system would encounter significant barriers on its way to becoming a dominant system in Canada.

First and foremost, the second-generation biofuel technologies essential to its success—including energy from cellulosic biomass sources such as woody residue and switchgrass—are not technically and commercially viable today and would need to advance substantially. Even then, the requisite cost declines due to economies of scale and knowledge spillovers could prove more elusive than for other types of energy systems, since most of the world lacks sufficient biomass to pursue these solutions. Canada might need to drive the required innovations unilaterally instead of benefitting from innovations in other parts of the world (as it would with the other two energy systems, electrification and hydrogen in particular).[41]

The biofuels system would also require significant investment in the infrastructure required to produce these fuels, with entirely new capital stock needed in some cases. There are also potential feedstock constraints, owing to competing land uses that could affect the amount of land available for feedstock production (Johansson et al., 2012). This kind of land-use conversion would also oftentimes have implications for Indigenous rights and may be at odds with Indigenous perspectives on how to mitigate climate change.

41 Adoption of biofuels in other countries might even *increase* the costs of this system, particularly if demand in the United States for regionally available feedstocks were to drive up their costs, a phenomenon that we observe in scenarios where other countries (including the United States) keep pace with Canada in their own transitions to net zero.

An electrification and hydrogen energy system

An electrification and hydrogen energy system, the third potential type of net zero energy system identified in our analysis, would make emissions-free electricity the dominant form of energy, with hydrogen employed for specific energy uses such as freight transportation and certain types of industrial production that are difficult to electrify. Energy use for personal transportation, heating and cooling, and all other industrial production, meanwhile, would largely become electrified.

Electricity in this energy system would be produced primarily from renewable sources such as wind, solar, and hydro. The mix could also include fossil fuels with CCUS[42], nuclear energy (including small modular reactors), and emerging renewable technologies such as geothermal energy (see Box 11). The specific range of technologies employed would depend on the evolution of different technologies and would likely vary from region to region within Canada, depending on local resources and policy choices.

In this system, hydrogen would provide energy for the remaining energy uses—either "green" hydrogen (produced via electrolysis, using renewable electricity) or "blue" hydrogen (produced from natural gas with the emissions captured using CCUS technologies[43]). Hydrogen would also act as a form of energy storage, with excess electricity from intermittent sources such as wind and solar used to produce hydrogen. This hydrogen could be combusted immediately or it could be used to generate electricity later, when production from intermittent sources are reduced.

This energy system has the following implications for Canada's economy and population:

- This energy system leads to more substantial structural change in the economy compared to the other two options, since it represents the greatest departure from the status quo. It relies neither on fossil fuels nor the bulk of the infrastructure currently used in the production, transportation, and distribution of fossil fuels.
- Though disruptive, these structural changes would create significant opportunities for economic diversification. Potential economic benefits would be particularly strong for Western Canada, which has both the renewable energy potential for green hydrogen production and the natural gas resources and geology for blue hydrogen. Hydroelectricity-rich provinces like Quebec and Manitoba, meanwhile, could see opportunities in green hydrogen due to their excess electricity generation capacity.
- This energy system could also create international opportunities for Canada in the export of technology and know-how in the renewable energy, end-use electrification, and grid management sectors. There is potential as well for the direct export of clean electricity to the United States, which could leverage existing North-South grid interties. And this energy system could present Canada with hydrogen export opportunities to countries that are likely to be significant importers, including the United States, Japan, South Korea, and Germany (Layzell et al., 2020).

42 CCUS may leave up to 10 per cent of emissions uncaptured in some cases, so these would need to be offset with negative emissions for this type of electricity generation to be consistent with net zero.

43 CCUS may leave up to 10 per cent of emissions uncaptured in some cases, so any remaining emissions would need to be offset with negative emissions for blue hydrogen production to be consistent with net zero.

- This energy system offers the largest potential air quality benefits of the three systems. Because it relies on neither fossil fuels nor biofuels, this system would slash air pollution from energy production and use in Canada to near zero.[44] And because hydrogen combustion produces only water as a byproduct, there would be virtually no air pollutant emissions from that part of the system.[45] Air pollution would remain a challenge, however, because air pollution from climate change impacts such as more frequent and severe wildfires and rising temperatures (which can lead to higher ground-level ozone concentrations) will increase regardless of which energy system Canada adopts.

- An electrification and hydrogen energy system would affect lower-income Canadians in complex ways. It would reduce overall energy costs for Canadian households, but realizing these savings would require larger upfront investments that, without government support or equitable financing mechanisms, could be difficult for lower-income households to manage.[46] This system could also create challenges for households in rural and remote communities that tend to be more reliant on fossil fuels. Even in a future with widespread electrification, sparsely populated rural areas would likely lag dense urban centres in terms of access to some kinds of electricity-based solutions and alternatives (Krechowicz, 2011).

- The non-climate environmental impacts of this energy system would depend on the mix of electricity generation sources and hydrogen production methods employed. Solar and wind, for example, tend to have limited local environmental impacts, while hydroelectric dams can have substantial effects on local ecosystems and biodiversity. The environmental impacts of hydrogen will similarly depend on which production processes are used—some will require greater volumes of water as an input, for example, affecting local water availability in different ways depending on regional conditions. The production of blue hydrogen, which uses natural gas as a feedstock, would have local environmental impacts. Where deployment of this electricity generation and hydrogen production infrastructure has a significant land use footprint (or requires long-distance transmission infrastructure), it would also come with implications for Indigenous rights.

- Resilience to climate change will also vary across specific electricity generation, transmission, and distribution systems. Centralized electricity transmission and distribution networks are often more vulnerable than decentralized ones to climate impacts such as high temperatures, severe winds, wildfires, ice storms, and flooding, creating a greater risk of supply disruptions. Damages from climate impacts to wood utility poles and substation transformers could be especially costly if adaptation measures are not implemented. And

44 Where electricity was generated using fossil fuels equipped with CCUS, these technologies would also capture much of the air pollutant emissions associated with combusting fossil fuels.

45 Constraints in our ability to represent the full potential of this energy system in our modelling also constrain our ability to quantify its air pollution benefits, as we do for the two other energy systems. But improved health outcomes under this system would likely be significantly larger than under the other two possible net zero energy systems, due to the greater reductions in air pollution.

46 While all three of the net zero energy systems would require significant capital investment, an electrification and hydrogen energy system asks households to shoulder a larger share of the related expenses, due to the need to switch to electrically powered technologies. Ensuring that lower-income households can participate and benefit equally in the shift to this system would likely require supportive policy, innovative financing solutions, or both.

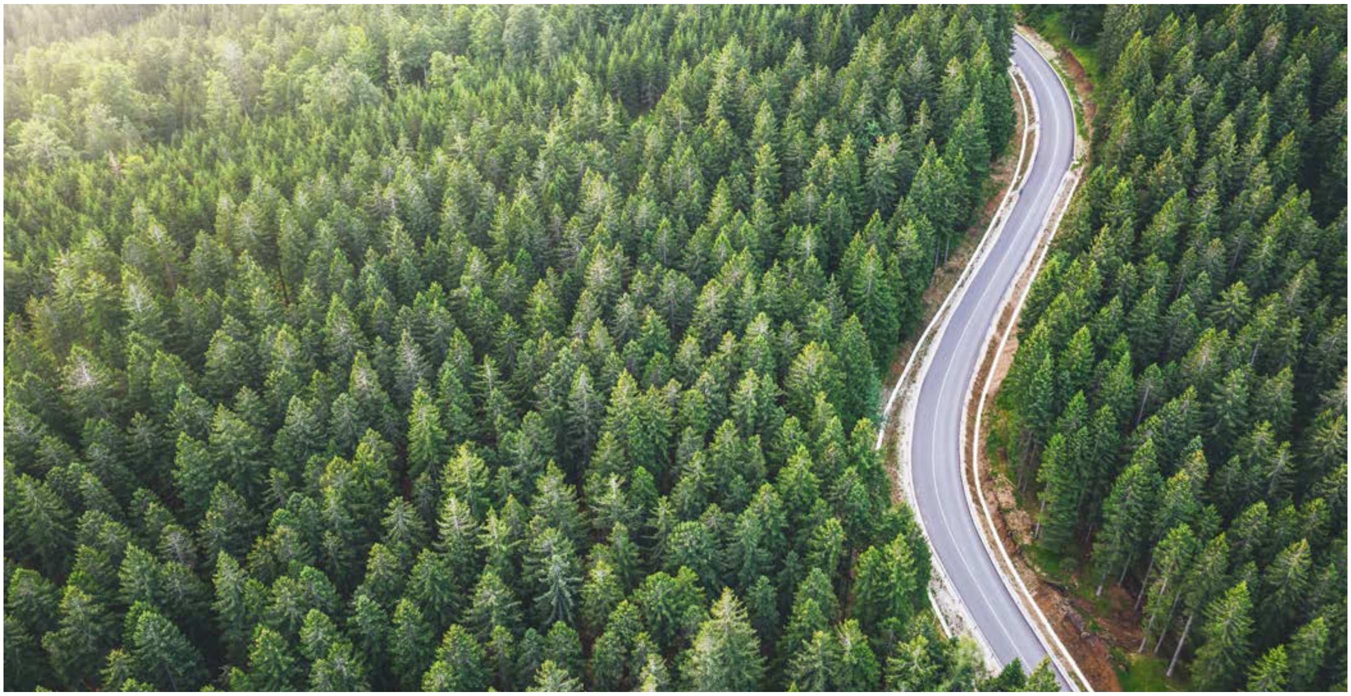
particular types of generation may be more exposed to certain climate impacts—hydroelectric power, for example, could be affected by changes in rainfall patterns and drought (Allen-Dumas et al., 2019).

The deployment of the electricity and hydrogen energy system faces three main challenges.

First, implementing this system would require significant investment in new capital stock, including a massive scale-up of generation capacity and transmission infrastructure and the replacement of end-use technologies built for fossil fuels with electric-powered gear. A network for hydrogen production, transportation, and storage would also need to be built, including pipelines and fuelling stations for the freight sector. And equipment such as boilers would need be retrofitted or replaced.

The potential costs also present problems. Hydrogen production, distribution, and end-use technologies would need to decline significantly in cost to enable widespread deployment of this energy system. And although renewable electricity and many electric-powered technologies are already cost-effective, consumer electricity prices would need to be kept low to drive rapid, widespread deployment of electrified end-use technologies. To facilitate this, the costs of "firm" non-emitting power would need to come down significantly (see Box 11).

Third, this energy system would require very complicated logistics. Widespread electrification would involve a large number of new generation and transmission projects, each with unique design and approval processes. Grids, grid operators, and utilities would have to learn to manage a much more complex supply and demand relationship than exists for electricity today. In response, utility mandates and business models might need to be revised in order to support and incentivize this energy system. Better integration of regional electricity grids, markets, and regulatory systems may also be needed, which would come with significant challenges and complexities and possibly require the construction of East–West regional grid interties.



5.3 PRIMARY DRIVERS OF CANADA'S NET ZERO FUTURE

Because Canada's path to net zero will be affected both by some factors within the country's control and others that are not, Canada will not be able to choose its future energy system entirely on its own. But Canada also cannot allow those external forces to make the choice entirely. The trade-offs between these different energy systems matter for Canadians, and the differences in the kind of shift to net zero that each would create will have significant implications for livelihoods, health, society, and the environment. Households, businesses, governments, and Indigenous Peoples in Canada should be deliberate about these choices. Doing so will require making decisions under conditions of uncertainty and carefully managing risk as trends, international developments, and Canadian priorities shift.

We have summarized some of the main conditions required for the emergence of each of the three energy systems in Table 1, along with an overview of some of the overarching questions regarding the relative desirability of these systems.

Canada will need to consider a range of factors as it makes these choices. These include: resource endowments, whether in terms of natural resources, built capital, or human capital; Canada's industrial strategy and potential areas of comparative advantage in a decarbonizing world; impacts and opportunities for households of all incomes and in all regions; impacts on Indigenous Peoples; and the perspectives of citizens, companies, and rightsholder and stakeholder groups. All three of the systems we discuss involve trade-offs. All three also face significant barriers to widespread deployment. Whichever option (or options) Canada pursues, the transition will be complex and challenging. And it will require significant investment in the development of wild card solutions. But it will also present opportunities that Canada can capitalize on through smart and strategic decision-making.

Table 1: Key conditions and questions related to the wide-scale deployment of three types of possible net zero energy systems in Canada

	A fossil fuels + negative emissions energy system	A biofuels energy system	An electrification + hydrogen energy system
Conditions that Canada can affect	Domestic infrastructure development (e.g., CO_2 pipelines, CCUS facilities)	Land use priorities and the potential scaling of feedstock production for second-generation forms of biofuels Infrastructure development (e.g., biofuel production capacity)	The build-out of Canada's electricity generation and transmission capacity Infrastructure development (grids, hydrogen pipelines and refuelling stations, etc.) Reform of energy (including electricity) markets and pricing
Conditions outside Canada's control	The degree of international deployment of engineered forms of negative emissions solutions International mechanisms for trading negative emissions	The ultimate technical viability of second-generation forms of biofuels	International innovation in and deployment of non-emitting forms of electricity generation, grid technologies, and electric energy end-use technologies International demand for low- or zero-emissions hydrogen
Big questions	What are the implications for the necessary transition to net negative emissions in the latter half of this century? How should the business-as-usual aspects of this energy system, including continued health impacts from fossil fuels, affect choices?	What influence should the fact that other countries are unlikely to follow this path have for Canadian decisions? What implications does the significant land-use footprint of this system have, including for Indigenous rights?	Do the potential export opportunities associated with this energy system matter for Canada's decisions? What could affect Canada's ability to compete globally in these markets? What implications does the logistical complexity of realizing this type of energy system have?
	Will Canadian climate policy (at all orders of government) guide the development of a net zero energy system such that one comes to dominate, or will it embrace a diversity of systems across regions and sectors? Will there be an effort to ensure the compatibility of Canadian energy systems with one another and to realize the potential that interlinkages (either within Canada or with the United States) could offer? How will Canada reconcile its decentralized governance (especially as it relates to energy) with the need to develop a coherent overall approach to realizing a net zero energy system (or systems)?		

6 MAIN FINDINGS

In this report, we have explored potential pathways to net zero for Canada and the roles that various technologies and solutions may play in reaching that goal. We have examined the implications of alternative pathways and energy systems for Canadians, as well as the primary hurdles that must be overcome down each pathway. Here, we distill this analysis into eight main findings.

