Environment and Climate Change Canada / Environnement et Changement climatique Canada

Exploring Approaches for Canada's Transition to Net-Zero Emissions

Canada's Long-Term Strategy Submission to the United Nations Framework Convention on Climate Change

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Canada

Executive Summary

Rigorous science underpins global concern about climate change, our understanding of the increasing risk that climate change poses to individuals, businesses and communities in Canada and around the world, and the corresponding need to reduce emissions to net-zero. Leaders around the world agree on the need to move towards a net-zero emissions future. The 2022 G7 communiqué included a commitment for countries to submit a net-zero emissions aligned Long Term Strategy (LTS) to the United Nations Framework Convention on Climate Change (UNFCCC) ahead of COP27. In submitting this document, *Exploring Approaches for Canada's Transition to Net-Zero Emissions*, Canada is fulfilling its commitment to submit a net-zero emissions aligned LTS to the UNFCCC.

With less than a decade left to 2030, and with countries around the world racing to achieve the jobs, investment, and security that comes with a low-carbon economy, Canada is laying the foundation to support an affordable, reliable, and sustainable transition to 2050. This includes adopting a 2030 greenhouse gas (GHG) emissions reduction target of 40-45 per cent below 2005 levels as Canada's enhanced Nationally Determined Contribution (NDC).

Data show that Canada's efforts to reduce emissions and achieve its 2030 NDC are making an impact. In 2015, Canada's emissions were on a steep climb and projected to be 12 per cent above 2005 levels by 2030. However, Canada has been able to reverse the upward trend of emissions. According to the 2022 National Inventory Report, Canada's greenhouse gas emissions decreased to 672 megatonnes (Mt) of carbon dioxide equivalent in 2020[1] , representing a net decrease of 69 Mt (or 9.3 per cent) from 2005. With current and future measures in place, emissions are projected to be about 40 per cent below 2005 levels by 2030.

In June 2021, the *Canadian Net-Zero Emissions Accountability Act* (the Act) received Royal Assent, legislating Canada's 2030 NDC and target of net-zero emissions by 2050. To improve transparency and accountability as Canada works to achieve these commitments, the Act codifies the process for setting national emissions reduction targets every 5 years and introduces planning and reporting mechanisms to achieve those targets up to 2050. The Act also establishes the Net-Zero Advisory Body, which will provide the Minister of Environment and Climate Change with independent advice with respect to achieving net-zero emissions by 2050. In March 2022, Canada released its climate plan – the 2030 Emissions Reduction Plan (ERP) – which provides a detailed sector-by-sector road map that identifies the measures and strategies needed for

[1] The year 2020 was marked by the COVID-19 pandemic, coinciding with a decrease in emissions of 66 Mt or 8.9% across numerous sectors. Notable examples include Transport (-27 Mt or -12%) largely due to fewer kilometers driven and a decrease in air traffic; and Public Electricity and Heat Production (-7.4 Mt or -11%) due to decreased coal consumption partially offset by an increase in natural gas consumption.

Canada to reach its 2030 emissions target and put in the place building blocks to achieving net-zero emissions by 2050.

There are many potential pathways for Canada to achieve net-zero emissions. Canada's LTS is a technical analysis that leverages economic modelling to explore different approaches to Canada's transition to net-zero emissions by 2050. Canada's LTS is not a climate plan – it is a depiction of various future scenarios that can complement Canada's existing climate plans, and support future emissions reduction plans to be developed pursuant to the Act.

The LTS presents illustrative scenarios that consider key enabling conditions that could play an important role in reducing emissions across all sectors of the economy: widespread electrification, increased use of renewable and alternative fuels, and increased use of engineered CO_2 removal technologies, such as carbon capture and storage (CCS) technologies. While this report is aligned with the 2030 ERP, it is not policy prescriptive, and does not identify the range of policies, measures and regulations that would be undertaken. The Government of Canada will continue to engage with partners, stakeholders, Canadians and experts, including the Net-Zero Advisory Body, to define Canada's pathway to reach net-zero emissions by 2050. Canada submits this report to the UNFCCC under the premise that the content of the report will continue to be updated and adjusted as Canada advances toward a net-zero emissions economy. Pursuant to the Act, Canada will also develop detailed emissions reduction plans for each national GHG emissions reduction target, including one by the end of 2045 for its target of net-zero emissions in 2050.

While the LTS is focused on climate change mitigation, adaptation is also a key objective under the Paris Agreement. Canada has joined other parties in committing to strengthened cooperation to enhance adaptation efforts, build resilience, and reduce vulnerability to climate change. Ongoing efforts to advance this commitment, underpinned by numerous scientific analyses,[2] include the development of Canada's first National Adaptation Strategy, which is set to be released in Fall 2022.

[2] Canada in a Changing Climate

1. The Net-Zero Emissions Imperative

To avoid the worst impacts of climate change, there is an urgent need to move towards a global net-zero emissions economy. According to the IPCC report *Climate Change 2022: Impacts, Adaptation, and Vulnerability*, at current rates, global warming of 1.5°C will likely be reached between 2030 and 2052. Achieving deep emissions reductions by 2030 and net-zero emissions by 2050 is key to limit warming to 1.5°C and avert severe climate-related risks. The impacts of climate change are particularly strong in Canada, as Canada is warming at twice the global average, with Canada's North warming three times as fast. The effects of widespread climate change are already evident in many parts of Canada, and are projected to intensify in the future, including more frequent and severe weather extremes.

> **What does net-zero emissions mean?**
>
> Net-zero emissions means that any GHG emissions released into the atmosphere are offset by carbon dioxide removals. Removals can include natural carbon sinks such as wetlands and forests, or sequestration using emerging technologies like carbon capture, use and storage (CCUS).

In response to the scientific evidence on the need to act, as well as the significant economic opportunities[3] a low-carbon economy presents, momentum for increased global climate action continues to build among governments, businesses, and individuals with more and more countries making net-zero emissions commitments to keep global warming below 1.5°C. To play its part, Canada has joined over 130 countries, including all other G7 and G20 nations, and a host of Canadian municipalities, Indigenous communities, and businesses in committing to achieve net-zero emissions by 2050.

Canada has adopted a 2030 emissions reduction target of 40-45 percent below 2005 levels as its Nationally Determined Contribution (NDC), and announced significant new investments and measures to help achieve this result. Canada has also enshrined its 2030 and 2050 climate targets in federal law, establishing robust accountability structures, including reporting obligations, to support the achievement of these goals.

Actions to date on climate change put Canada on a path to net-zero emissions by 2050 and achieving the goals of the Paris Agreement, while also making Canada's economy stronger and more competitive. Decarbonizing Canada's economy offers many new opportunities in emerging clean technology industries. For example, the International Energy Agency estimates that emerging technologies may be needed for up to half of the emissions reductions required to achieve net-zero emissions by 2050.

The transition also presents opportunities to increase the competitiveness of traditional sectors in a global decarbonized economy, and Canada is well positioned to leverage

[3] According to Clean Energy Canada, the clean energy sector's GDP is forecast to grow 58% by 2030 (the fossil fuels sector will grow only 9%) and will make up 29% of Canada's total energy GDP, up from 22% in 2020. Economic activity and employment in Canada's clean technology industry are forecast to rise by roughly 50% over the next eight years and by 2025, the sector's contribution to Canada's GDP is expected to grow to $80 billion from $26 billion in 2016.

these opportunities through its existing expertise in the natural resource sector. The transition to a cleaner future will bring new, dynamic opportunities across the labour force, but also changes. Ensuring a people-centered approach where workers have the skills, training, and supports they need to move to new opportunities will be critical, as will ensuring that underrepresented groups, communities, and Indigenous Peoples in Canada are actively involved in the development of transition plans. In addition, supporting opportunities for Canadians who have traditionally faced barriers to employment in resource sectors, such as women, racialized Canadians, people with disabilities, and the 2SLGBTQ+ community, is paramount.

There is no one-size-fits-all solution for achieving net-zero emissions. Different regions, sectors and groups will have their own pathways that reflect their unique circumstances. Developing concrete, just, and achievable pathways to net-zero emissions that leave no one behind will require continued engagement and collaboration with provinces, territories, Indigenous Peoples, industry, stakeholders, and civil society – reflecting input from independent experts, the latest science, and Indigenous Knowledge.