A net zero Canada is possible but requires strong policy

Our analysis found not just *one* pathway but *multiple* potential pathways to net zero. All of these pathways also meet Canada's 2030 target on the path to net zero. They have been mapped using internally consistent logic and assumptions, with consideration of both domestic choices and international factors beyond Canada's control. While some of these factors could result in some pathways proving non-viable, enough potential routes to net zero exist overall that we can conclude that the net zero goal is achievable.

But just because Canada can reach net zero certainly does not guarantee that it will. Doing so will require strong policies. The federal government's new climate plan puts Canada on track to its 2030 target, and other orders of government can strengthen their own climate policies to drive even deeper reductions. Implementation of the federal plan and increased ambition from other orders of government will be critical to creating the incentives for the widespread uptake of safe bets on the path to Canada's 2030 and 2050 targets.

Achieving these ambitious goals will also likely require some "wild card" solutions. Their viability will depend in part on initiatives abroad creating innovations at global scale—and the resulting shifts in markets and technology. This international context, however, is definitely not a justification for delay. For Canada to not only achieve its own goals but also prosper in changing international markets, policies are needed now to develop *both* safe bet and wild card solutions in ways that keep pace with international shifts outside Canada's control.

Big transitions are inevitable—especially due to global trends

Canada's transition to net zero will create significant changes in the structure of the economy.

The pathways we examined involve dramatic new approaches to producing and consuming energy, heating buildings, moving people and goods, and producing the goods and services that drive Canada's economy. These changes will come with costs for many existing industries, even as they present opportunities to emerging innovators. And the distributional implications of the net zero transition—the way it will spread costs and benefits differently from region to region, sector to sector, and household to household—will be significant.

Many of the challenges created by this transition, however, will occur independent of Canadian policy choices and Canada's net zero push. In particular, changing market dynamics or international climate policy (or both) could dramatically reduce global demand for oil. These factors, largely outside of Canada's control, could cause significant changes in the economic structure of the country's oil-producing regions.

Structural changes to Canada's economy on this scale will pose challenges, but all the pathways to net zero that we examined also create new opportunities across Canada, including in oil-producing regions. Seizing these opportunities will be vital to smoothing the transition for workers and communities in regions at risk of disruption. Planning for these transitions must begin now to encourage the economic diversification and support that those most affected will require.

Canada has competitive advantages in pursuit of net zero

The Canadian economy is uniquely positioned to capitalize on opportunities emerging from the pursuit of emissions reductions at home and around the world. One significant opportunity is Canada's potential to become a leading supplier of the minerals and metals that will be needed to produce many of the clean technologies that countries pursuing lower emissions will place in high demand (such as electric vehicle batteries). Canada's electricity sector, which is already low in emissions, presents significant opportunities today—for example, in the export of low-emissions aluminum—and will present others in the future, such as in the production and export of green hydrogen from hydroelectric-rich provinces like Manitoba and Quebec. In addition, provinces with large biomass feedstock capacities—including British Columbia, Alberta, Ontario, Quebec, and New Brunswick—could see new local economic opportunities in the production and refining of biofuels.

A net zero transition also presents oil and gas producing regions with opportunities to grow and diversify their economies. Emerging industrial sectors such as hydrogen, biofuels, engineered negative emissions solutions, and CCUS would leverage existing infrastructure, resources, and know-how in these regions. And oil and gas companies themselves will be well positioned to pivot and become key players in these emerging sectors.

Canada also enjoys unique advantages in all three of the potential net zero energy systems we examined. The country's resources, infrastructure, and know-how create more options for success in these energy systems than are available in many other countries. And regardless of which pathway Canada's own energy system transition follows, Canada could find export opportunities around the world in all three systems, as other countries undergo their own energy transitions.

Scaling up safe bets is crucial and there is no reason to delay

Our analysis has found numerous emission-reducing technologies and solutions that are already commercially available and face no major constraints to scaling. In all the scenarios we considered, at least 64 per cent of emissions reductions by 2030 would rely on these safe bet solutions, which play consistent roles in every scenario, especially in the short to medium term. Among the most prominent safe bet solutions are improving energy efficiency, shifting to non-emitting electricity, and adopting heat pumps and electric vehicles.

We also found that the uncertainty and risk associated with wild card solutions and international climate policy action neither undermine the case for safe bets nor present barriers to reaching Canada's 2030 target. There are advantages to acting quickly and decisively, since delay will only raise the costs of the net zero transition and increase the risk of stranded assets.

Decision makers can move ahead confidently with safe bets in the near term. The federal government's new climate plan, announced late last year and featuring a carbon price rising to $170 per tonne by 2030, is consistent with deploying safe bets. In response to these kinds of policy incentives, companies and households can move forward with safe bet solutions over the near term.

Wild cards have an important role to play in Canada's transition to net zero

Wild cards should be understood as a complement to—not a substitute for—safe bets. Safe bets are crucial to reaching net zero, which is why advancing their deployment is such an essential first step. The real potential for wild cards, meanwhile, lies in expanding the range of possibilities for deeper and more cost-effective emissions reductions (as well as export opportunities) over the longer term. While many wild card technologies come with drawbacks and all of them must still overcome significant barriers to widespread use, they nevertheless have the potential to fundamentally change Canada's path to net zero for the better.

Action is required immediately to ensure wild cards will be ready when Canada needs them. Failing to act now will decrease the range of options available and could lead to costly delays in the net zero transition. Moving these solutions forward will require government policy and support, including research and development, demonstration and pilot projects, incentives, international cooperation and coordination, and possibly even direct public investment. But taking action now on wild cards also needs careful management of risk and uncertainty. Betting on the wrong pathway could significantly increase the costs of Canada's transition and jeopardize its efforts to achieve net zero if factors outside its control do not materialize as expected.

Safe bets and wild cards should be considered separately

The promise of wild cards does not justify a wait-and-see approach to the net zero transition overall. Even in scenarios where engineered negative emissions solutions, for example, see significant uptake, safe bets still do much of the heavy lifting to reduce emissions, especially before 2030.

Too often, policy debates in Canada have led to paralysis by conflating the challenges and opportunities across safe bets and wild cards. Although expanding the use of both sets of solutions are related challenges, our research shows the value of separating wild cards and safe bets in the policy discussion.

Decision makers that focus too much on the role of wild card solutions risk being distracted from critical near-term action and investments focused on safe bets. There are reasons to advance both at the same time, but they represent separate policy problems. Safe bet solutions have clear paths forward. The technologies are commercially available and the barriers to their deployment are mostly manageable. The path forward for wild cards, on the other hand, is much less clear. These solutions face far greater risk and uncertainty, posing wholly different challenges and questions regarding policy. Wild cards make for complicated policymaking, because Canada does not fully control all of the factors required to overcome hurdles to their successful uptake and deployment, and decisions made outside Canada can matter as much as domestic choices.

Navigating a successful transition to net zero will require decision makers to manage the very different challenges of safe bets and wild cards simultaneously. They must push forward with the safe bets we know can take Canada most of the way to its 2030 emissions goals and well on its way to net zero by 2050, while at the same time creating the conditions for the development, deployment, and adoption of wild cards.

Engineered forms of negative emissions are a special type of wild card

Shifting to an energy system driven by fossil fuels and engineered negative emissions solutions might seem like an attractive option to incumbents, because these technologies would involve much less structural change in the economy than other systems in the pursuit of net zero. However, such a system should be treated with caution, for several reasons.

First, engineered negative emissions solutions present a seductive but risky possibility of incumbents being able to continue their current approach (producing emissions-intensive products, for example) and the structure of the economy remaining mostly unchanged. But the risk is that if this system fails to come together as planned, it would create delays in emissions reductions and structural changes, significantly increasing the costs of Canada reaching its target. It could even cause Canada to miss it altogether, which would exacerbate global climate change both directly (via Canada's higher emissions) and indirectly (by limiting the opportunity to leverage Canada's action and example into greater global action). This failure would also pose the risk of trade sanctions from other countries that were making deeper cuts to their own emissions (as the European Union is currently considering through Border Carbon Adjustments).

Developing a fossil fuels and engineered negative emissions energy system at scale would also face many significant hurdles. It would require engineered negative emissions to prove cost-effective and scalable—an outcome that is far from certain. It would also demand a scale and pace of facility construction and technology deployment with few, if any, precedents. And it would very likely have to overcome public opposition, including from Indigenous Peoples on whose lands such systems would often operate.

At the same time, negative emissions solutions do present some important potential opportunities:

- Helping avoid the most difficult and costly emissions cuts elsewhere in the economy (for example, in parts of heavy industry);
- Putting existing Canadian infrastructure and skills to work;
- Compensating for failures or unexpected emissions reductions setbacks in the rest of the economy; and
- Assisting with emissions cuts beyond net zero to net negative, which may ultimately be required to stabilize the global climate even after broad cuts in gross emissions are made in the rest of the economy.

Negative emissions solutions are best viewed not as a substitute but as a complement to the ongoing implementation of other solutions (especially the safe bets).

Pathways to 2050 have implications for the well-being of Canadians

As governments and citizens nationwide are focused on containing COVID-19 and the related economic fallout, this might seem like an inopportune time to reflect on Canada's prosperity and well-being in 2050. But the choices Canada makes today—the policies, investments, and initiatives that emerge as priorities after the pandemic—will have far-reaching implications.

Managed effectively, the net zero transition can maintain or improve the prosperity and well-being of all Canadians. The net zero shift can improve air quality and health outcomes. It can also have positive economic impacts by decreasing energy costs for most households. But careful attention must be paid to the uneven impacts of climate policy to ensure these benefits are available to everyone and to ensure that net zero initiatives recognize Indigenous rights and advance reconciliation.

Canada's net zero transition must ensure that Canadian households continue to find employment and income opportunities sufficient to ensure their economic prosperity. To help accomplish this, policy makers will need to rely as much as possible on cost-effective policies and avoid expensive, inefficient ones that create unnecessary drag on the economy. They will also need to provide transitional support to make sure individual Canadians aren't left behind in this transition.

The COVID-19 pandemic has dramatically underscored the risks of not being prepared in advance and not working collaboratively to address a common challenge. We know that climate change and the transition to net zero will present significant social challenges and disruption, but Canada can minimize these impacts (and create new opportunities to prosper) by acting now.

7 RECOMMENDATIONS

1. Governments at all levels should increase the stringency of existing policies to create incentives for widespread deployment of safe bet solutions

The path to net zero by 2050 starts with a series of steps in the right direction. And Canada's first step in reaching both 2030 and 2050 targets is to continue to drive forward the safe bet solutions identified by our analysis. Potential long-term contributions by wild card solutions do not justify delay on safe bets. Delay is costly, and there are numerous solutions that Canada can pursue with confidence starting today. The safe bet solutions that are particularly promising in the near term include: improving energy efficiency; shifting to non-emitting electricity; adopting heat pumps and electric vehicles; reducing methane emissions from oil and gas production; reducing the use of HFCs; and adopting CCUS for concentrated gas streams.

Policy can and should send clear signals to proceed with these safe bets and provide strong incentives broadly throughout the economy. The policy architecture to create these incentives is already in place. Flexible regulations such as the federal Clean Fuel Standard, British Columbia's Low Carbon Fuel Standard, and British Columbia and Quebec's Zero Emission Vehicle mandates can be readily expanded and accelerated. Building codes can be strengthened. And the stringency of carbon pricing can be increased, as set out under the new federal climate plan.

We do not make precise recommendations about specific instruments or regulations. Governments have many options, and different governments will put them to work in different ways depending on their unique situations and priorities. The crucial step for all governments is to provide the necessary policy stringency in a coordinated and predictable way to make the widespread deployment of safe bets a reality. As they do so, careful attention should be paid to avoid a patchwork of policies that could create unnecessary inefficiencies or lead to unintended consequences.

2. Governments should manage the risks and opportunities posed by wild card solutions through a portfolio approach

Relying only on safe bets for the net zero transition would fail to realize the substantial potential that wild card solutions have for making the deeper, cost-effective emissions cuts necessary to reach the goal. Unlocking this potential, however, will not be easy. Each of the three net zero energy systems we examined requires significant innovation, policy change, and investment in emerging technologies or in enabling infrastructure.

Policy choices can help overcome the hurdles that each system faces but not render them free of risk. To manage this risk, Canadian policy should commit to multiple potential wild card solutions (but not so many that support becomes too diluted).[47] It should also create an enabling environment that reduces barriers to innovation, creates opportunities for the development and deployment of emerging technologies, incentivizes the involvement of the private and civil sectors, and remains flexible to unpredictable technological and global change.

This report does not provide advice regarding which wild card solutions or energy system(s) Canadian governments should invest in. Instead, our analysis is intended to serve as a platform for broader conversations with industry, Indigenous representatives, organized labour, and Canadian citizens about the feasibility and the desirability of the available options. These conversations should aim to identify priorities that not only support Canada's net zero ambitions but also generate a range of social, economic, and environmental benefits. They should also reflect (and contribute to) similar conversations underway internationally.

3. Governments should increase policy certainty by implementing robust climate accountability frameworks

Governments can use existing policy infrastructure—especially policies that are broad, flexible, and stringent—to lay the groundwork for longer-term innovations and the deployment of wild card solutions. Sending clear signals that establish expectations for the future stringency of policy is particularly helpful, as these expectations create powerful incentives for innovation by signalling that there will be demand for emissions-reducing technologies, practices, and innovations. Climate accountability frameworks can help create these expectations by linking together a credible series of steps on the long-term pathway to net zero and creating incentives for follow-through on them.

Climate accountability frameworks are a set of governance structures and processes that connect long-term emissions-reduction targets to near-term policy actions through regular and transparent monitoring and reporting (Beugin et al., 2020). These frameworks can help define required increases in policy stringency by breaking long-term targets into discrete, manageable, short-term segments. They can create more certainty about long-term policy stringency by legislating future milestones on the path to net zero. They can also support follow-through by helping the public keep governments accountable to their climate

47 Negative emissions solutions merit specific mention here. There is a case for driving innovation and enabling deployment of negative emissions technologies as part of a portfolio-based net zero strategy. However, any such support should be in addition to other policy measures, rather than instead of them.

targets and policy commitments through transparent, independent monitoring of progress.

Accountability processes can also create opportunities for course correction. By regularly taking stock of progress, they can provide governments with independent advice on next steps for the short and medium term and help manage the uncertainties associated with the evolution of wild card solutions.

Late last year, the Government of Canada tabled the *Canadian Net-Zero Emissions Accountability Act* (Bill C-12), which, if passed, will establish a federal climate accountability framework. The draft legislation includes many core elements of a strong accountability framework, such as independent expert advice, interim emissions reductions milestones, and regular and transparent monitoring and reporting. The legislation could go further, however, to increase accountability, provide greater certainty, and engage other orders of government in meeting national climate targets. Such changes would help to provide a stronger signal that wild card solutions will be needed and valued.

Similarly, other orders of government should consider developing their own accountability frameworks to create expectations for provincial, territorial, municipal, or Indigenous policy pathways. Increased transparency on ambition and policy at every order of government can also bring challenging conversations about coordinating policies between governments to the surface.

4. Governments should work to ensure that the transition to net zero is fair and inclusive

Regardless of which path Canada takes to net zero, accompanying policies should explicitly address the distributional implications of the transition. Reducing emissions will not inevitably lead to a just and equitable society, and the net zero transition could even exacerbate existing inequalities and injustices in the absence of careful and supportive policy.

Canadian governments should provide support to lower-income households to ensure that climate policies do not impose disproportionate costs or undermine their well-being, and to enable them to take the actions needed to reduce emissions. They should provide support to workers in those sectors and regions that will undergo the most dramatic transitions. And they should engage directly with the transitions in rural, remote, and Indigenous communities, helping them to overcome existing structural barriers to their prosperity and self-sufficiency.

It is vital that governments understand the full range of implications the transition will have on all of Canada's regions, sectors, workers, communities, and income groups. This is necessary to ensure that policies successfully address adverse impacts and work to lift up groups who have historically been left behind, instead of exacerbating those inequalities. This will require direct engagement with all of those groups.

It will also require better tracking of indicators. Emissions are not the only metric that needs to be monitored on the path to net zero. Progress should be tracked against a set of comprehensive climate, economic, and social indicators so that climate policies also drive inclusive economic growth, strengthen Canada's resilience to climate impacts, and improve the well-being of all Canadians (Arnold et al., 2020).

In some cases, the impacts of the transition will be caused by forces outside of Canada's control (such as policy action in the rest of the world or declining global demand for certain goods and services). Where this is the case, governments should implement the necessary supports so that these risks and impacts are minimized. Other factors driving the transition—particularly Canada's own policy actions—are well within domestic control. These policies should be used as tools not only to reduce emissions but also to advance social, economic, and environmental justice across Canada.

ANNEXES

Annex 1: An overview of key findings from similar studies

STUDY	JURISDICTION OF FOCUS	GHG TARGET	METHODOLOGY	SCENARIOS	KEY INSIGHTS
Pathways to Deep Decarbonization in Canada (Bataille et al., 2015)	Canada	80 per cent below 2015 levels by 2050	The study uses an energy-economy model to forecast demand for GHG-intense goods, energy balance, technology deployment, and emissions. A macroeconomic, regionally and sectorally disaggregated Computable General Equilibrium model was used to forecast GDP, employment, economic structure, and trade.	The study models six decarbonization pathways. Some pathways reinforce current trends (such as decarbonization in electricity generation, energy efficiency, and emissions cuts from heavy industries), whereas others employ transformative technologies (such as CCUS or alternative fuels) or reorient the economy toward less emissions-intensive activities.	• Canada can make significant GHG cuts by decarbonizing the electricity grid, by using mainly renewable energy sources and some fossil fuels with CCUS, and by replacing combustion-based energy sources with electricity in many sectors. • Deep decarbonization will require significant investment and adoption of next-generation technologies. • Political action from federal and provincial governments is needed immediately to minimize costs.
Canada's Mid-Century Long-Term Low-Greenhouse Gas Development Strategy (ECCC, 2016)	Canada	80 per cent below 2005 levels by 2050	This report conducts a literature review of Canada-wide approaches including the Deep Decarbonization Pathways Project, the Trottier Energy Futures Project, and Acting on Climate Change: Solutions from Canadian Scholars. Other relevant information is retrieved from Canada-specific data and reports.	The report reviews many modelling scenarios from several studies. The aggregated results from the scenarios are used to understand potential decarbonization pathways.	• To effectively transition to a low-carbon economy, Canada will need to fundamentally transform all economic sectors, especially patterns of energy production and consumption, and will require significant investment in research, development, and innovation. • Deep decarbonization will rely heavily on non-emitting electricity and electrification of all sectors of the economy.

STUDY	JURISDICTION OF FOCUS	GHG TARGET	METHODOLOGY	SCENARIOS	KEY INSIGHTS
Canada's Challenge and Opportunity: Transformations for Major Reductions in GHG Emissions (Trottier Energy Futures Project, 2016)	Canada	80 per cent below 1990 levels by 2050	This study uses two models to develop its scenarios and identify pathways to the 2050 target at minimized costs: the NATEM and CanESS models. Both models include separate representations of the sectors in Canada's economy, as well as for all provinces and territories. Analysis is also based on expert input and literature review.	The study employs two complementary models, in combination and independently, to analyze 11 future GHG emissions-reduction scenarios. The approach aims at assessing how the 80 per cent reduction target can be met based on currently deployed technologies with plausible extrapolations for future improvements and cost reductions.	• To achieve deep emissions cuts, Canada should focus on reducing the use of fossil fuels for end-uses, implementing cost-effective energy efficiency measures in all sectors, decarbonizing the electricity supply, and increasing the use of biomass and biofuels. • In 2050, there is still demand for fossil fuels, especially diesel for heavy freight and rail and jet fuel for air transportation. This is largely due to biofuel feedstock supply constraints, limitations on the use of electricity for heavy freight and rail transportation, and high marginal costs for other energy sources.
United States Mid-Century Strategy for Deep Decarbonization (Government of the United States, 2016)	United States	80 per cent below 2005 levels by 2050	This report uses a mix of analytical tools, including literature review, expert input, and modelling. It reviews previous studies on deep decarbonization in the United States, integrates input from stakeholders and other jurisdictions aiming for deep decarbonization by 2050, and uses a number of modelling tools, including the Global Change Assessment Model, the Global Timber Model, the U.S. Forest Assessment Service Model, and the National Energy Modelling System.	The scenarios examined differ in the technologies and strategies they use. Two scenarios focus on the potential of achieving different levels of negative emissions by 2050, three scenarios explore pathways with different assumptions with regard to low-carbon energy transition, and the Beyond 80 scenario explores a pathway where the U.S. exceeds the 80 per cent reduction target by 2050.	• Three important actions will be required to achieve deep decarbonization: 1) a transition to a low-carbon energy system; 2) sequestration of carbon through land and technologies; 3) reduction of non-CO_2 emissions. • Strong international action will be critical in achieving a successful transition toward a low-carbon global economy.

STUDY	JURISDICTION OF FOCUS	GHG TARGET	METHODOLOGY	SCENARIOS	KEY INSIGHTS
Canadian Energy Outlook: Horizon 2050 (Langlois-Bertrand et al., 2018)	Canada	30 per cent below 2005 levels by 2030 and 80–83 per cent below 2005 levels by 2050	The study uses the North American TIMES Energy Model to examine a number of energy-related scenarios that mainly vary in terms of GHG reductions. The emissions reduction scenarios are based on provincial, federal, and international targets. The scenarios are modelled on the 2030 and 2050 horizons with results disaggregated at the provincial level. The study projects Canada's energy production and consumption into the next decades based on the National Energy Board's demand scenario.	The study compares four emissions reduction scenarios and a business-as-usual case: 1) the provincial scenario, which imposes individual provincial targets where they exist (with no federal involvement); 2) a scenario that imposes the federal government's stated 2030 and 2050 targets, where 25 per cent of reductions come from international carbon credits; 3) a scenario with the federal government's targets but no carbon credits; and 4) a more aggressive emissions reduction scenario (83 per cent below 2005 levels by 2050).	• The oil and gas sector is expected to experience significant reduction in demand. Demand for oil products is set to decrease (even in the business-as-usual case) as early as 2030. • All scenarios see some continued fossil fuel use, even in the most stringent scenarios. • All scenarios point to an accelerated electrification of the Canadian energy system, mainly generated from non-emitting sources. • The transformation of the transportation sector will be central to emissions-reduction efforts.
Trajectoires de réduction d'émissions de GES du Québec – Horizons 2030 et 2050 (Ministère de l'environnement et de la lutte contre les changements climatiques, 2019)	Quebec	37.5 per cent reduction in 2030 and 80–95 per cent reduction by 2050	The study uses an optimization model (NATEM-Canada), which is a technological-economic model that details the energy system in Canada, GHG emissions, pan-national and pan-provincial fluxes, their long-term trajectories, and technologies.	The authors model four emissions pathway scenarios, each with different targets for both 2030 and 2050. Eight additional scenarios are modelled to assess their effects on emissions, the energy system, and costs. The additional scenarios include a reduction in demand, an increase in biomass, modifications to the food system, different technology availability, and the use of CCUS.	• Quebec can achieve its 2030 target of a 37.5 per cent reduction in emissions, as well as a 75 per cent reduction by 2050, using existing low-carbon technologies alone. • Achieving an 85 per cent reduction by 2050 will require reduction in energy demand. • Achieving an 87.5 per cent reduction by 2050 without purchasing international carbon credits will require the use of new technologies (e.g., BECCS) or changes in behaviour, in particular declines in energy demand.

STUDY	JURISDICTION OF FOCUS	GHG TARGET	METHODOLOGY	SCENARIOS	KEY INSIGHTS
Pathways to 2050: Alternative Scenarios for Decarbonizing the U.S. Economy. (Lempert et al., 2019)	United States	80 per cent below 2005 levels by 2050	The report is informed by a series of workshops where a group of 20 companies examined potential scenarios for achieving decarbonization goals by 2050. The input from the workshops shaped the modelling approach, which is undertaken with the Global Change Assessment Model, a global, long-term, multi-sector human–Earth systems model.	The study considers three scenarios that differ in their policy mix and technologies. A Competitive Climate includes strong international action on climate change, Climate Federalism has strong climate policies at the state level, and Low-Carbon Lifestyle is based on technological breakthroughs, strong demand for low-carbon products, and new businesses and technologies.	• Deep decarbonization of the U.S. economy will require decarbonization of the power sector; fuel switching in transportation, buildings, and industry; increased end-use energy efficiency; use of CCUS; and reduction of other potent greenhouse gases (e.g., methane). • Significant decarbonization will require action on all fronts and from all actors. This will require high levels of public support, as well as increased demand for low-carbon goods and services.
Net Zero: the UK's Contribution to Stopping Global Warming (Committee on Climate Change, 2019)	United Kingdom	100 per cent reduction by 2050	Results from this study are based on 10 research projects, three expert advisory groups, and reviews of the work of the IPCC and other researchers. It also draws on results from climate models, such as IAM, that integrate interactions between global energy, agriculture, land use, and climate systems.	The scenarios that the study examines are divided into three categories. The first identifies a set of core measures that would achieve net zero while minimizing costs and relying on existing policies. The second category relies on a low-carbon hydrogen economy and extensive use of CCUS and land-use management. The third category groups alternative options such as changes in demand and extensive technological breakthroughs.	• Reaching net zero by 2050 is achievable with current technologies. • CCUS and BECCS will both play a role in achieving net zero by 2050. • One-fifth of the U.K.'s agricultural land must shift to alternative uses that support emissions sequestration, such as afforestation, biomass production, and peatland restoration. • Current policies are insufficient to reach net zero. Clear, stable, and well-designed policies are needed across the economy.

STUDY	JURISDICTION OF FOCUS	GHG TARGET	METHODOLOGY	SCENARIOS	KEY INSIGHTS
Towards Net-Zero Emissions in the EU Energy System by 2050, (Tsiropoulos et al., 2020)	European Union	50 per cent reduction by 2030 and 100 per cent reduction by 2050	This report aggregates and analyzes results from different models and scenarios published between 2017 and 2019, including the Global Energy Perspective, the CTI-EU, the PRIMES model, the ETP-TIMES model, and the World Energy Model.	The report compares eight scenarios that achieve more than 50 per cent reduction in greenhouse gas emissions by 2030 compared to 1990 and 16 scenarios that reach net zero by 2050.	• All scenarios see a near complete phase-out of coal and a 75 per cent reduction in oil and natural gas use. • In 2050, renewables provide between 70 per cent and 100 per cent of electricity. Biofuels increase from 9 per cent of total energy to 20 per cent, largely for use in the aviation and shipping sectors. • Nature-based and engineered negative emissions solutions will be required to reach carbon neutrality by 2050. • Electric vehicle technologies will account for 65 to 90 per cent of the total fleet, with battery electric vehicles forming the majority of this.
Making Mission Possible: Delivering a Net-Zero Economy (Energy Transitions Commission, 2020)	Global	100 per cent reduction by 2050 for developed countries 100 per cent reduction by 2060 for developing countries	The report brings together, and builds upon, findings from past publications by the Energy Transition Commission (ETC), developed in collaboration with experts from industry, academia, and non-governmental organizations. It draws on analysis carried out by a number of organizations as well as broader literature review.	The report compares across several scenarios, including its own ETC zero-emissions scenarios as well as other deep decarbonization scenarios, including from the International Energy Agency.	• Net zero by mid-century is technically and economically possible without the permanent or significant use of offsets from nature-based or engineered negative emissions solutions. • The costs of achieving net zero by 2050 are very small, especially compared to the costs of unmitigated climate change. Achieving net zero will also generate important benefits and improve overall well-being. • Reaching net zero will mean a profound transformation of the energy system. Fossil fuels will largely be replaced by clean electricity, complemented by hydrogen, some sustainable biomass, and limited fossil fuel use with CCUS. Significant energy productivity gains will also play a role.

Annex 2: Detailed breakdown of modelling scenarios

For more information on modelling assumptions, parameters and sources, and scenarios, see Navius Research (2021).