Indigenous Knowledge and the United Nations Declaration on the Rights of Indigenous Peoples

Indigenous Peoples in Canada have been at the forefront of the impacts of climate change. Many Indigenous leaders have reinforced the need to take action to reduce pollution, to adapt to the impacts of climate change, and to improve the ways in which the natural environment is respected and protected. In doing so, Indigenous leadership and knowledge have an important place in meeting Canada's climate objectives, including achieving net-zero emissions by 2050. The Government of Canada supports the *United Nations Declaration on the Rights of Indigenous Peoples* (*UN Declaration*), and supports Indigenous approaches and ways of doing by acknowledging Indigenous Knowledge systems as an equal part in policy development, programs, and decision-making. Canada has an ongoing commitment to improve the reflection of the *UN Declaration* in all of its policy and programming and to work with Indigenous partners to better support their climate priorities. *The Canadian Net-Zero Emissions Accountability Act* also requires that Canada take into account Indigenous Knowledge when setting emission reduction targets, as well as consider the *UN Declaration* in the establishment of emission reduction plans.

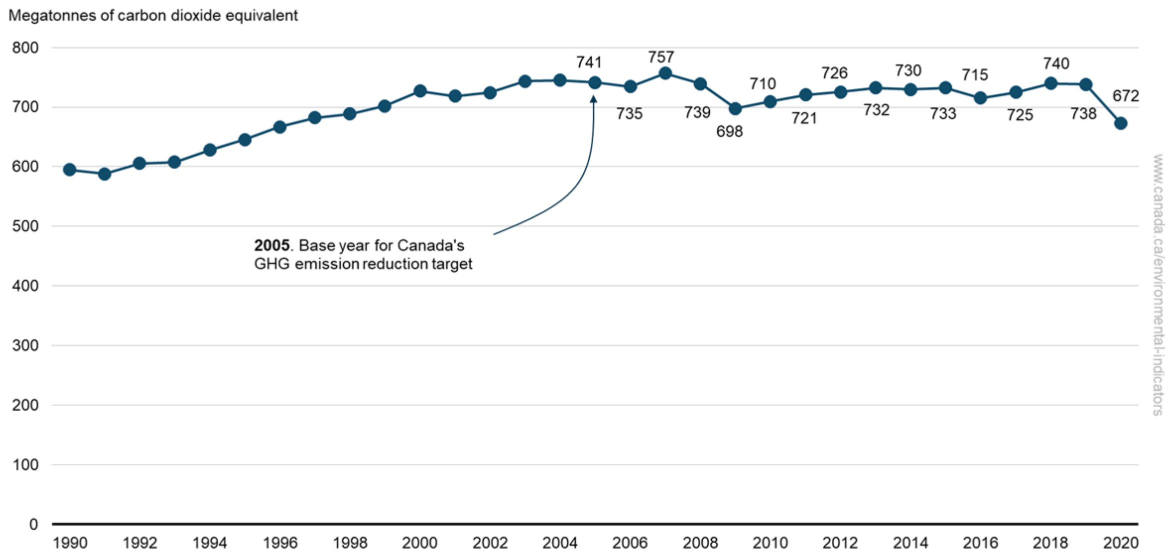
Role of Science in Achieving Net-Zero Emissions by 2050

Building scientific knowledge and reflecting new understanding is essential to inform ambitious action, measure progress and refine climate actions. Environment and Climate Change Canada is leading the development of Canada's first National Climate Change Science & Knowledge Plan, set for publication in late 2022. The Plan will identify priority science research and knowledge synthesis activities for investment that will deliver results over the next 5 to 10 years. These will enable progress on longer-term science challenges related to understanding how future warming will affect planned infrastructure improvements and renewable energy, technological and nature-based solutions, and will emphasize the science challenges and priorities to inform the transformational changes needed to reach 2050 objectives. Scientific advancements in Canada are also leading to enhanced climate modelling capability that will allow detailed simulation of carbon sources and sinks in both managed and natural landscapes, and in the coastal ocean. This reflects the growing scientific capability to model the carbon cycle and freshwater resource impacts to understand the potential magnitude of carbon sinks in mitigation planning and sustainability in natural resource sector operations. The development of atmospheric GHG observations is creating opportunities to complement National Inventory Reporting, with ongoing improvements in estimating emissions, their levels, location and change over time in Canada. To strengthen the science underpinning GHG emissions reporting as part of the *Canadian Net-Zero Emissions Accountability Act*, there is opportunity to align investment and capacity in research and monitoring, to mobilize available information on emission sources, sinks, capture and storage, and pace of reductions in Canada, commensurate with ambition of the targets. Enhancing the nationally coordinated strategic science effort will continue to leverage existing and future national science capacity.

Canada's current emissions profile and historical trends provide guidance on where Canada's emissions need to be by 2030 and 2050. In 2015, Canada's emissions were on a steep climb and projected to be 12 per cent above 2005 levels by 2030. However, Canada has been able to reverse the upward trend of emissions. According to the 2022 National Inventory Report, Canada's greenhouse gas emissions decreased to 672 megatonnes of carbon dioxide equivalent in 2020[4] , representing a net decrease of 69 Mt (or 9.3 per cent) from 2005 and, with current and future measures in place, are projected to be about 40 per cent below 2005 levels by 2030.

[4] The year 2020 was marked by the COVID-19 pandemic, coinciding with a decrease in emissions of 66 Mt or 8.9% across numerous sectors. Notable examples include Transport (-27 Mt or -12%) largely due to fewer kilometres driven and a decrease in air traffic; and Public Electricity and Heat Production (-7.4 Mt or -11%) due to decreased coal consumption partially offset by an increase in natural gas consumption.

Greenhouse Gas Emissions, Canada, 1990 to 2020



Source: NIR, 2022

As Canada works to achieve its 2030 NDC, it is also exploring pathways to support emissions reductions, clean growth, and a just and inclusive net-zero emissions future. The LTS builds on the 2016 *Mid-Century Strategy*, reaffirms Canada's commitment to realizing net-zero emissions by 2050 and explores potential approaches to get there.

Canada's 2016 Mid-Century Strategy

In November 2016, Canada submitted its Mid-Century Strategy (MCS) to the UNFCCC, making it one of the first countries to articulate its long-term, deep decarbonization considerations under the Paris Agreement. Informed through engagement with Canadian experts, the Mid-Century Strategy outlined various non-policy prescriptive pathways to a low-carbon economy by 2050, while acknowledging areas where emissions reductions will be more challenging. For the purpose of the Mid-Century Strategy, Canada examined various pathways to achieve an illustrative 80 per cent reduction in GHG emissions from 2005 levels and identified key building blocks that remain relevant in the context of net-zero emissions planning, including:

- Electrification of end-use applications and clean electricity generation;
- Energy efficiency and demand-side management;
- Abatement of non-carbon dioxide GHGs such as methane and hydrofluorocarbons;
- Sequestration from Canada's forests and lands; and,
- The role of innovation, a scale up of research, development and deployment (RD&D), and private sector investment in easing the transition to a low-carbon economy.

As a key milestone to achieving net-zero emissions by 2050, Chapter 2 of this document presents Canada's current approach to meeting its enhanced 2030 NDC, including the measures and strategies recently announced in Canada's 2030 Emissions Reduction Plan (ERP). Chapter 3 examines four potential modelled scenarios to net-zero emissions by 2050, reflecting three enabling conditions that will influence every sector of the economy—electrification, increased use of renewable and alternative fuels, and engineered CO_2 removal technologies. These scenarios are illustrative, reflect Canada's current understanding of technological capabilities and progress, and will focus on the sectoral impacts of the different emissions pathways. Chapter 3 also highlights the mechanisms in place to ensure Canada remains transparent and accountable as it works toward net-zero emissions by 2050.

Communicating Canada's Progress on Climate Change: Canada's LTS vs Biennial Reports

Communicating Canada's progress toward climate goals is important in demonstrating transparency to support global ambition under the Paris Agreement. Canada's LTS, shows illustrative approaches to 2050 based on modelled scenarios, and builds off Canada's current projected pathway to 2030 through actions outlined in the 2030 ERP. This approach is called for in the Paris Agreement in Article 4.19. Updates on Canada's emissions trends and projections, detailed information on existing policies and measures that support climate mitigation and updates of National GHG inventories are communicated periodically through Canada's Biennial Reports on Climate Change and fulfill Canada's reporting requirements to the UNFCCC as a signatory to the Paris Agreement. Canada will be submitting its next Biennial Report to the UNFCCC in December 2022.