ASSUMPTION	DESCRIPTION
Electric vehicle costs	
Reference	Reference cost of battery EVs declines over time according to a declining capital cost and a declining intangible cost curve. Reference battery EV capital costs are modelled at \$23,700 (\$25,100 with charger) by 2030.
Low	Steeper cost declines for battery EVs, including capital and intangible costs, reflecting more rapid global penetration of EVs and batteries and stronger "learning by doing." Low battery EV capital costs are modelled at \$22,120 (\$23,540 with charger) by 2030.
Hydrogen costs and blending rates	
Reference	Hydrogen blending in natural gas pipelines is constrained by operational and safety considerations. Currently, certain infrastructure is unable to handle more than a 2 per cent hydrogen blending rate (by volume), the reference blending rate used in our analysis. Starting reference costs for delivered hydrogen range from \$4.90/kg or \$34.70/GJHHV* to \$9.50/kg or \$68.30/GJHHV, depending on the production technology. The reference cost of hydrogen fuel cell vehicles declines over time according to a declining capital cost and declining intangible cost curve. Reference fuel cell vehicle costs are modelled to decline as a function of adoption to a potential minimum of \$32,810 but only decline to a low of \$51,500 by 2050 in this analysis.
Low costs, high blending rate	Changes to the natural gas pipeline network could potentially allow it to support a 20 per cent hydrogen blending rate (by volume), the high blending rate used in our analysis. Low costs for hydrogen production range from 10–20 per cent below reference case estimates, depending on the production technology, reflecting stronger "learning by doing" given global market penetration. Low fuel cell vehicles costs (including both capital and intangible costs) are modelled to decline to a potential minimum of \$23,825 but only decline to a low of \$42,950 by 2050 in this analysis.
Non-emitting "firm" electricity generation costs	
Reference	The cost of constructing new non-emitting firm electricity generation capacity is modeled at \$152/MWh.
High	No new firm electricity generation capacity is built in Canada because it is assumed to be prohibitively expensive or face other barriers that inhibit its development.
Climate policy action in other major countries	
Other major countries lagging Canada	To model lack of action on climate change in the rest of the world, the scenario assumes that the United States continues along its reference case emissions trajectory, with no new climate policy implemented. Other major countries are also assumed to be lagging Canada in their climate policy implementation. As a result, there is a slower cost decline for clean technologies such as electric vehicles, hydrogen, and renewables due to weak adoption abroad.
Other major countries keeping pace with Canada	To model climate action in the rest of the world, a cap was imposed on United States emissions to simulate new policy. This results in an accelerated cost decline for clean technologies, as adoption increases in the United States. To model other major countries also keeping pace with Canada in their climate policy implementation, the global price for commodities was adjusted to account for trade and policy interactions, with foreign commodity prices adjusted based on the change in production costs in North America when net-zero climate policy is implemented.

ASSUMPTION	DESCRIPTION
Availability of engineered forms of negative emissions solutions and advanced forms of CCUS	
Available	When direct air capture (DAC), carbon capture, utilization, and storage (CCUS), and bioenergy with carbon capture and storage (BECCS) are assumed to be available, the cost of DAC starts at \$368/tonne CO_2e and declines as experience with the technology increases, to a potential price floor of \$125/tonne CO_2e by 2050. The cost of CCUS is dependent on the end-use and the cost of capture ranges from \$20–\$120/tonne CO_2e for non-combustion technologies and from \$50–\$150/tonne CO_2e for combustion technologies. The cost of CCUS also varies by region due to costs of CO_2 transport and storage, which range from an additional \$3.60/tonne CO_2e in Alberta to \$17.90/tonne CO_2e in British Columbia.
Unavailable	Under this assumption, DAC and CCUS for (unconcentrated) combustion emission sources are either not technically feasible at scale or prohibitively costly. A limited amount of CCUS is available for non-combustion, concentrated emission sources, such as process emissions in hydrogen, cement, and fertilizer production. The cost of capture for non-combustion emission sources ranges from \$20–\$120/tonneCO_2e depending on the end-use, plus additional costs of transport and storage, which range from \$3.60/tonne CO_2e in Alberta to \$17.90/tonne CO_2e in British Columbia.
Mix	Under this assumption, DAC is either not technically feasible or prohibitively costly. CCUS is assumed to be available for both (unconcentrated) combustion emissions and for (concentrated) process emissions. The cost of CCUS is dependent on the end-use and the cost of capture ranges from \$20–\$120/tonne CO_2e for non-combustion emissions and from \$50–\$150/tonne CO_2e for combustion emissions. The cost of CCUS also varies by region due to costs of CO_2 transport and storage, which range from an additional \$3.60/tonne CO_2e in Alberta to \$17.90/tonne CO_2e in British Columbia.
Global oil price	
High	\$63(USD2020)/barrel by 2030 and \$87(USD2020) by 2050.
Low	\$38(USD2020)/barrel by 2030 and \$36(USD2020) by 2050.
Competitiveness protection measures	
On	Measures are in place to protect against carbon leakage in emissions-intensive, trade-exposed sectors, maintain their competitiveness, and incentivize industrial emitters to reduce their emissions.
Off	No such measures are in place.
Availability of second-generation biofuels	
Available	Biofuels made from second-generation feedstocks are technically viable. These feedstocks are available for an "at-the-plant" cost of \$81/ODt** for agricultural residue and \$94/ODt for forest harvest residue. These residue feedstock costs act as a proxy for the availability and costs of other types of second-generation feedstocks (e.g., switchgrass) that are not directly represented in the modelling.
Unavailable	Biofuels made from second-generation feedstocks do not prove technically viable.
Improvements in the emissions intensity of oil sands production	
Reference	Reference case forecasts of emissions intensity improvements in the oil sands are 0.03 tonnes CO_2e/barrel by 2030 for mining and 0.07 tonnes CO_2e/barrel by 2030 for in situ production, falling further to 0.02 tonnes CO_2e/barrel by 2050 for mining and 0.05 tonnes CO_2e/barrel by 2050 for in situ production.
Accelerated Improvement	GHG intensity pathways in the oilsands under a scenario of improvements that exceed reference case forecasts have emissions intensity in the oil sands at 20 per cent lower than the reference scenario by 2030 and 30 per cent lower by 2050 (these figures are based on projections from the Canadian Association of Petroleum Producers).

Note: All dollar figures are in 2020 Canadian dollars unless otherwise specified. *High Heating Value **Oven Dry Tonnes

ASSUMPTIONS

SCENARIO NUMBER	Electric vehicle costs		Hydrogen costs and blending rate potential		New non-emitting "firm" electricity generation costs		Climate policy action in other major countries		Availability of engineered forms of negative emissions solutions and advanced forms of CCUS			Global oil price		Competitiveness protection measures		Availability of second-generation biofuels		Oil sands production emissions intensity improvements	
	Reference	Low	Reference	Low costs, high blending rates	Reference	High	Other major countries lagging Canada	Other major countries keeping pace	Available	Unavailable	Mix	High	Low	On	Off	Available	Unavailable	Reference	Accelerated improvement
1	✓		✓			✓	✓		✓			✓			✓	✓		✓	
2	✓		✓			✓	✓			✓		✓			✓	✓		✓	
3	✓		✓			✓		✓	✓			✓			✓	✓		✓	
4	✓		✓			✓		✓		✓			✓		✓	✓		✓	
5	✓		✓		✓		✓			✓		✓			✓	✓		✓	
6	✓		✓		✓			✓		✓			✓		✓	✓		✓	
7		✓	✓			✓	✓		✓			✓			✓	✓		✓	
8		✓	✓			✓	✓			✓		✓			✓	✓		✓	
9		✓	✓			✓		✓	✓			✓			✓	✓		✓	
10		✓	✓			✓		✓		✓			✓		✓	✓		✓	
11		✓	✓		✓		✓			✓		✓			✓	✓		✓	
12		✓	✓		✓			✓		✓			✓		✓	✓		✓	
13		✓		✓		✓	✓		✓			✓			✓	✓		✓	
14		✓		✓	✓		✓			✓		✓			✓	✓		✓	
15		✓		✓		✓		✓	✓			✓			✓	✓		✓	
16		✓		✓		✓		✓		✓			✓		✓	✓		✓	
17	✓		✓			✓	✓		✓			✓		✓		✓		✓	
18	✓		✓			✓	✓			✓		✓		✓		✓		✓	
19	✓		✓			✓		✓	✓			✓		✓		✓		✓	
20	✓		✓			✓		✓		✓		✓		✓		✓		✓	
21	✓		✓		✓		✓			✓		✓		✓		✓		✓	

ASSUMPTIONS

SCENARIO NUMBER	Electric vehicle costs		Hydrogen costs and blending rate potential		New non-emitting "firm" electricity generation costs		Climate policy action in other major countries		Availability of engineered forms of negative emissions solutions and advanced forms of CCUS			Global oil price		Competitiveness protection measures		Availability of second-generation biofuels		Oil sands production emissions intensity improvements	
	Reference	Low	Reference	Low costs, high blending rates	Reference	High	Other major countries lagging Canada	Other major countries keeping pace	Available	Unavailable	Mix	High	Low	On	Off	Available	Unavailable	Reference	Accelerated improvement
22	✓		✓		✓			✓		✓			✓	✓		✓		✓	
23		✓	✓			✓	✓		✓			✓		✓		✓		✓	
24		✓	✓			✓	✓			✓		✓		✓		✓		✓	
25		✓		✓		✓	✓		✓			✓		✓		✓		✓	
26		✓	✓			✓		✓	✓			✓		✓		✓		✓	
27		✓	✓			✓		✓		✓			✓	✓		✓		✓	
28		✓		✓		✓		✓	✓			✓		✓		✓		✓	
29		✓	✓		✓		✓			✓		✓		✓		✓		✓	
30		✓		✓	✓		✓			✓		✓		✓		✓		✓	
31		✓	✓		✓			✓		✓			✓	✓		✓		✓	
32		✓		✓	✓			✓		✓			✓	✓		✓		✓	
33	✓		✓			✓	✓				✓	✓			✓	✓		✓	
34		✓	✓			✓	✓				✓	✓			✓	✓		✓	
35	✓		✓		✓		✓				✓	✓			✓	✓		✓	
36		✓	✓		✓		✓				✓	✓			✓	✓		✓	
37		✓		✓	✓		✓				✓	✓			✓	✓		✓	
38	✓		✓			✓	✓				✓	✓		✓		✓		✓	
39		✓	✓			✓	✓				✓	✓		✓		✓		✓	
40	✓		✓		✓		✓				✓	✓		✓		✓		✓	
41		✓	✓		✓		✓				✓	✓		✓		✓		✓	
42		✓		✓	✓		✓				✓	✓		✓		✓		✓	

ASSUMPTIONS

SCENARIO NUMBER	Electric vehicle costs		Hydrogen costs and blending rate potential		New non-emitting "firm" electricity generation costs		Climate policy action in other major countries		Availability of engineered forms of negative emissions solutions and advanced forms of CCUS			Global oil price		Competitiveness protection measures		Availability of second-generation biofuels		Oil sands production emissions intensity improvements	
	Reference	Low	Reference	Low costs, high blending rates	Reference	High	Other major countries lagging Canada	Other major countries keeping pace	Available	Unavailable	Mix	High	Low	On	Off	Available	Unavailable	Reference	Accelerated improvement
43	✓		✓			✓		✓			✓		✓		✓	✓		✓	
44		✓	✓			✓		✓			✓		✓		✓	✓		✓	
45	✓		✓		✓			✓			✓		✓		✓	✓		✓	
46		✓	✓		✓			✓			✓		✓		✓	✓		✓	
47		✓		✓	✓			✓			✓		✓		✓	✓		✓	
48	✓		✓			✓		✓			✓		✓	✓		✓		✓	
49		✓	✓			✓		✓			✓		✓	✓		✓		✓	
50	✓		✓		✓			✓			✓		✓	✓		✓		✓	
51		✓	✓		✓			✓			✓		✓	✓		✓		✓	
52		✓		✓	✓			✓			✓		✓	✓		✓		✓	
53	✓		✓		✓		✓			✓		✓		✓		✓			✓
54		✓	✓		✓		✓			✓		✓		✓		✓			✓
55		✓		✓	✓		✓			✓		✓		✓		✓			✓
56	✓		✓		✓			✓		✓			✓	✓		✓			✓
57		✓		✓	✓			✓		✓			✓	✓		✓			✓
58	✓		✓		✓			✓		✓		✓		✓		✓		✓	
59		✓		✓	✓			✓		✓		✓		✓		✓		✓	
60		✓		✓	✓		✓			✓		✓		✓			✓	✓	
61	✓		✓		✓		✓			✓		✓		✓			✓	✓	
62		✓	✓		✓		✓			✓		✓		✓			✓	✓	

Annex 3: Canada's greenhouse gas emissions by economic sector, selected years ($Mt\ CO_2eq$)

ECONOMIC SECTOR	1990	2005	2018*
Mt CO_2 EQUIVALENT			
National GHG total	**603**	**730**	**729**
Oil & gas	**106**	**158**	**193**
Upstream oil & gas	**86**	**134**	**173**
Natural gas production and processing	36	55	50
Conventional oil production	23	30	29
Oil sands	15	37	84
Oil, natural gas & CO_2 transmission	12	12	11
Downstream oil & gas	**20**	**23**	**21**
Petroleum refining	18	22	19
Natural gas distribution	2	1	1
Electricity	**95**	**119**	**64**
Transportation	**121**	**161**	**186**
Passenger transport	71	90	99
Freight transport	31	60	78
Other	19	10	9
Heavy industry	**97**	**87**	**78**
Mining	7	7	8
Smelting & refining	17	14	10
Pulp & paper	15	9	8
Iron & steel	16	16	16
Cement	10	13	11
Lime & gypsum	3	3	2
Chemicals & fertilizers	29	25	24
Buildings	**74**	**86**	**92**
Service industry	28	40	46
Residential	47	46	47
Agriculture	**57**	**72**	**73**
On farm fuel use	11	12	14
Crop production	15	16	24
Animal production	32	44	36
Waste	**21**	**20**	**18**
Coal production	**4**	**2**	**3**
Light manufacturing	**21**	**17**	**14**
Construction	**6**	**6**	**6**
Forest resources	**1**	**1**	**1**

Source: ECCC, 2020b.
Notes: Totals may not add up due to rounding.
*Most recent year for which data is available.

Annex 4: GHG reduction pathways in different economic sectors

Figure 21: Buildings

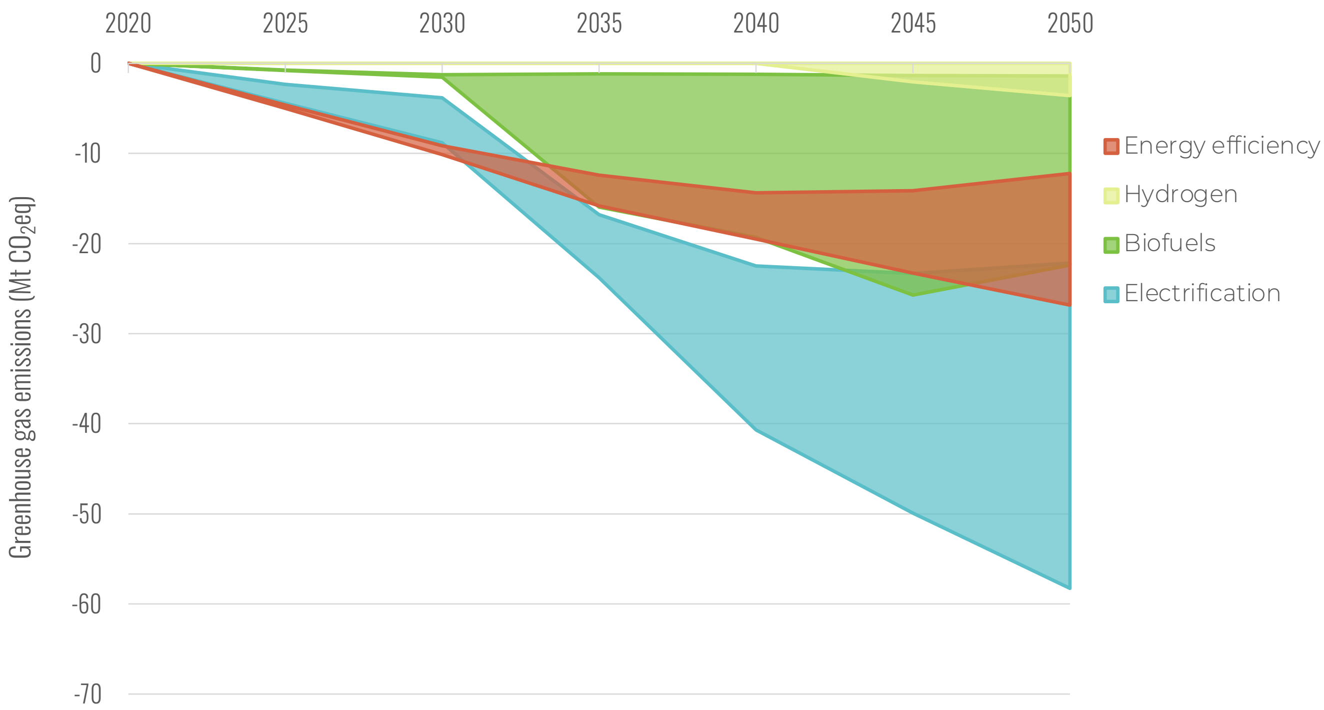


Figure 22: Personal transportation

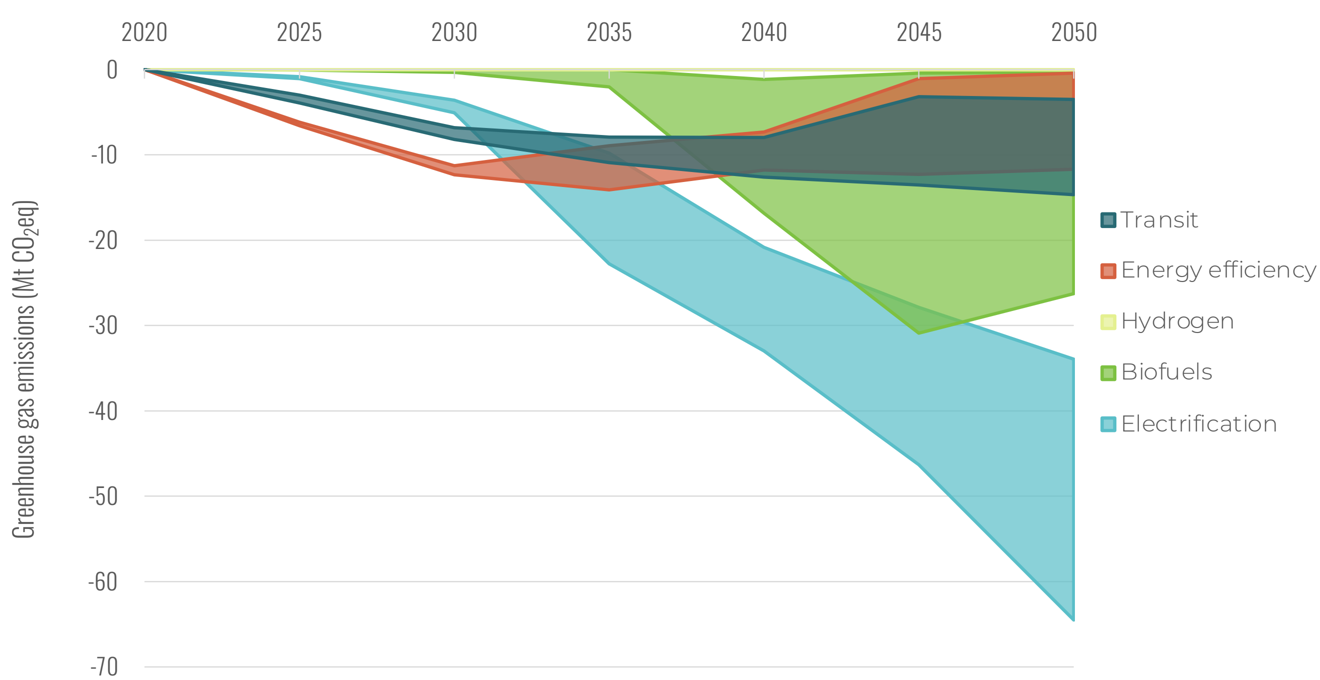


Figure 23: Medium- and heavy-duty transportation

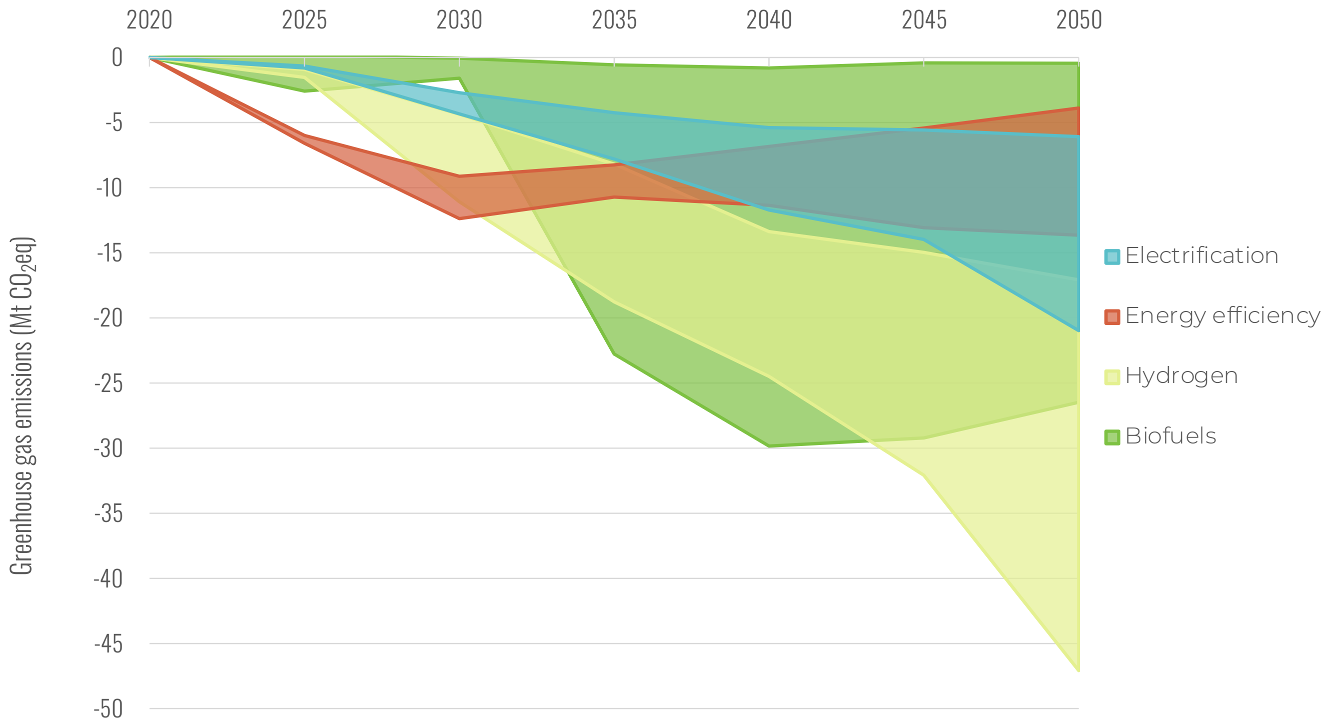


Figure 24: Industry

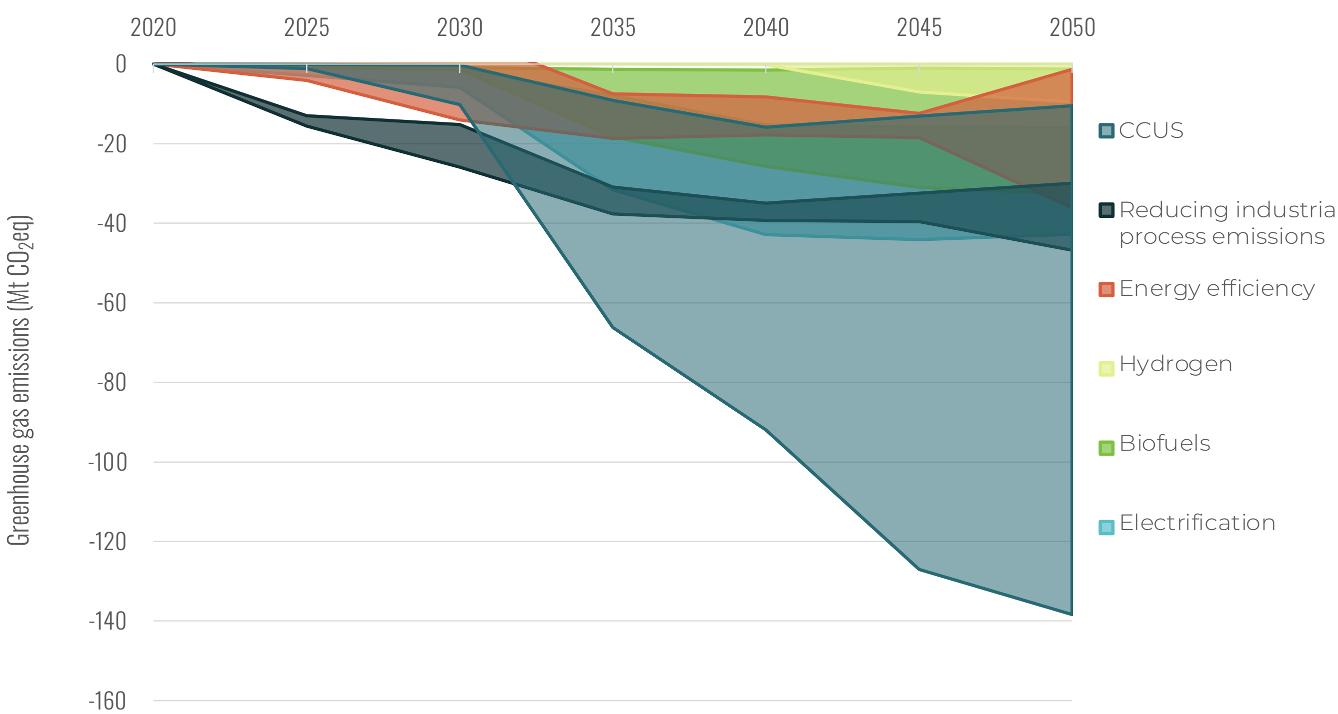
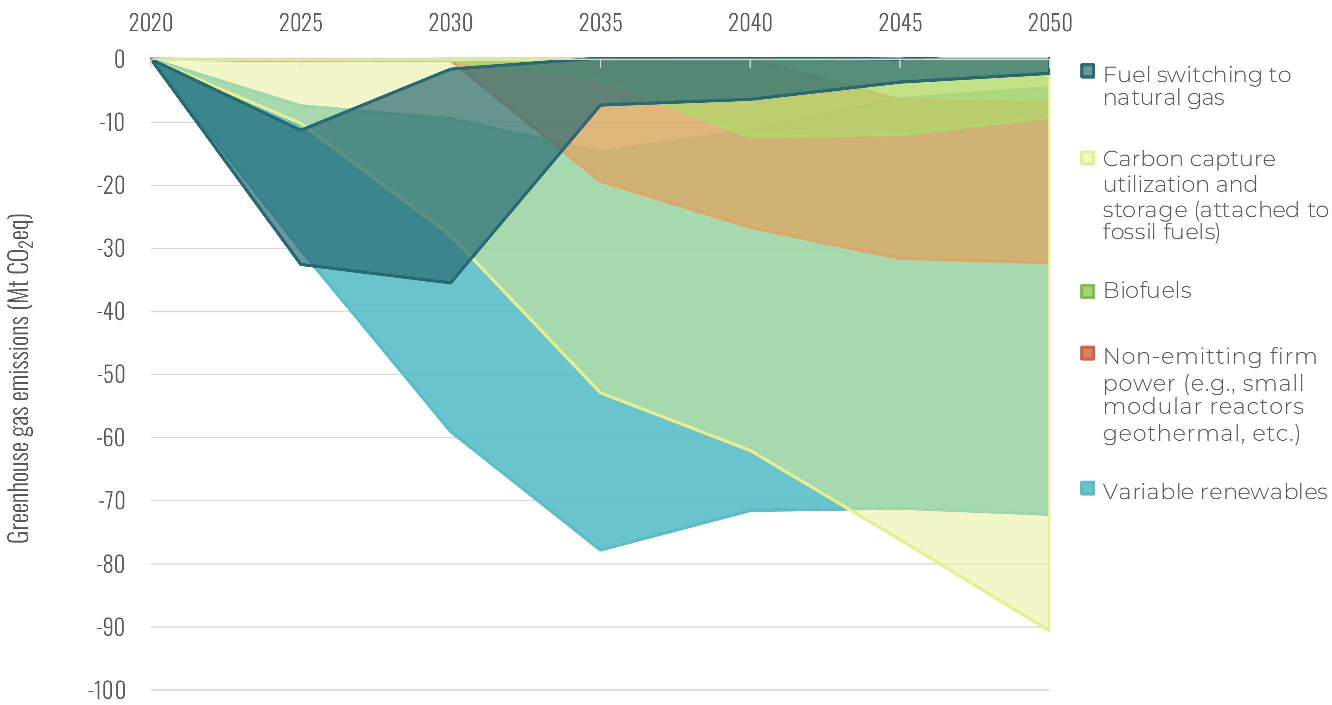