2. Canada's 2030 Net-Zero Emissions Foundation: 2030 Emissions Reduction Plan

Actions to Date

Canada has a strong foundation in place to achieve net-zero emissions by 2050. Efforts to date across Canada's climate plans since 2016 – including the more than 100 climate measures and $120 billion in climate action investments committed over that time – and collective action from all levels of government, Indigenous Peoples, industry, and civil society has enabled Canada to bend the curve of its emissions trajectory downwards. The following section highlights key areas of progress.

Pan-Canadian Framework on Clean Growth and Climate Change

Canada's first-ever national climate plan, the Pan-Canadian Framework on Clean Growth and Climate Change (PCF), was adopted in 2016 – just after the release of the Mid-Century Strategy. The PCF was developed in collaboration with Canada's provinces and territories, and in consultation with national Indigenous organizations and representatives, industry stakeholders, and Canadians. The PCF is comprised of over 50 joint and individual measures, and introduced key pillars of Canada's approach to reducing emissions, such as introducing a price on carbon pollution.

Driven by measures in the PCF alone, Canada's emissions were projected to be 19 per cent below 2005 levels by 2030 (227 Mt decrease). The measures in the PCF remain central to Canada's efforts to reduce emissions by 2030, help build resilience across the country, and support the development of the clean technology needed for clean economic growth. Progress on implementation of these measures has been reported annually since the release of the PCF through Synthesis Reports.

A Healthy Environment and a Healthy Economy – Canada's Strengthened Climate Plan

In December 2020, Canada introduced a strengthened federal climate plan – A Healthy Environment and a Healthy Economy. This strengthened climate plan detailed a series of commitments that build on PCF measures to reduce emissions to 31 per cent below 2005 levels by 2030.

The plan also includes commitments to further green Canada's government operations, work to make Canada more resilient to its changing climate, partner with Indigenous Peoples in Canada as well as provincial and territorial governments, and collaborate with international partners.

Canada’s Enhanced Nationally Determined Contribution

In July 2021, shortly after the passage of the *Canadian Net-Zero Emissions Accountability Act*, Canada submitted its enhanced NDC of 40-45 per cent below 2005 levels by 2030 to the UNFCCC. This enhanced target reflects the best available science, and is consistent with the results of a survey of Canadians in which the vast majority of respondents called for increased climate ambition for 2030. Canada’s enhanced NDC submission reflects input received from provincial and territorial governments, as well as from First Nations, Inuit, and the Métis Nation. Canada is among the first countries to include substantive input from subnational bodies and Indigenous Peoples into its NDC submission.

2030 Emissions Reduction Plan: Clean Air, Strong Economy

The 2030 Emissions Reduction Plan: Clean Air, Strong Economy, serves as a roadmap that outlines a sector-by-sector path for Canada to reach its emissions reduction target of 40-45 per cent below 2005 levels by 2030, and lays the groundwork to net-zero emissions by 2050.

The 2030 ERP reflects input from over 30,000 Canadians, provinces and territories, Indigenous Peoples, and the Net-Zero Advisory Body. It is designed to be evergreen, and will identify and respond to new opportunities as governments, businesses, non-profits, and communities across Canada work to reach the 2030 target.

The following section summarizes Canada’s approach to meeting its 2030 NDC, as outlined in the 2030 ERP.

CANADA'S EMISSIONS REDUCTION PLAN FOR 2030 AND PATHWAY TO 2050

Buildings

Transitioning Canada's building stock to net-zero over the long term creates new opportunities to promote a low-carbon supply chain, adopt net-zero ready building codes, transform space and water heating, improve affordability through energy efficiency, and accelerate private financing and workforce development to support transition.

Electricity

Working towards net-zero electricity by 2035 will expand non-emitting energy across Canada, connect regions to clean power, and foster more clean, reliable, and affordable electricity supply. It will also help reduce emissions from other sectors, such as industry, buildings, and transportation.

Heavy Industry

Emissions reductions will come from efforts to decarbonize large emitters, and strengthening Canada's mining sector. Enhancing clean growth in the sector will create new job opportunities, enhance Canada's industrial low-carbon advantage in global markets, and create investment opportunities in Canadian clean technology.

Oil and Gas

There is an opportunity to transform the sector into the cleanest global oil and gas producer, while also moving to provide low-carbon and non-emitting energy products and services in a manner that will ensure economic competitiveness, prosperity, and create good jobs for Canadians.

Transportation

Actions to reduce emissions will enable cleaner public transit, more active transportation, make ZEVs more affordable and accessible, and provide cleaner modes of air, marine, and rail travel. Efforts will also create new jobs in areas like ZEV manufacturing and public transit construction.

Agriculture

Enhancing climate action will create opportunities to leverage agricultural lands to store carbon, stimulate the adoption of new, clean technologies on farms, and support farmers in adopting greener, on-farm practices to reduce emissions.

Waste

Decreasing emissions from waste brings new opportunities for job creation and local economic transformation. Moving towards a circular economy can also increase the value of waste emissions through transforming raw material into fertilizers and renewable energy.

Nature-Based Solutions

Efforts to protect, manage, and restore Canada's lands and waters will reduce emissions while bringing co-benefits to society, like cleaner air, better climate resilience and protection for communities from climate risk, and more opportunity for Canadians to enjoy nature.

Economy-Wide

Economy-wide strategies to reduce emissions, like carbon pricing, clean fuels, and reducing methane emissions, will enable Canada to reduce emissions in the most flexible and cost-effective way. They will also provide policy certainty to businesses and Canadians, allowing everyone to make more informed decisions as Canada's economy decarbonizes.

Clean Tech and Climate Innovation

Actions to advance Canadian clean technology and innovation will not only help to reduce emissions, but will allow Canada to secure a foothold in the rapidly growing global clean tech market, and create jobs and investment opportunities across the economy, from emerging high-tech industries to longstanding sectors like energy, resource development, and manufacturing.

Sustainable Finance

Enhancing sustainable finance will leverage the expertise of Canada's financial sector to crowd-in and guide the private sector capital needed to finance the transition to a net-zero emissions economy, as well as promote financial stability related to climate risk.

Skills and People-Centred Transition

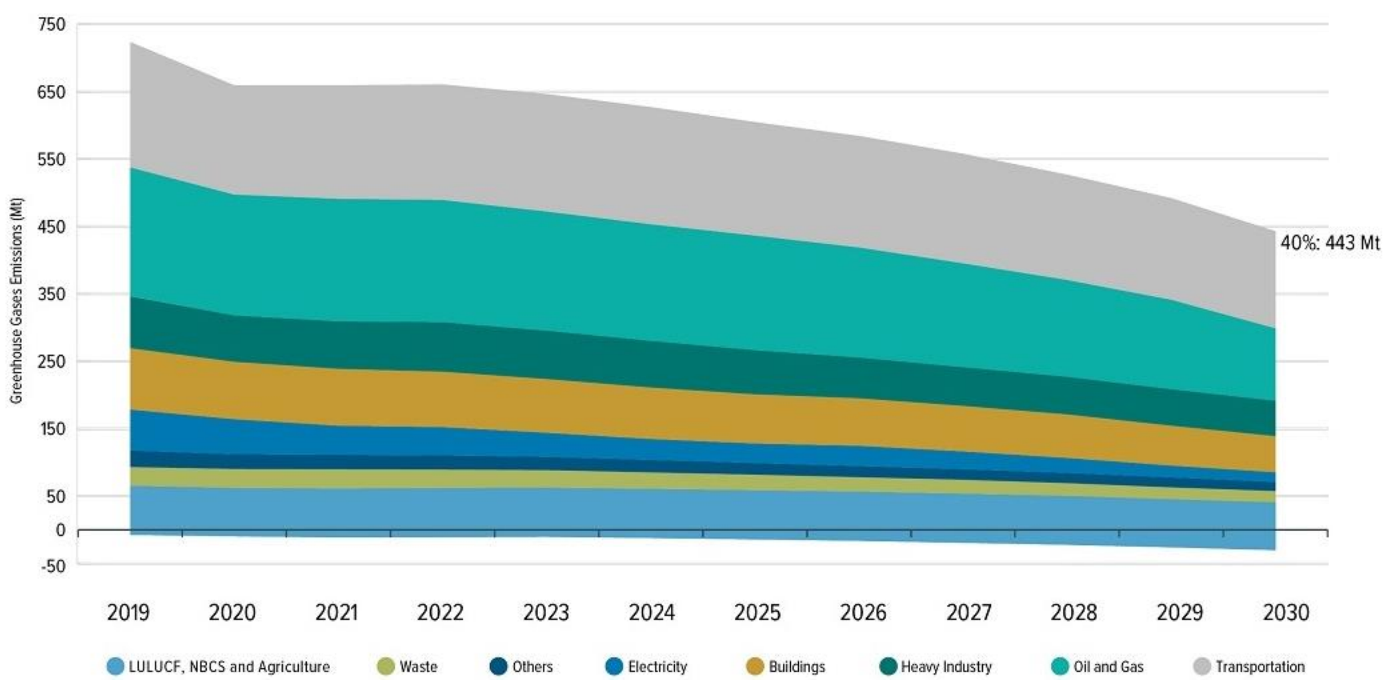
Taking action to reduce emissions will position Canada and Canadians to become leaders in clean energy, clean technology, natural resources management, nature-based solutions, agri-food, and more. This will mean opportunities for workers to obtain new jobs and start new businesses, and to enhance their skillsets to be on the leading edge of the global transition to a net-zero emissions economy. Transitioning to sustainable jobs is also an opportunity to advance equity, inclusion, and justice, and address current barriers to underrepresentation in certain industries.