Figure 25: Electricity generation



REFERENCES

Alberta Carbon Capture and Storage Development Council. 2009. *Accelerating Carbon Capture and Storage Implementation in Alberta: Final Report*. https://keith.seas.harvard.edu/files/tkg/files/accelerating_carbon_capture_and_storage_implementa.pdf

Allen-Dumas, M., K.C., Binita, and C. Cunliff. 2019. *Extreme Weather and Climate Vulnerabilities of the Electric Grid: A Summary of Environmental Sensitivity Quantification Methods*. Climate Change Science Institute. Oak Ridge National Laboratory. https://www.energy.gov/sites/prod/files/2019/09/f67/Oak%20Ridge%20National%20Laboratory%20EIS%20Response.pdf

Ambrose, Jillian. 2020. "Scottish homes to be first in world to use 100% green hydrogen." *The Guardian*, 30 November 2020. https://www.theguardian.com/environment/2020/nov/30/scottish-green-hydrogen-fife

Arctic Council. 2020. "The Old Crow Solar Project." 14 December 2020. https://arctic-council.org/en/news/the-old-crow-solar-project/

Arnold, J., R. Samson, W. Ahmed, D. Beugin, and J. Bourque. 2020. *11 Ways to Measure Clean Growth*. Canadian Institute for Climate Choices. https://climatechoices.ca/wp-content/uploads/2020/09/11-WAYS-TO-MEASURE-CLEAN-GROWTH_report.pdf

Axsen, J., and M. Wolinetz. 2019. *Shifting Gears: Climate Solutions for Transportation in Cities, Metro Vancouver Case Study.* David Suzuki Foundation. https://davidsuzuki.org/science-learning-centre-article/shifting-gears-climate-solutions-for-transportation-in-cities-metro-vancouver-case-study/

Bataille, C. 2020. "Physical and policy pathways to net-zero emissions industry." *WIREs Climate Change* 11(2), e633. https://doi.org/10.1002/wcc.633

Bataille, C., D. Sawyer., and N. Melton. 2015. *Pathways to deep decarbonization in Canada.* Sustainable Development Solutions Network. https://cmcghg.com/wp-content/uploads/2015/07/Final-Canada-DDPP-Country-Report-July-14.pdf

Beugin, D., J. Dion, A. Kanduth, C. Lee, D. Sawyer, and J. Arnold. 2020. *Marking the Way: How legislating climate milestones clarifies pathways to long-term goals.* Canadian Institute for Climate Choices. https://climatechoices.ca/reports/marking-the-way/

Bigg, Martin. 2018. "Despite Cars Becoming More Powerful, Fuel Economy Is Improving." *CarBuzz*, 23 June 2018. https://carbuzz.com/news/despite-cars-becoming-more-powerful-fuel-economy-is-improving#:~:text=And%20yet%20despite%20the%20fact,on%20data%20analysis%20by%20Edmunds.

Billimoria, S., L. Guccione, M. Henchen, and L. Louis-Prescott. 2018. *The Economics of Electrifying Buildings.* Rocky Mountain Institute. https://rmi.org/insight/the-economics-of-electrifying-buildings/#:~:text=In%20Rocky%20Mountain%20Institute's%20new,time%20to%20support%20grid%20needs

BloombergNEF. 2020. "Hydrogen Economy Outlook 2020" https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

Bows-Larkin, Alice. 2015. "All adrift: aviation, shipping, and climate change policy." *Climate Policy* 15(6): 681–702.

Canada Energy Regulator. 2017. "Market Snapshot: Explaining the high cost of power in northern Canada." Government of Canada. Ottawa, ON. https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2017/market-snapshot-explaining-high-cost-power-in-northern-canada.html

Canada Green Building Council. 2019. *Making the case for building to zero carbon*. https://www.cagbc.org/cagbcdocs/advocacy/Making_the_Case_for_Building_to_Zero_Carbon_2019_EN.pdf

Canadian Utilities Limited. 2020. "ATCO to build Alberta's first hydrogen blending project with ERA support." 21 July 2020. https://www.atco.com/en-ca/about-us/news/2020/122900-atco-to-build-alberta-s-first-hydrogen-blending-project-with-era.html

Carton, W., A. Asiyanbi, S. Beck, H.J. Buck, and J.F. Lund. 2020. "Negative emissions and the long history of carbon removal." Wiley *Interdisciplinary Reviews: Climate Change* (August): e671.

Catlin, J.R., and Y. Wang. 2013. "Recycling gone bad: When the option to recycle increases resource consumption." *Journal of Consumer Psychology* 23(1): 122–127.

CBC. 2017. "Paris to ban all gas-powered cars by 2030." 12 October 2017. https://www.cbc.ca/news/business/paris-gasoline-car-ban-1.4351377

CGTN. 2020. "China calls for global green revolution in the post-COVID era." 24 September 2020. https://news.cgtn.com/news/2020-09-22/Xi-Jinping-China-aims-to-achieve-carbon-neutrality-by-2060-TZX22EfJiE/index.html

City of Vancouver. 2020. "Streets and Transportation: Walk, Bike and Transit." https://vancouver.ca/streets-transportation/walk-bike-and-transit.aspx

Clean Technology Table. 2019. *The Innovation and Competitiveness Imperative: Seizing Opportunities for Growth — Report of Canada's Economic Strategy Tables: Clean Technology*. Innovation, Science and Economic Development Canada. Government of Canada. Ottawa, ON. https://www.ic.gc.ca/eic/site/098.nsf/vwapj/ISEDC_CleanTechnologies.pdf/$file/ISEDC_CleanTechnologies.pdf

Committee on Climate Change. 2019. *Net Zero: The UK's contribution to stopping global warming*. London, U.K. https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

Coulombel, N., V. Boutueil., L. Liu, V. Viguié, and B. Yin. 2019. "Substantial rebound effects in urban ridesharing: Simulating travel decisions in Paris, France." *Transportation Research Part D: Transport and Environment* 71: 110–126.

Cox, E., E. Spence, and N. Pidgeon. 2020. "Public perceptions of carbon dioxide removal in the United States and the United Kingdom." *Nature Climate Change* 10, 744–649.

Crider, J. 2020. "TransAlta Uses Tesla Megapacks to Power WindCharger." *CleanTechnica*, 22 October 2020. https://cleantechnica.com/2020/10/22/transalta-uses-tesla-megapacks-to-power-windcharger/

Davis, S.J., N.S. Lewis, M. Shaner, S. Aggarwal, D. Arent, I.L. Azevedo, S.M. Benson, T. Bradley, J. Brouwer, Y-M. Chiang, C.T.M. Clack, A. Cohen, S. Doig, J. Edmonds, P. Fennell, C.B. Field, B. Hannegan, B.M. Hodge, M.I. Hoffert, E. Ingersoll, P. Jaramillo, K.S. Lackner, K.J. Mach, M. Mastrandrea, J. Ogden, P.F. Peterson, D.L. Sanchez, D. Sperling, J. Stagner, J.E. Trancik, C-J. Yang, and K. Caldeira. 2018. "Net-zero emissions energy systems." *Science 360* no. 6396 (June). https://science.sciencemag.org/content/360/6396/eaas9793

Delucchi, Mark. 2006. *Lifecycle Analyses of Biofuels*. Institute of Transportation Studies. University of California. Davis, CA. https://escholarship.org/uc/item/1pq0f84z

Devlin, A., L. Frank, and J. VanLoon. 2009. *Physical activity and transportation benefits of walkable approaches to community design in British Columbia*. British Columbia Recreation and Parks Association. http://atl.sites.olt.ubc.ca/files/2011/07/BCRPA_Transportation_Study_2009.pdf

Dowling, J.A., K.Z. Rinaldo, T.H. Ruggles, S.J. David, M. Yuan, F. Tong, N.S. Lewis, and K. Caldeira. 2020. "Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems." *Joule* 4(9): 1907–1928. https://doi.org/10.1016/j.joule.2020.07.007

ECCC (Environment and Climate Change Canada). 2016. *Canada's Mid-Century Long-Term Low-Greenhouse Gas Development Strategy.* Government of Canada. Gatineau, QC. https://unfccc.int/files/focus/long-term_strategies/application/pdf/canadas_mid-century_long-term_strategy.pdf

ECCC (Environment and Climate Change Canada). 2019a. "Government of Canada releases emissions projections, showing progress towards climate targets." *Government of Canada*, 20 December 2019. https://www.canada.ca/en/environment-climate-change/news/2019/12/government-of-canada-releases-emissions-projections-showing-progress-towards-climate-target.html

ECCC (Environment and Climate Change Canada). 2019b. *Canada's Fourth Biennial Report on Climate Change*. Government of Canada. Gatineau, QC. https://www4.unfccc.int/sites/SubmissionsStaging/NationalReports/Documents/1687459_Canada-BR4-1-Canada%E2%80%99s%20Fourth%20Biennial%20Report%20on%20Climate%20Change%202019.pdf

ECCC (Environment and Climate Change Canada). 2020a. *A Healthy Environment and a Healthy Economy: Canada's strengthened climate plan to create jobs and support people, communities and the planet*. Government of Canada. Gatineau, QC. https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climate-plan/healthy_environment_healthy_economy_plan.pdf

ECCC (Environment and Climate Change Canada). 2020b. *National Inventory Report 1990–2018: Greenhouse Gas Sources and Sinks in Canada*. Government of Canada. Gatineau, QC. https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory.html

EDC (Export Development Canada). 2020. "Shining a light on Canada's cleantech future." https://www.edc.ca/en/guide/canada-cleantech-future.html#:~:text=Shining%20a%20light%20on%20Canada's,strength%20depends%20on%20export%20sales.&text=Read%20EDC's%20report%20on%20the,in%20this%20growing%20global%20market

Edger, R., C. Howard, M. Lem, J. Zigby, C. Pétrin-Desrosiers, H.M. Doyle, G.T. Kitching, O.D. Luo, A. Cohen, K. Wu, J.J. Kirsh Carson, S.G. Létourneau, and J. Kuhl. 2020. *Healthy Recovery Plan: For a Safe and Sustainable Future*. Canadian Association of Physicians for the Environment. https://cape.ca/wp-content/uploads/2020/07/CAPE_Report2020_EN_HealthyRecoveryPlan.pdf

EESI (Environmental and Energy Study Institute). 2019. "Fact Sheet: The Growth in Greenhouse Gas Emissions for Commercial Aviation." https://www.eesi.org/papers/view/fact-sheet-the-growth-in-greenhouse-gas-emissions-from-commercial-aviation

Electric Mobility Canada. 2020. "Electric Mobility Canada Sales Report 2020 Q1."

Emissions Reduction Alberta. 2020. "Alberta Zero Emissions Truck Electrification Collaboration (AZTEC)." https://eralberta.ca/projects/details/alberta-zero-emissions-truck-electrification-collaboration-azetec/

Energy Transitions Commission. 2020. *Making Mission Possible: Delivering a Net-Zero Economy.* https://www.energy-transitions.org/publications/making-mission-possible/

Ewing, R., and R. Cervero. 2001. "Travel and the Built Environment: A Synthesis." *Transportation Research Record* 1780, no. 1: 87–114.

Fardet, A. and E. Rock. 2020. "Ultra-Processed Foods and Food System Sustainability: What are the Links?" *Sustainability* 12, no. 15: 6280.

Fortis BC. 2020a. "Services: Renewable Natural Gas." https://www.fortisbc.com/services/sustainable-energy-options/renewable-natural-gas

Fortis BC. 2020b. "FortisBC first to purchase Renewable Natural Gas made from wood waste." 30 April 2020. https://www.fortisbc.com/news-events/media-centre-details/2020/04/30/fortisbc-first-to-purchase-renewable-natural-gas-made-from-wood-waste

Frank, L.D., and P.O. Engelke. 2001. "The built environment and human activity patterns: Exploring the impacts of urban form on public health." *Journal of Planning Literature* 16, no. 2 (November). 202–218.

Frenette, E., O. Bahn, and K. Vaillancourt. 2017. "Meat, dairy and climate change: assessing the long-term mitigation potential of alternative agri-food consumption patterns in Canada." *Environmental Modeling & Assessment* 22, no. 1 (February): 1–16.

Fuhrman, J., H. McJeon, P. Patel, S.C. Doney, W.M. Shobe, and A.F. Clarens. 2020. "Food-energy-water implications of negative emissions technologies in a +1.5ºC future." *Nature Climate Change* 10: 920–927. https://doi.org/10.1038/s41558-020-0876-z

Furman, J., R. Shadbegian, and J. Stock. 2015. "The costs of delaying action to stem climate change: A meta-analysis." VOXeu, Centre for Economic Policy Research. https://voxeu.org/article/cost-delaying-action-stem-climate-change-meta-analysis#fn

Garcia-Oliva, F., and O.R. Masera. 2004. "Assessment and Measurement Issues Related to Soil Sequestration in Land-Use, Land-Use Change, and Forestry (LULUCF) Projects under the Kyoto Protocol." *Climate Change* 65: 374–364. https://doi.org/10.1023/B:CLIM.0000038211.84327.d9

Giles-Corti, B., S. Foster, T. Shilton, and R. Falconer. 2010. "The co-benefits for health of investing in active transportation." *New South Wales Public Health* Bulletin 21, no 6 (August): 122–127.

Gould, G., D. McCollum, and D. Greene. 2009. *Greenhouse Gas Emissions from Aviation and Marine Transportation: Mitigation Potential and Policies*. Pew Center on Global Climate Change. https://www.c2es.org/site/assets/uploads/2009/12/ghg-emissions-aviation-marine-transportation-mitigation-potential-policies.pdf

Gouvernement du Québec. 2020. "Plan pour une économie verte 2030." https://www.quebec.ca/en/government/policies-orientations/plan-green-economy/

Government of British Columbia. 2018. *Clean BC*. Government of British Columbia. Victoria, B.C. https://blog.gov.bc.ca/app/uploads/sites/436/2019/02/CleanBC_Full_Report_Updated_Mar2019.pdf

Government of British Columbia. 2020. "Province puts in place rules for 100% electric-vehicle sales by 2040." 30 July 2020. https://news.gov.bc.ca/releases/2020EMPR0031-001416

Government of Canada. 2016. *Working Group on Specific Mitigation Opportunities: Final Report*.

Government of Canada. 2019. "About methane emissions." https://www.canada.ca/en/environment-climate-change/services/climate-change/global-methane-initiative/about-methane-emissions.html

Government of the United Kingdom. 2020. "PM outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs." 18 November 2020. https://www.gov.uk/government/news/pm-outlines-his-ten-point-plan-for-a-green-industrial-revolution-for-250000-jobs

Government of the United States. 2016. *United States Mid-Century Strategy for Deep Decarbonization*. https://unfccc.int/files/focus/long-term_strategies/application/pdf/mid_century_strategy_report-final_red.pdf

Hall, Max. 2019. "Alberta approves Canada's largest PV project — free of subsidy and planned on a merchant basis." *PV Magazine*, 28 August 2019. https://www.pv-magazine.com/2019/08/28/alberta-gives-approval-for-canadas-largest-pv-project/

Hampel, Carrie. 2019. "Sweden to ban sales of fossil-fuel powered cars by 2030." *Electrive*, 22 January 2019. https://www.electrive.com/2019/01/22/sweden-joins-nations-dropping-combustion-engines-target-2030/

Hawken, Paul. 2017. *Drawdown: The most comprehensive plan ever proposed to reverse global warming*. New York, NY: Penguin Books.

Health Canada. 2012. *Human Health Risk Assessment for Biodiesel Production, Distribution and Use in Canada*. Government of Canada. Ottawa, ON. https://www.canada.ca/en/health-canada/services/publications/healthy-living/human-health-risk-assessment-biodiesel-production-distribution-use-canada.html

Health Canada. 2019a. *Health Impacts of Air Pollution in Canada: Estimates of morbidity and premature mortality outcomes*. Government of Canada. Ottawa, ON. http://publications.gc.ca/collections/collection_2019/sc-hc/H144-51-2019-eng.pdf

Health Canada. 2019b. *Human Health Risk Assessment of Diesel Exhaust*. Government of Canada. Ottawa, ON. https://www.canada.ca/en/health-canada/services/publications/healthy-living/human-health-risk-assessment-diesel-exhaust-summary.html

Hill, J., S. Polasky, E. Nelson, D. Tilman, H. Huo, L. Ludwig, J. Neumann, H. Zheng, and D. Bonta. 2009. "Climate change and health costs of air emissions from biofuels and gasoline." *Proceedings of the National Academy of Sciences* 106, no. 6 (February): 2077–2082.

Hoegh-Guldberg, O., D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K.L. Ebi, F. Engelbrecht, J. Guiot, Y. Hijioka, S. Mehrotra, A. Payne, S.I. Seneviratne, A. Thomas, R. Warren, and G. Zhou. 2018. "Impacts of 1.5°C Global Warming on Natural and Human Systems." In *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, eds. V. Masson-Delmotte, P. Zhai, H-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield. Intergovernmental Panel on Climate Change. Geneva. https://www.ipcc.ch/sr15/chapter/chapter-3/

Hoicka, C.E., K. Savic, and A. Campney. 2020. *Reconciliation through renewable energy? Surveying communities, involvement, and Indigenous peoples in Canada*. Working Paper. Toronto, ON: York University.

Husky Energy. 2020. "Lloydminster Ethanol Plant." https://huskygrain.com/lloydminster/lloydminster-ethanol-plant.asp

Hyland, J.J., M. Henchion, M. McCarthy, and S.N. McCarthy. 2017. "The role of meat in strategies to achieve a sustainable diet lower in greenhouse gas emissions: A review." *Meat Science* 132: 189-185. https://doi.org/10.1016/j.meatsci.2017.04.014

ICAO (International Civil Aviation Organization). 2019. *2019 Environmental Report: Aviation and Environment*. ICAO publications. https://www.icao.int/environmental-protection/Documents/ICAO-ENV-Report2019-F1-WEB%20(1).pdf

IEA (International Energy Agency). 2011. "Technology Roadmap: Smart Grids." https://www.iea.org/reports/technology-roadmap-smart-grids

IEA (International Energy Agency). 2019a. "Heat pumps." https://www.iea.org/reports/heat-pumps

IEA (International Energy Agency). 2019b. "Innovation Gaps." https://www.iea.org/reports/innovation-gaps

IEA (International Energy Agency). 2020a. Energy Technology Perspectives. IEA Reports. Paris. https://www.iea.org/reports/energy-technology-perspectives-2020

IEA (International Energy Agency). 2020b. "ETP Clean Energy Technology Guide." https://www.iea.org/articles/etp-clean-energy-technology-guide

IEA (International Energy Agency). 2020c. Aviation. IEA Reports. Paris. https://www.iea.org/reports/aviation

IEA (International Energy Agency). 2020d. Global EV Outlook 2020. IEA Reports. Paris. https://www.iea.org/reports/global-ev-outlook-2020

IISD (International Institute for Sustainable Development). 2017. Costs of Pollution in Canada: Measuring the impacts on families, businesses and governments. IISD publications. Winnipeg, MB. https://www.iisd.org/system/files/publications/costs-of-pollution-in-canada.pdf

IMO (International Maritime Organization). 2020. "Sulphur 2020: cutting sulphur oxide emissions." https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx

Indigenous Caucus Statement. 2020. "Indigenous Peoples Statement on Nature-Based Climate Solutions." Nature-Based Climate Solutions Summit, 5–6 February 2020. https://static1.squarespace.com/static/5dee67fbbfc3d2411199251b/t/5e87db456df85b022533a73a/1585961801593/Indigenous+Caucus+Statement.pdf

Indigenous Clean Energy. 2020. Accelerating Transition: Economic Impacts of Indigenous Leadership in Catalyzing the Transition to a Clean Energy Future Across Canada. https://icenet.work/attachment?file=HGQf2DFTWWhIlc6jcRtUCg%3D%3D

Indigenous Leadership Initiative. 2020. "Indigenous Guardians Program." https://www.ilinationhood.ca/guardians

IPCC (Intergovernmental Panel on Climate Change). 2018. "Summary for Policymakers." In Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, eds. V. Masson-Delmotte, P. Zhai, H-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T.Maycock, M.Tignor, and T. Waterfield. https://www.ipcc.ch/sr15/chapter/spm/

IRENA (International Renewable Energy Agency). 2015. Renewable Energy Options for Shipping: Technology Brief. International Renewable Energy Agency. Abu Dhabi.

IRENA (International Renewable Energy Agency). 2019. Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects. International Renewable Energy Agency. Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf

IRENA (International Renewable Energy Agency). 2020. Renewable Power Generation Costs in 2019. International Renewable Energy Agency. Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf

Israël, B., and E. Flanagan. 2016. Out with the Coal, in with the New: National benefits of an accelerated phase-out of coal-fires power. Pembina Institute. https://www.pembina.org/reports/out-with-the-coal-in-with-the-new.pdf

Jaccard, M., J. Hoffele, and T. Jaccard. 2018. "Global carbon budgets and the viability of new fossil fuel projects." Climate Change 150: 15–28. https://doi.org/10.1007/s10584-018-2206-2

Jaccard, M., R. Murphy, B. Zuehlke and M. Braglewicz. 2019. "Cities and greenhouse gas reduction: Policy makers or policy takers?" Energy Policy 134: 110875. https://doi.org/10.1016/j.enpol.2019.07.011

Jayasundara, Susantha, J.A.D. Ranga Niroshan Appuhamy, Ermias Kebreab, and Claudia Wagner-Riddle. 2016. "Methane and nitrous oxide emissions from Canadian dairy farms and mitigation options: An updated review." Canadian Journal of Animal Science 96 no. 3 (May): 306–331.

Jenkins, J.D., M. Luke, and S. Thernstrom. 2018. "Getting to Zero Carbon Emissions in the Electric Power Sector." Joule 2 no. 12: 2498–2510. https://doi.org/10.1016/j.joule.2018.11.013

Johansson, T.B., A. Patwardhan, N. Nakicenovic, L. Gomez-Echeverri, W.C. Turkenburg, and Global Energy Assessment GEA Council. 2012. GEA, 2012: Global Energy Assessment Toward a Sustainable Future. Cambridge, U.K.: Cambridge University Press.

JWN. 2020. "New future for Alberta bitumen in advanced materials." JWN Energy. https://www.jwnenergy.com/article/2020/1/16/new-future-alberta-bitumen-advanced-materials/

Kampman, N., A. Busch, P. Bertier, J. Snippe, S. Hangx, V. Pipich, Z. Di, G. Rother, J.F. Harrington, J.P. Evans, A. Maskell, H.J. Chapman, and M.J. Bickle. 2016. "Observational evidence confirms modelling of the long-term integrity of CO_2-reservoir caprocks." Nature Communications 7, 12268. http://dx.doi.org/10.1038/ncomms12268

Krechowicz, Dana. 2011. The Effect of Carbon Pricing on Low-Income Households, and Its Potential Contribution to Poverty Reduction. Sustainable Prosperity. https://institute.smartprosperity.ca/sites/default/files/effect-carbon-pricing-low-income-households-and-its-potential-contribution-poverty-reduction.pdf

Lachapelle, U., and D.G. Pinto. 2016. "Longer or more frequent walks: examining the relationship between transit use and active transportation in Canada." Journal of Transport & Health 3, no. 2 (June), 173–180.

Langlois-Bertrand, S., K. Vaillancourt, O. Bahn, L. Beaumier, and N. Mousseau. 2018. *Canadian Energy Outlook 2018: Horizon 2050*. Institut de l'énergie Trottier and e3 Hub. http://iet.polymtl.ca/energy-outlook/

Layzell, D.B., C. Young, J. Lof, J. Leary, and S. Sit. 2020. "Towards Net-Zero Energy Systems in Canada: A Key Role for Hydrogen." *Transition Accelerator* Reports 2, Issue 3. https://transitionaccelerator.ca/towards-net-zero-energy-systems-in-canada-a-key-role-for-hydrogen/

Lelieveld, J., A. Pozzer, U. Pöschl, M. Fnais, A. Haines, and T. Münzel. 2020. "Loss of life expectancy from air pollution compared to other risk factors: a worldwide perspective." *Cardiovascular Research* 116, 11(March), 1910–1917.

Lempert, R., J. Edmonds, T. Wild, M. Binsted, and E. Diringer. 2019. *Pathways to 2050: Alternative scenarios for decarbonizing the U.S. economy*. Center for Climate and Energy Solutions (C2ES). https://www.c2es.org/site/assets/uploads/2019/05/pathways-to-2050-scenarios-for-decarbonizing-the-us-economy-final.pdf

Leyden, Kevin M. 2003. "Social capital and the built environment: the importance of walkable neighborhoods." *American Journal of Public Health* 93, no. 9 (September): 1546–1551.

Litman, Todd. 2015. *Evaluating public transit benefits and costs*. Victoria Transport Policy Institute. https://www.vtpi.org/tranben.pdf

Little Bear, Leroy. 2009. *Naturalizing indigenous knowledge, synthesis paper*. University of Saskatchewan, Aboriginal Education Research Centre, and First Nations Adult and Higher Education Consortium. http://neatoeco.com/iwiseconference.org/wp-content/uploads/2015/08/NaturalizingIndigenousKnowledge_LeroyLittlebear.pdf

Little Bear, Leroy. 2012. "Traditional knowledge and humanities: A perspective by a Blackfoot." *Journal of Chinese Philosophy* 39(4), 518–527.

Lovekin, D., J. Moorhouse, V. Morales, and B. Salek. 2020. *Diesel Reduction Progress in Remote Communities*. Pembina Institute. https://www.pembina.org/pub/diesel-reduction-progress-remote-communities

Lund, Hollie. 2002. "Pedestrian environments and sense of community." *Journal of Planning Education and Research* 21, no. 3 (March): 301–312.

Mai, Trieu, Paige Jadun, Jeffrey Logan, Colin McMillan, Matteo Muratori, Daniel Steinberg, Laura Vimmerstedt, Ryan Jones, Benjamin Haley, and Brent Nelson. 2018. *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States.* National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy18osti/71500.pdf

Makortoff, Kayleena. 2020. "Make climate risk reports mandatory for 480 FTSE firms, say investors." *The Guardian*, 19 October 2020. https://www.theguardian.com/environment/2020/oct/19/call-climate-risk-reports-mandatory-ftse-listed-firms

Manisalidis, I., E. Stavropoulou, A. Stavropoulos, and E. Bezirtzoglou. 2020. "Environmental and Health Impacts of Air Pollution: A Review." *Frontiers in Public Health* 8. https://doi.org/10.3389/fpubh.2020.00014

McKinsey and Company. 2020. "Climate math: What a 1.5-degree pathway would take." *McKinsey Quarterly*, 30 April 2020. https://www.mckinsey.com/business-functions/sustainability/our-insights/climate-math-what-a-1-point-5-degree-pathway-would-take

McLaren, Duncan Peter, David P. Tyfield, Rebecca Willis, Bron Szerszynski, and Nils O. Markusson. 2019. "Beyond 'Net-Zero': a case for separate targets for emissions reduction and negative emissions." *Frontiers in Climate* 1: 4.

Milman, Oliver. 2020. "Carbon capture 'moonshot' moves closer, as billions of dollars pour in." *The Guardian*,. 7 October 2020. https://www.theguardian.com/environment/2020/oct/07/carbon-capture-moonshot-moves-closer-as-billions-of-dollars-pour-in

Ministère de l'environnement et de la lutte contre les changements climatiques. 2019. *Trajectoires de réduction d'émissions de GES du Québec – Horizons 2030 et 2050*. Gouvernement du Québec. Québec City, QC. http://www.environnement.gouv.qc.ca/changementsclimatiques/trajectoires-emissions-ges.pdf

Namazu, Michiko, Don MacKenzie, Hisham Zerriffi, and Hadi Dowlatabadi. 2018. "Is carsharing for everyone? Understanding the diffusion of carsharing services." *Transport Policy* 63 (April): 189–199.