Canada's Projections to 2030

Broken down by sector, Canada's pathway to 2030 is based on today's understanding of the potential for each sector to reduce emissions by 2030. Given the economic interactions and interdependencies within and between sectors, the exact areas for emissions reduction potential may shift in the future as Canada further decarbonizes.

Canada's 2030 trajectory is indicative of where there is emissions reduction potential in sectors to make additional progress. It is important to note that pathways are not sectoral targets, but projected sectoral contributions. The emissions reductions ultimately contributed by each sector will likely vary over time as Canada responds to real-world changes, such as other countries implementing their climate plans and changes in global demand for oil and natural gas.

Pathway to 2030



Potential reductions presented for each sector, in the chart above and table below, represent only one possible pathway to achieving the 2030 target, using a model-based approach that considers the most economically efficient way to achieve the lower bound of Canada's 2030 target. This offers an illustrative understanding of how emissions reductions could be distributed across sectors. Other important factors, such as operational feasibility, labour availability, and enabling infrastructure, which cannot be modelled, will also influence, and could limit, Canada's trajectory to 2030 by sector.

Over the same period, enhanced climate ambition from provinces and territories, Indigenous Peoples, municipalities, industry, the financial sector, and others could drive further reductions and allow Canada to meet and exceed the upper bound of its 2030 target and lay an even stronger foundation for net-zero emissions by 2050.

Table 1: 2030 ERP Projected Sectoral Contributions[5]

Sector	Where we were in 2005 (Mt)	Where we were in 2019 (Mt)	Where we could be in 2030 (Mt)	Per Cent Reductions from 2005 levels*
Buildings	84	91	53	-37%
Electricity	118	61	14	-88%
Heavy Industry	87	77	52	-39%
Oil and Gas	160	191	110	-31%
Transportation	160	186	143	-11%
Agriculture**	72	73	71	-1%
Waste and Others	57	51	29	-49%
Land Use, Land Use Change, and Forestry (LULUCF)*, Natural Climate Solutions	-	-	-30	-
Total*	739	730	443	-40%

*Totals may not add up due to rounding

** 30 Mt from LULUCF and NCS includes emissions from Agriculture sector. Emissions attributed to the agriculture sector are divided between the agriculture category and the LULUCF category. Emissions from the agriculture sector consist of emissions from crop production, livestock production, and on-farm fuel use, whereas a significant portion of LULUCF category can be attributed to agricultural croplands, demonstrating the sector's important contribution to removals from cropland.

These indicative figures were based on the best available information at the time, including emissions data from Canada's 2021 National Inventory Report. Canada will continue to refine and update projections through future progress reports required under the *Canadian Net-Zero Emissions Accountability Act*, as well as through UNFCCC reporting. Canada will submit its Fifth Biennial Report to the UNFCCC by the December deadline.

Key Sector-by-Sector Strategies

To achieve the projected sectoral contributions illustrated above, the 2030 ERP outlines the various measures and strategies that are being pursued in each sector to achieve Canada's 2030 target. These actions are summarized below.

Economy-wide

Cross-cutting measures provide policy certainty across the economy and are foundational to Canada's 2030 pathway. Increasing the price on carbon pollution every year to 2030 and exploring approaches to provide more certainty on the carbon pollution price trajectory to 2030, ensuring provincial and territorial carbon pollution pricing systems meet federal benchmark criteria, advancing clean fuels, reducing methane across the economy, and implementing an advanced and enhanced Low Carbon Economy Fund are all critical elements of Canada's economy-wide climate approach.

[5] For more detail on ERP modelling, please see Chapter 3.

Buildings

A whole-of-government and whole-of-economy effort focusing on regulatory, policy, investment, and innovation levers will drive decarbonization of the buildings sector. To this end, Canada is developing a national strategy for net-zero and resilient buildings, the Canada Green Building Strategy, and supporting communities to upgrade and retrofit homes and buildings, including affordable housing though the Greener Homes Loan Program.

Electricity

Significant effort has been made to decarbonize Canada's electricity grid, which is already 82 per cent non-emitting. Achieving a net-zero electricity grid by 2035 will be key to powering Canada's economy with clean energy. Key measures will continue to increase the supply of clean energy and the construction of interties while maintaining reliability and affordability.

Heavy Industry

Canada will build on the progress made to decarbonize its heavy industry by expanding the Industrial Energy Management System to support ISO 50001 certification of energy managers, supporting retrofits for small-to-moderate projects, and introducing a Buy Clean Strategy for federal investments to prioritize the use of made-in Canada low carbon products in Canadian infrastructure projects.

Oil and Gas

Canada will pair measures to reduce emissions from the oil and gas sector with a range of supporting policies and investments, including for workers. This includes a cap on oil and gas sector emissions designed in collaboration with partners and stakeholders, phase-out of inefficient fossil fuel subsidies, and a CCUS investment tax credit. Reducing methane emissions in the sector will also be key to meeting the 2030 target. At COP26, Canada joined the Global Methane Pledge, which aims to reduce global anthropogenic methane emissions across all sectors by at least 30% by 2030, relative to 2020 and has released *a* strategy to meet this target. Canada was also the first country to commit to further reduce methane from oil and gas operations by at least 75% below 2012 levels by 2030, as called for by the International Energy Agency.

Transportation

Efforts are ongoing to make zero-emission vehicles (ZEVs) more affordable and accessible for all Canadians through rebates and investments in charging infrastructure. To accelerate the transition to ZEVs, Canada is developing a mandatory sales target that at least 60 per cent of all new Light Duty Vehicle (LDV) sales be zero-emissions by 2030, as an interim step to achieving 100 per cent by 2035. For medium-and heavy-duty vehicles (MHDVs), Canada will develop a Medium and Heavy Duty Vehicle ZEV regulation to require 100%

MHDV sales to be ZEVs by 2040 for a subset of vehicle types based on feasibility, with interim 2030 regulated sales requirements.
Canada is also investing in public and active transportation, and pursuing efforts to decarbonize air, rail, and marine transportation.

Agriculture

Recognizing the important role Canada's agricultural sector plays in the fight against climate change, and in the context of an increasing global demand for food, actions are focused on increasing the ability of farmlands to store carbon and by exploring a variety of tools to incent further emissions reductions in the agricultural sector. This includes further investments to support adoption of clean technologies and natural climate solutions to sequester carbon and generate other environmental benefits, as well as working towards a national fertilizer emissions reduction target of 30 per cent below 2005 levels by 2030.

Waste and Others

Despite its small GHG footprint, Canada is exploring ways to reduce emissions in the waste sector further by supporting the development of waste and water capital projects, advancing a "made-in-Canada" approach to the circular economy, and exploring opportunities to reduce food waste.

Natural Climate Solutions

Natural climate solutions have an important role to play in meeting Canada's 2030 target and also provide important co-benefits for society. Increasing funding for the Natural Climate Solutions Fund and protecting lands and oceans that store and sequester carbon are two key priorities for meeting the 2030 target.

Clean Technology

Canada is working to ensure its clean technology ecosystem to supports the achievement of its 2030 and 2050 climate targets. Canada is exploring its climate innovation trajectory, through efforts such as regulatory ambition, investments in clean tech deployment, low-carbon procurement, and more. This will be achieved through actions such as strengthening investments in RD&D for emerging net-zero technologies, and new tax credits for clean tech and zero-emissions technology.