National Research Council of Canada. 2019. "Plant-based protein market: global and Canadian market analysis." Government of Canada. Ottawa, ON. https://nrc.canada.ca/en/research-development/research-collaboration/programs/plant-based-protein-market-global-canadian-market-analysis

Nature United. 2020. "Łutsël K'é Dene First Nation Wins Prestigious Equator Prize for its Work on Thaidene Nëné." 5 June 2020. https://www.natureunited.ca/newsroom/thaidene-nene-equator-prize/#:~:text=%C5%81uts%C3%ABl%20K'%C3%A9%20was%20recognized,Nedh%C3%A9%20(Great%20Slave%20Lake)

Navius Research. 2015. *A Plan for Climate Leadership in British Columbia: Forecasting the Benefits and Costs of Strengthening British Columbia's Greenhouse Gas Policies*. Prepared for Clean Energy Canada. https://cleanenergycanada.org/wp-content/uploads/2018/03/A-Plan-for-Climate-Leadership-in-BC-Final-Oct-27-12pm-2015.pdf

NRCan (Natural Resources Canada). 2016. "Barriers to Individual Participation in Greenhouse Gas Reduction Activities — An Evaluation." Government of Canada. https://www.nrcan.gc.ca/energy/efficiency/communities-infrastructure/transportation/idling/4467

NRCan (Natural Resources Canada). 2017. "Enabling Clean Energy Applications with Canadian Minerals and Metals." Government of Canada. https://www.nrcan.gc.ca/maps-tools-publications/publications/minerals-mining-publications/enabling-clean-energy-applications/19447

NRCan (Natural Resources Canada). 2019a. "Residential Secondary Energy Use (Final Demand) by Energy Source and End Use." Government of Canada. https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=HB&sector=res&juris=00&rn=1&page=0

NRCan (Natural Resources Canada). 2019b. "Aluminum Facts." Government of Canada. https://www.nrcan.gc.ca/science-data/science-research/earth-sciences/earth-sciences-resources/earth-sciences-federal-programs/aluminum-facts/20510

NRCan (Natural Resources Canada). 2020a. *Energy Fact Book 2019–2020.* Government of Canada. https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/energy-factbook_EN-feb14-2020.pdf

NRCan (Natural Resources Canada). 2020b. "Greenhouse Gas Equivalencies Calculator." Government of Canada. https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/calculator/ghg-calculator.cfm

NRCan (Natural Resources Canada). 2020c. "Crude oil facts." Government of Canada. https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/energy-facts/crude-oil-facts/20064

NRCan (Natural Resources Canada). 2020d. "Natural Gas Facts." Government of Canada.https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/energy-facts/natural-gas-facts/20067

NRCan (Natural Resources Canada). 2020e. "The Atlas of Canada — Remote Communities Energy Database." Government of Canada. Ottawa, ON. https://atlas.gc.ca/rced-bdece/en/index.html

NRCan (Natural Resources Canada). 2020f. "Fuel-efficient driving techniques." Government of Canada. Ottawa, ON. https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-transportation/personal-vehicles/fuel-efficient-driving-techniques/21038

NRTEE (National Round Table on the Environment and the Economy). 2011. *Paying the Price: The Economic Impacts of Climate Change for Canada.* Ottawa, ON. https://data.fcm.ca/documents/reports/PCP/paying_the_price_EN.pdf

Office of Governor Gavin Newsom. 2020. "Governor Newsom Announces California Will Phase Out Gasoline-Powered Cars and Drastically Reduce Demand for Fossil Fuel in California's Fight Against Climate Change." 23 September 2020. https://www.gov.ca.gov/2020/09/23/governor-newsom-announces-california-will-phase-out-gasoline-powered-cars-drastically-reduce-demand-for-fossil-fuel-in-californias-fight-against-climate-change/

Passive House Canada. 2020. "Fort St. John 50 Unit Passive House." https://www.passivehousecanada.com/projects/fort-st-john-multi-family-housing/

Phanord-Cadet, M-N., K. Pineault, K. She, A. Sinha, and G. Reed. 2018. *Work in Progress: Empowering Canada's Workforce in the Global Energy Transition*. Public Policy Forum. http://www.actioncanada.ca/wp-content/uploads/2019/03/PPF-Work-in-Progress-EN-March2018.pdf

Phillips 66. 2020. "Phillips 66 Plans to Transform San Francisco Refinery into World's Largest Renewable Fuels Plant." 12 August 2020. https://investor.phillips66.com/financial-information/news-releases/news-release-details/2020/Phillips-66-Plans-to-Transform-San-Francisco-Refinery-into-Worlds-Largest-Renewable-Fuels-Plant/default.aspx

Reisinger, Andy, Harry Clark, Ross Abercrombie, Mark Aspin, Peter Ettema, Mark Harris, Andrew Hoggard, Matthew Newman, and Greg Sneath. 2018. *Future options to reduce biological GHG emissions on-farm: critical assumptions and national-scale impact.* Report to the Biological Emissions Reference Group (BERG).

Sanderson, B.M., and B.C. O'Neill. 2020. "Assessing the costs of historical inaction on climate change." *Scientific Reports* 10, no. 9173 (2020). https://doi.org/10.1038/s41598-020-66275-4

Sawyer, D. 2020. "Canada's performance in six key areas of clean-energy exports is growing three times faster than all other product exports." *Policy Options*, 17 November 2020. https://policyoptions.irpp.org/magazines/november-2020/canadas-clean-energy-gazelles-are-outperforming-fossil-fuels/

Sawyer, D., R. Ness, D. Clark, and D. Beugin. 2020. *Tip of the Iceberg: Navigating the Known and Unknown Costs of Climate Change for Canada.* Canadian Institute for Climate Choices. https://climatechoices.ca/reports/tip-of-the-iceberg/

Sepulveda, N.A., J.D. Jenkins, F.J. de Sisternes, and R.K. Lester. 2018. "The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation." *Joule* 2, no. 11: 2403–2420. https://doi.org/10.1016/j.joule.2018.08.006

Shell. 2018. *Sky: Meeting the Goals of the Paris Agreement*. Shell Scenarios. https://www.shell.com/promos/business-customers-promos/download-latest-scenario-sky/_jcr_content.stream/1530643931055/eca19f7fc0d20adbe830d3b0b27bcc9ef72198f5/shell-scenario-sky.pdf

Sims R., R. Schaeffer, F. Creutzig, X. Cruz-Núñez, M. D'Agosto, D. Dimitriu, M.J. Figueroa Meza, L. Fulton, S. Kobayashi, O. Lah, A. McKinnon, P. Newman, M. Ouyang, J.J. Schauer, D. Sperling, and G. Tiwari. 2014. "Transport." In *Climate change 2014: Mitigation of climate change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, eds. O. Edenhofer et al. Cambridge and New York: Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf

Soltanzadeh, M., and A. Hakami. 2020. *Air quality health co-benefits of CO_2 reductions in various decarbonization pathways*. Canadian Institute for Climate Choices. https://climatechoices.ca/wp-content/uploads/2020/12/Air-Quality-Health-Co-benefits-o[...]eductions-in-Various-Decarbonization-Pathways-Nov-2020-2.pdf

St-Louis, E., K. Manaugh, D. van Lierop, and A. El-Geneidy. 2014. "The happy commuter: A comparison of commuter satisfaction across modes." *Transportation Research Part F: Traffic Psychology and Behaviour* 26 (September): 160–170.

Statistics Canada. 2017. "Journey to work: Key results from the 2016 Census." Government of Canada. https://www150.statcan.gc.ca/n1/en/daily-quotidien/171129/dq171129c-eng.pdf?st=6EI_Dgrq

Statistics Canada. 2020. "One in ten Canadian households living in core housing need in 2018." Government of Canada. https://www150.statcan.gc.ca/n1/daily-quotidien/201002/dq201002a-eng.htm

Suncor. 2020. "Biofuels." https://www.suncor.com/en-ca/about-us/biofuels

Thamo, T., and D.J. Pannell. 2016. "Challenges in developing effective policy for soil sequestration: perspectives on additionality, leakage, and permanence." *Climate Policy* 16, no. 8: 973–992. https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.1080%2F14693062.2015.1075372

The Economist. 2020. "Not so choppy: How covid-19 put wind in shipping companies' sails." 10 October 2020. https://www.economist.com/business/2020/10/10/how-covid-19-put-wind-in-shipping-companies-sails

Thirgood, J., S. McFatridge, M. Marcano, and J. Van Ymeren. 2017. *Decent Work in the Green Economy*. Mowat Centre for Policy Innovation. https://munkschool.utoronto.ca/mowatcentre/decent-work-in-the-green-economy/

Thomas, Gregory O., Ian Walker, and Charles Musselwhite. 2014. "Grounded Theory analysis of commuters discussing a workplace carbon-reduction target: Autonomy, satisfaction, and willingness to change behaviour in drivers, pedestrians, bicyclists, motorcyclists, and bus users." *Transportation Research Part F: Traffic Psychology and Behaviour* 26 (September): 72–81.

Townsend, J., F. Moola, and M-K. Craig. 2020. "Indigenous Peoples are critical to nature-based solutions to climate change." *iPolitics*, 26 October 2020. https://ipolitics.ca/2020/10/26/indigenous-peoples-are-critical-to-nature-based-solutions-to-climate-change

Transport Canada. 2011. *Active Transportation in Canada: A Resource and Planning Guide*. Government of Canada. Ottawa, ON. http://www.missionridesbikes.org/uploads/8/1/8/0/81809998/active_transporation_guide.pdf

Trottier Energy Futures Project. 2016. *Canada's Challenge and Opportunity: Transformations for major reductions in GHG emissions*. Trottier Family Foundation, The Canadian Academy of Engineering, and David Suzuki Foundation. https://davidsuzuki.org/wp-content/uploads/2017/09/REPORT-canada-challenge-opportunity-transformations-major-reductions-GHG-emissions.pdf

Tsiropoulos, I., W. Nijs, D. Tarvydas, and P. Ruiz. 2020. *Towards net-zero emissions in the EU energy system by 2050*. European Commission. https://www.buildup.eu/sites/default/files/content/toward1.pdf

U.S. Department of Energy. 2020. "Grid Modernization and the Smart Grid." https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid

Vivid Economics. 2020. *An investor guide to negative emissions technologies and the importance of land use*. https://www.unpri.org/download?ac=11980

World Health Organization. 2016. *Ambient air pollution: A global assessment of exposure and burden of disease*. https://apps.who.int/iris/bitstream/handle/10665/250141/9789241511353-eng.pdf

Wynes, Seth, and Kimberly A. Nicholas. 2018. "Reply to Second comment on 'The climate mitigation gap: education and government recommendations miss the most effective individual actions.'" *Environmental Research Letters* 13, no. 6 (July): 068002.

ACKNOWLEDGEMENTS

STAFF AUTHORS

Jason Dion, Mitigation Research Director, Canadian Institute for Climate Choices

Anna Kanduth, Research Associate, Canadian Institute for Climate Choices

Jeremy Moorhouse, Senior Research Associate, Canadian Institute for Climate Choices

Dale Beugin, Vice President Research and Analysis, Canadian Institute for Climate Choices

MITIGATION EXPERT PANEL WORKING GROUP

Louis Beaumier, Directeur exécutif, Institut de l'énergie Trottier

Kathryn Harrison, Professor of Political Science, University of British Columbia

Mark Jaccard, Director and Distinguished Professor, School of Resource and Environmental Management, Simon Fraser University

David Layzell, Director, Canadian Energy Systems Analysis Research (CESAR), University of Calgary

Justin Leroux, Associate Professor of Economics, HEC Montreal

Nancy Olewiler, Professor, School of Public Policy, Simon Fraser University

Catherine Potvin, Canada Research Chair, Climate Change Mitigation and Tropical Forests, McGill University

Nicholas Rivers, Canadian Research Chair, Climate and Energy Policy, University of Ottawa

Jennifer Winter, Assistant Professor, Department of Economics and Scientific Director, Energy and Environmental Policy Research Division, University of Calgary

EXTERNAL REVIEWERS

Sarah Burch, Canada Research Chair in Sustainability Governance and Innovation, University of Waterloo

Ron Mock, Past President and CEO, Ontario Teachers Pension Plan Board

Graeme Reed, PhD Candidate, University of Guelph

Blake Shaffer, Assistant Professor, Department of Economics and School of Public Policy, University of Calgary

OTHER REVIEW AND GUIDANCE

Jonathan Arnold, Senior Research Associate, Canadian Institute for Climate Choices

Audrey Aubertin, Master's Candidate, Resource and Environmental Management (REM), School of Resource and Environmental Management, Simon Fraser University

Chris Bataille, Senior Researcher, Institut du Développement Durable et des Relations Internationales (IDDRI); Adjunct professor, Simon Fraser University Faculty of the Environment

Alicia Campney, Research Assistant, Canadian Institute for Climate Choices

Dylan Clark, Senior Research Associate, Canadian Institute for Climate Choices

Caroline Lee, Senior Research Associate, Canadian Institute for Climate Choices

Melina Laboucan-Massimo, Just Transition Director at Indigenous Climate Action and research fellow at the David Suzuki Foundation

James Meadowcroft, Professor of Political Science and Public Policy, Carleton University

Katherine Monahan, Engagement Manager, Vivid Economics.

Rachel Samson, Clean Growth Research Director, Canadian Institute for Climate Choices

Dave Sawyer, Principal Economist, Canadian Institute for Climate Choices

Maria Shallard, Senior Advisor, Indigenous Engagement and Research, Canadian Institute for Climate Choices

Chris Turner, Author and Energy Communications Strategist

PRODUCTION SUPPORT

Design and layout: Laurie Barnett, Graphic Designer

Proofreading: Julie Stauffer, Cadmium Red Communications (English); Edith Sans Cartier (French)

Information design by Voilà: chezVoila.com

Figure 18 photo: Jens Johnsson on Unsplash

Translation: Edgar (report text) and Sabine Monnin (figures)

Cover design: Alex Wittholz

Cover photography: Paul Zizka, a kayaker on Goat Pond, AB

Recommended citation:
Dion, J., A. Kanduth, J. Moorhouse, and D. Beugin. 2021. Canada's Net Zero Future: Finding our way in the global transition. Canadian Institute for Climate Choices.

This project was undertaken with the financial support of:

Environment and Climate Change Canada | Environnement et Changement climatique Canada