Skills and Workforce

Canada recognizes that as mitigation measures become more stringent, the need to support workers and communities will become more acute. Efforts such as advancing Just Transition legislation, investing in skills and training, and creating opportunities for under-represented people and communities to join the clean energy workforce are priorities.

Sustainable Finance

Decarbonization requires a transformation of Canada's financial system to be net-zero compatible and to mobilize more private sector financing. Efforts to advance sustainable finance in Canada, by incorporating environmental, social, and governance factors throughout financial decision-making, will be important in achieving Canada's 2030 and 2050 climate targets.

Partnerships and Collaboration

Partnerships and collaboration with provinces, territories, Indigenous Peoples, industry, international peers, and local governments is fundamental to meeting Canada's 2030 target. In Canada, the environment is an area of shared jurisdiction between federal, provincial and territorial governments, and municipalities have influence over approximately 50% of Canada's GHG emissions. Other levels of government therefore have a large role to play when it comes to reducing emissions in key sectors such as electricity and agriculture. In addition, as articulated in the *United Nations Declaration on the Rights of Indigenous Peoples*, self-government agreements, historic and modern treaties, Indigenous Peoples have rights over their lands, territories and resources. Provinces and territories, and in some cases Indigenous Peoples, are responsible for the policy levers for key emissions sources, and many provinces and territories and Indigenous communities have taken action to reduce emissions in their jurisdictions.

In addition, while more work needs to be done to ensure that Indigenous climate leadership is fully integrated into Canada's climate action, Canada has an ongoing commitment to improve the reflection of the *United Declaration on the Rights of Indigenous Peoples* in all of its policy and programming and to work with Indigenous partners to better support their climate priorities.

Canada is also committed to tackling climate in partnership with international peers, including through the G7, G20, United Nations, and other international fora and bilateral relationships.

Canada's 2030 Emissions Reduction Plan and Canada's LTS

Although both documents support Canada in meeting its climate objectives, the 2030 ERP and Canada's LTS are unique exercises and serve different purposes.

The 2030 ERP is a detailed climate plan that will position Canada to achieve its 2030 NDC of 40-45% below 2005 levels. Projections in the 2030 ERP are based on these detailed measures and strategies, and will guide emissions reductions in every sector in order to meet the 2030 target.

On the other hand, Canada's LTS is an exploratory document that complements the 2030 ERP. Canada's LTS leverages economic modelling to explore various scenarios of what net-zero emissions might look like for Canada in 2050. As Canada receives additional expert advice on transition pathways (including from the Net-Zero Advisory Body) and delivers on key milestones set out in the *Canadian Net-Zero Emissions Accountability Act*, the pathway to net-zero emissions will become clearer. In the meantime, Canada's LTS provides useful insight about the implications of different net-zero emissions futures for Canada, based on the best available information today.

3. Possible Approaches to Net-Zero Emissions in Canada

3.1 Key Elements of Net-Zero Emissions

All sectors of Canada's economy will have a role to play in the transition to net-zero emissions. For example, many sectors will need to increase energy efficiency to produce the same outputs with less energy, and generating more and cleaner electricity and improving electricity transmission infrastructure is needed to support widespread electrification. Further, the way that Canada moves people and goods will need to be decarbonized, through electrification such as electric vehicles, or alternative fuels such as hydrogen. Industrial processes that currently rely on emitting technologies will need to be transformed, either through alternative processes, or through new technologies. In a net-zero emissions future, Canada will also need to harness nature's ability to capture and store carbon by protecting and sustainably managing and restoring its land and oceans. Working with international partners to reduce emissions will also be essential. This may include the purchase of Internationally Transferred Mitigation Outcomes, as outlined in Article 6 of the Paris Agreement. While the precise role each of these elements is unclear at the moment, they will all be integral to Canada's ability to achieve net-zero emissions by 2050.

Regardless of the particular technologies and approaches each economic sector utilizes to achieve net-zero emissions, some elements of the transition will cut across all sectors. These include:

Putting People First

The transition to a net-zero emissions economy will impact regions, communities, and sectors of the economy differently. Canada's pathway to net-zero emissions must promote fairness, inclusion, and well-being for all. Canada is committed to ensuring that workers have the skills and opportunity to thrive in a net-zero world, regardless of who they are, where they live, or what they do.

Science and Research

Building scientific knowledge and reflecting new understanding is essential to inform ambitious action, measure progress and refine climate actions. Science and research will be important in both developing new clean technologies to help Canada and the world reduce emissions, and to advance understanding of the impacts of climate change.

Partnerships

The Government of Canada cannot achieve net-zero emissions on its own. Partnerships with provinces and territories, cities, industry, workers, communities, investors, entrepreneurs, Indigenous Peoples, and international partners will be essential.

Indigenous Knowledge

Canada supports the *United Nations Declaration on the Rights of Indigenous Peoples* (*UN Declaration*) and acknowledges that Indigenous Knowledge systems and ways of doing must be a cornerstone of Canadian climate policy. Indigenous Knowledge systems are diverse, but often share principles embedded in land, language, holistic worldviews, histories, and legal traditions. Inclusion of, and active support for, Indigenous Knowledge systems in Canada's climate plans helps ensure that federal climate action leads to the mitigation of climate impacts while advancing reconciliation and amplifying Indigenous climate leadership.

3.2. Overview of Modelling Approach

Reaching net-zero emissions by 2050 will require deep transformation across all sectors of the Canadian economy. This transition presents clear opportunities for Canada, such as increasing the competitiveness of traditional sectors and emerging clean technology industries. However, there are many different pathways that Canada could take to achieve net-zero emissions, each with their own unique challenges and opportunities. The world will continue to change between now and 2050, and the exact energy mix that will power Canadian society in 2050 is still being determined. Canada's path to 2050 will evolve as global and domestic policy changes influence market conditions, including the availability and commercial viability of the technologies needed to foster widespread decarbonization of Canada's economy. Despite this uncertainty, it is clear that some key enablers will play a role in reducing emissions across all sectors of the economy: electrification, renewable and alternative fuels, such as low-carbon hydrogen, and increased use of engineered CO_2 removal technologies, technologies such as Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC).

Based on this information, the purpose of Canada's LTS is to provide a sample of illustrative scenarios that demonstrate possible approaches for Canada to achieve net-zero emissions by 2050. Consistent with Canada's 2016 Mid-Century Strategy, Canada's LTS is not a blueprint for action nor is it policy prescriptive – it does not identify the range of policies, measures and regulations that would be necessary to transition Canada to a net-zero emissions economy, it also does not identify potential economic impacts such as GDP growth or employment. Instead, Canada's LTS shows the possible sectoral impacts, in terms of emissions and final energy use, as well as the electricity generation mix, under differing degrees of influence of three key enablers on a path to net-zero emissions in 2050. The three enabling conditions are:

- Electrification: widespread electrification across the economy supports energy transformation of end-use sectors including transportation, buildings, and industry, as well as making the electricity supply non-emitting.
- Renewable and Alternative Fuels: use of low-carbon hydrogen, as well as renewable fuels (e.g., renewable natural gas, renewable liquids, etc.) enables energy transformation of end-use sectors with a particular focus on buildings, power generation and heavy vehicles.

- Engineered CO_2 Removal Technologies: more rapid technical change and the greater use of carbon capture technologies, including CCS, and DAC enables achievement of net-zero emissions.

It is important to note that the scenarios presented here do not represent the most likely, or preferred pathways to net-zero emissions by 2050, and different outcomes within or beyond the range of these scenarios are possible and not limited to the findings of this analysis. In addition, this modelling analysis does not include other key enabling factors that could influence pathways to net-zero emissions in Canada, such as demand-side management for electricity and the full potential of nature-based solutions. Scenarios in Canada's LTS consider a national approach to reducing emissions, however, in practice, provincial and territorial governments will have an important role to play in reducing emissions in areas under their jurisdiction, including in key enablers identified in the LTS, such as electrification. Assumptions in Canada's LTS are based on the best available information today, and are therefore likely to change in the future as further developments in innovation and technology take place.

The modelling for Canada's LTS first considers a "current assumptions scenario" that reflects the understanding of assumptions and technologies available today, based on the best information available. This current assumptions scenario is then modified with different assumptions about the development of key technologies to present three scenarios: High Electrification, High Use of Renewable and Alternative Fuels, and High Use of Engineered CO_2 Removal Technologies. Across all scenarios, the modelling approach for Canada's LTS assumes a contribution of -100 Mt from LULUCF. While this figure is consistent with the assumption in the 2016 Mid-Century Strategy, Canada recognizes that accounting practices for the LULUCF sector are continuously evolving, including the development of more robust methodologies and studies of drivers of land use change in order to forecast future emissions in different scenarios. Canada will continue to update its projections and assumptions for LULUCF in line with IPCC guidelines as accounting methodologies improve.

Canada's LTS uses a "top-down" approach where emissions are capped at net-zero by 2050 and the model determines the most economically desirable path to achieve this, based on the enabling assumptions. All scenarios assume that Canada achieves its 2030 NDC of 40% below 2005 levels by 2030, as modelled in the 2030 ERP. Assumptions also include a variety of policies and measures that are already in place to set Canada's foundation to net-zero emissions (e.g., carbon pricing, net-zero electricity, widespread ZEV adoption, etc.) For more details on technology assumptions, please see Annex 1.

The modelling for Canada's LTS was performed using three international models: Global Change Analysis Model (GCAM), Environment Canada's Integrated Assessment Model (EC-IAM), and Environment Canada's Multi-sector, Multi-regional Computable General Equilibrium (CGE) Model (EC-MSMR). (Please see Annex 1 for more detail on each model and their assumptions). The combination of the three models provides a robust evaluation of different approaches to achieving net-zero emissions. GCAM and EC-IAM are both integrated assessment models, which are designed to assess the long-term implications of the dynamics of environmental, social and economic systems. EC-MSMR is an open-economy CGE model of the global economy that has the capacity to analyze the energy and economic transition associated with GHG pathways, and has higher industrial resolution.

To explore a wider range of possible approaches to achieve net-zero emissions by 2050, Canada's LTS also summarizes pre-existing third-party net-zero emissions modelling by the Canadian Climate Institute (CCI) and the Institut de l'énergie Trottier (Trottier Institute). While the assumptions and modelling approaches framing the third-party analysis differ from those of the modelling undertaken by Canada, the third-party and Government of Canada results help to highlight the importance of electrification, renewable and alternative fuels, and engineered CO_2 removal technologies to achieving net-zero emissions by 2050. Other organizations and third parties across Canada, such as the Canada Energy Regulator, are also working to produce their own net-zero emissions scenarios.

Table 2: Overview of Scenarios

Scenario	Possible Emissions Reduction Pathways: Electrification	H_2 and Bioenergy	CO_2 Removal Technologies	Description
Current Assumptions	Model Determined	Model Determined	Model Determined	The modelled pathway given assumptions based on today's understanding of the costs and constraints of achieving net-zero emissions. Meets Canada's commitments to reach net-zero emissions related to: • Zero-emitting new vehicle sales • Net-zero electricity by 2035
High Electrification	High	Low	Low	Electrify energy transformation and end-use sectors: • Building heating and other uses • Battery electric vehicle transport • Heavy industries • Electrolysis in hydrogen
High Use of Renewable and Alternative Fuels	Medium to High	Medium	Low	Use of hydrogen and alternative fuels in: • Heavy vehicles, aviation, maritime, and rail • Building heating with blending and new technologies • Heavy industries • Hydrogen with SMR/electrolysis
High Use of Engineered CO_2 Removal Technologies	Medium	Low	Medium to High	Cost-effectiveness of CO_2 technologies: • Direct Air Capture (DAC) • Carbon Capture and Storage (CCS)[6]

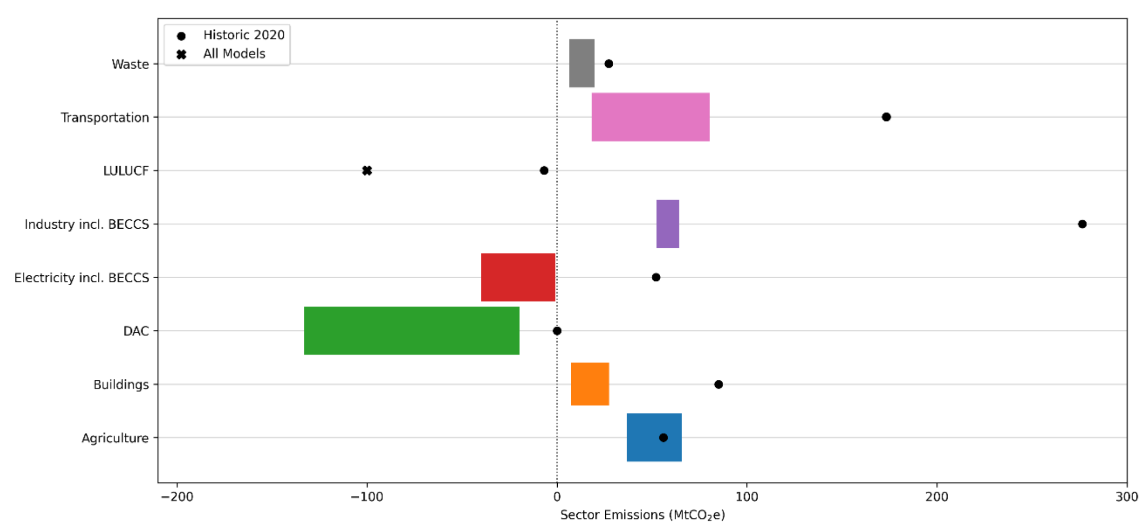
3.3. Scenario 1: Current Assumptions

The current assumptions scenario presents the range of results from models with different visions of the most cost-effective pathway to reach net-zero emissions, based on today's understanding of the costs and constraints of achieving net-zero emissions. As international models are being used for this analysis, the current assumptions scenario is influenced by both global and Canadian-specific assumptions.

[6] CCS includes Bioenergy with Carbon Capture and Storage (BECCS).

Modelled results demonstrate that achieving net-zero emissions across the Canadian economy will not necessarily mean that emission reductions are equal across sectors. As shown in Figure 1, while remaining emissions are low in the buildings sector and zero or even negative in the electricity sector, GHG emissions in transportation show variations across the models depending on their technology assumptions. The models find that aggregate industry emissions (including oil and gas emissions) remain with some uses of fossil fuel. These remaining GHG emissions are offset by net-negative technologies like BECCS, DAC and Land Use, Land Use Change, and Forestry (LULUCF). The total net-negative emissions of each model ranges from -139 to -249 $MtCO_2e$. These variations in the potential to abate remaining emissions highly influences model-specific pathways.[7]

Figure 1: Canada Emissions by Source in 2050 – Current Assumptions Scenario[8]



[7] Note that LULUCF is assumed to be 100 Mt across all models. This is consistent with the assumption in the 2016 Mid-Century Strategy. This estimate is based on analysis that does not take into account changing pressures on the land base from other sectors and does not necessarily account for activities on the land base that will be necessary to support a pathway to net-zero emissions (e.g., access to resources such as critical minerals and bio-materials).

[8] Industry sector includes non-metallic minerals, iron and steel, chemicals, pulp and paper, non-ferrous metals, transport equipment, textiles, food products, wood products, refining, construction, other manufacturing, as well as oil, gas, and coal extraction. Some of the models incorporate industry at an aggregate level while the other has a more detailed industry representation. However, each model can track the supply and demand for oil and gas products, as indicated in the Annex.

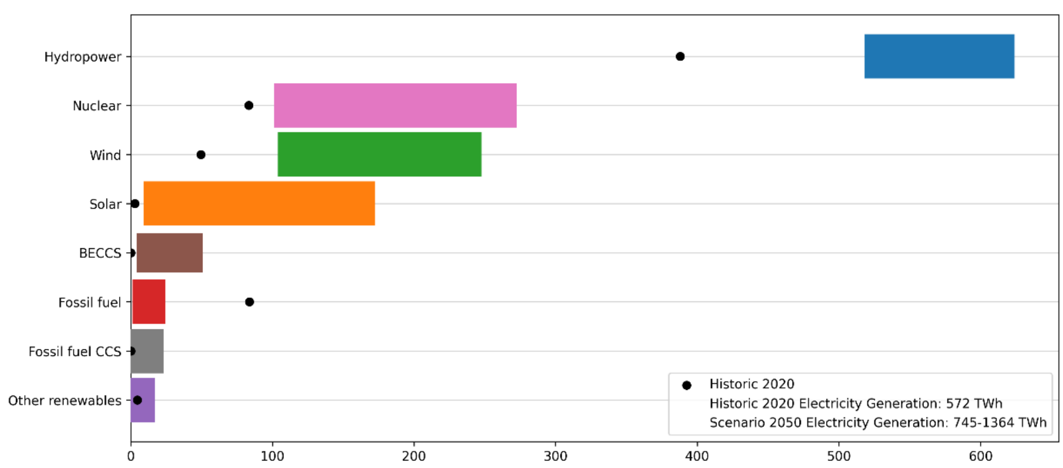
Variations and Ranges Across Models

ECCC modeled four scenarios to illustrate a wide range of possible energy and technological pathways to reach net-zero emissions. The modelling exercise used three ECCC international models; GCAM, EC-IAM and EC-MSMR. The range shown in the graphs represents the results across models. These range of values come from model-distinct structure and philosophy as well as model-specific assumptions and constraints. The way the models are structured (Top-Down or Bottom-Up) and that the costs are defined highly influences models dynamics. IAM models like GCAM and EC-IAM follow an engineering philosophy to represent technology resolution. CGE models like EC-MSMR follow an economic philosophy where technologies are defined via cost curve representation.

Each model treats scenario assumptions differently even if those assumptions are comparable across models. The merit of a modelling approach is its algorithm that allows activities from distinct sectors and regions to interconnect and make their best and unique decisions under market mechanisms. This market interaction can be further expanded through a global modelling option that links opportunities across regions to promote new technologies inevitable for a global issue such as climate change. Model and assumption details are presented in Annex 1.

Figure 2 shows the deep transformation to clean generation in the electricity sector, with the sector becoming net-negative. Total electricity generated by 2050 ranges from 745 to 1364 TWh. Compared to 2020[9], the increase in generation level in the current assumptions scenario ranges from 30% to 138%, depending on how cost-effective electrification is across models. In the current assumptions scenario, there is a significant deployment of renewable electricity generation. Renewable technologies represent a high share of electricity generation in 2050, with 77% to 86% of all generation in Canada being renewable. Including nuclear, clean electricity generation share is 97% to 100% in 2050. By 2050, fossil fuel, including with CCS, generates less than 3% of electricity over all models The deployment of CCS technologies in the current assumptions scenario is less significant than renewable technologies. BECCS technologies compensate for remaining emissions from the electricity sector and in other economic sectors.

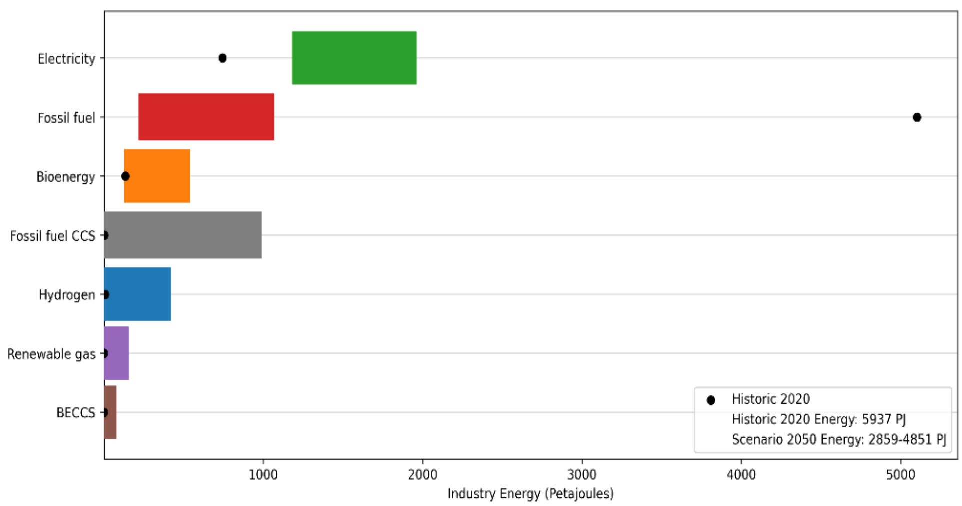
Figure 2: Canada Electricity Generation Mix in 2050 – Current Assumptions Scenario

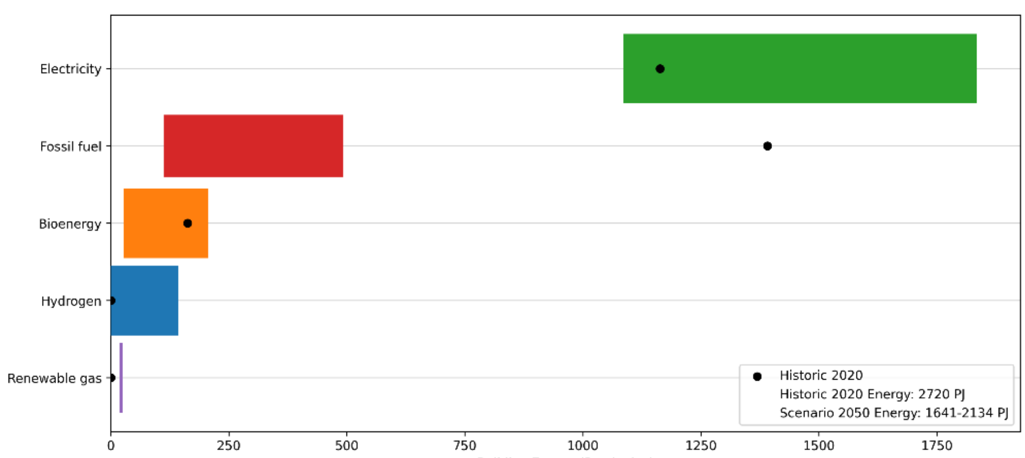


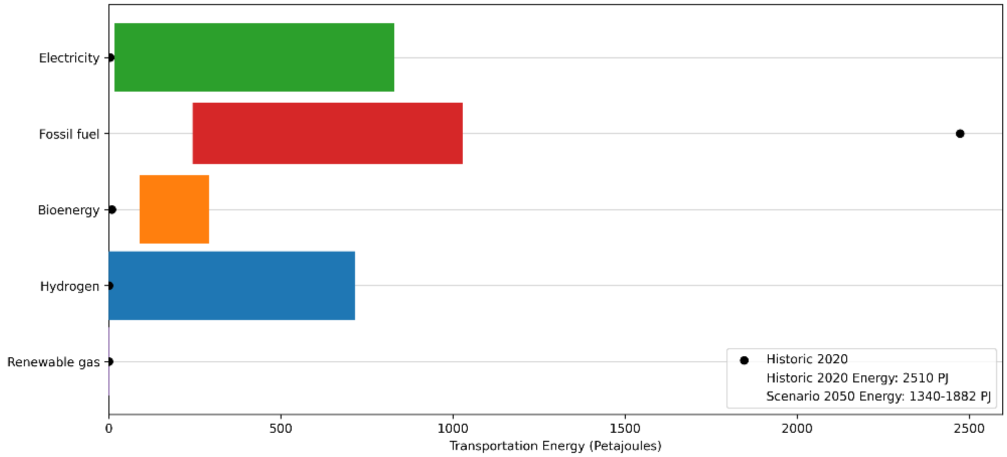
[9] Based on ECCC's E3MC reference case (Ref21)

Final energy end-use by sector shows a different pathway for each sector (see Figure 3). In the industry sector, certain models place more importance on fuel switching while others reduce energy requirements by efficiency gains. Across all models, fossil fuel energy needs are reduced in this sector, but not fully avoided, and carbon capture and storage (CCS) technologies contribute GHGs reductions from fossil fuels. Fuel use in residential and commercial buildings is replaced in favour of electricity. The transportation sector presents different pathways depending on the models. Some fossil fuel sources are switched to electricity or alternative fuels, such as bioenergy or hydrogen. Note that advanced electric technologies have higher energy efficiency than fossil fuel technologies in building and transportation sectors, and as such less energy is needed to provide the same amount of service.

Figure 3: Canada Final Energy Use by Sector in 2050 – Current Assumptions Scenario





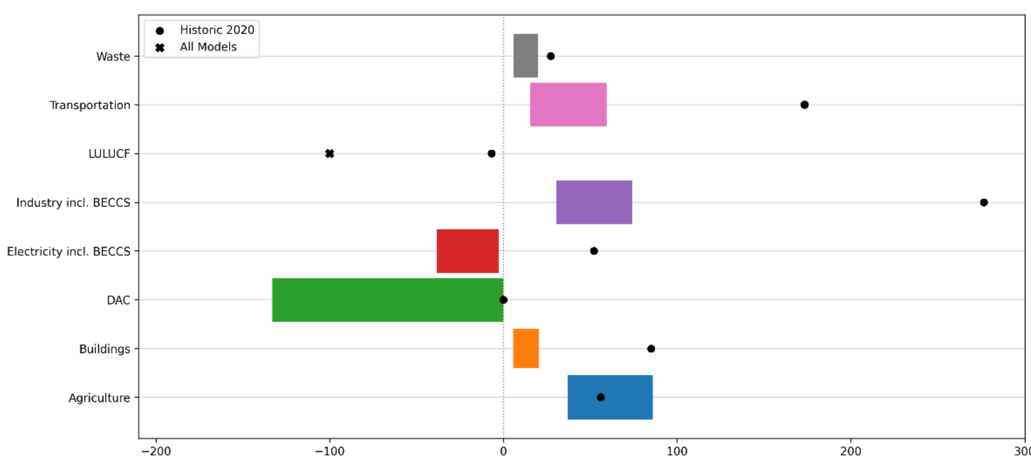


3.4. Scenario 2: High Electrification

The high electrification scenario shows widespread electrification across all sectors of the economy. To promote this increase in electrification, this scenario assumes that electricity-based technologies for end-use consumers become more affordable. Any residual emissions in this scenario are offset by afforestation (LULUCF) and engineered removals such as BECCS and DAC.

Residual emissions resulting from the high electrification scenario are presented in Figure 4. Similar to the current assumptions scenario, the agriculture, industry and transportation sectors have significant unabated emissions across all modelled results. To abate residual emissions, this scenario assumes that CO_2 removal technologies are deployed, including LULUCF, BECSS, and DAC, to remove between -124 to -249 $MtCO_2e$.

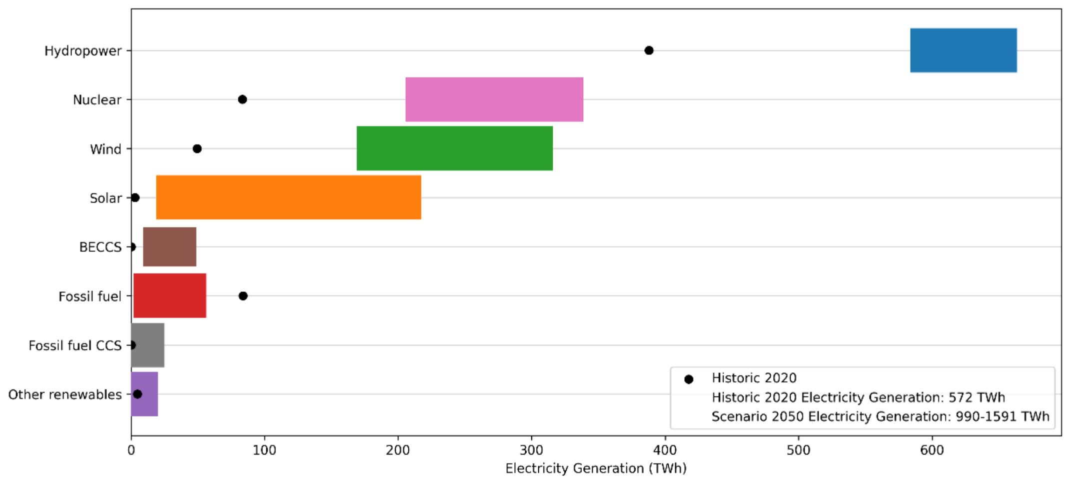
Figure 4: Canada Emissions by Source 2050 – High Electrification Scenario



Canada

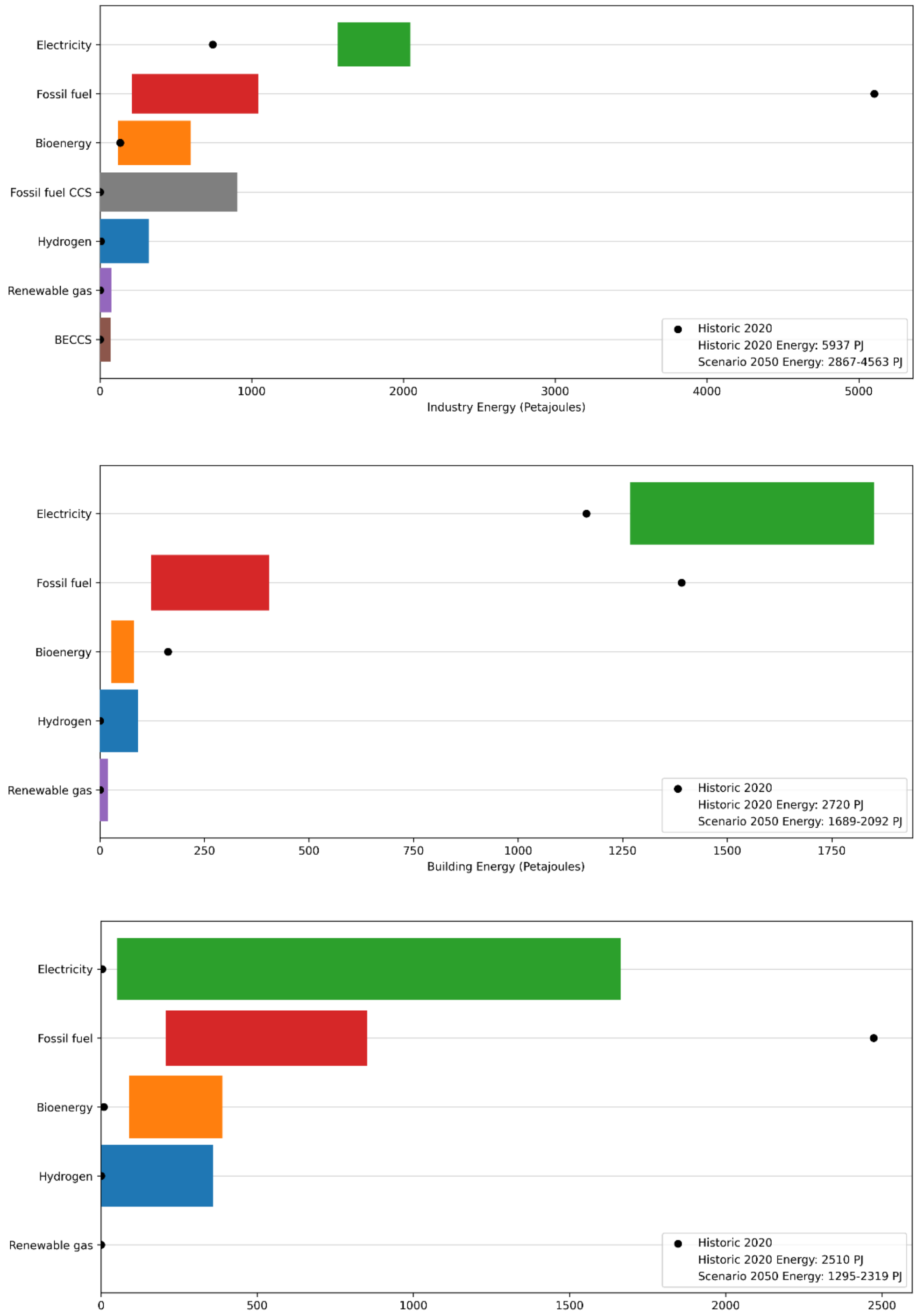
As shown in Figure 5, electricity generation in the high electrification scenario reaches a range of 990 to 1591 TWh, an increase of 18 to 33% compared to the current assumptions scenario. In this scenario, a net-zero electricity grid is achieved through a widespread mix of renewable energy sources, predominantly hydroelectricity, as well as low-carbon generation technologies (nuclear and CCS).

Figure 5: Canada Electricity Generation Mix in 2050 – High Electrification Scenario



This scenario estimates high electricity deployment (shown in Figure 6) due to electricity-based technologies becoming most cost-competitive relative to conventional fossil-based technologies across different sectors. The transport sector is able to reduce emissions through electrification of light, medium, and heavy-duty vehicles. Advanced technologies such as electric heat pumps in building heating systems allows for a large reduction in emissions. Similar to the current assumptions scenario, electricity will be dominant among all energy mixes in the industry sector, but the industry sector still shows a significant share of other energies in the energy mix mainly due to the diversification of production processes across industries.

Figure 6: Canada Final Energy Use by Sector in 2050 – High Electrification Scenario

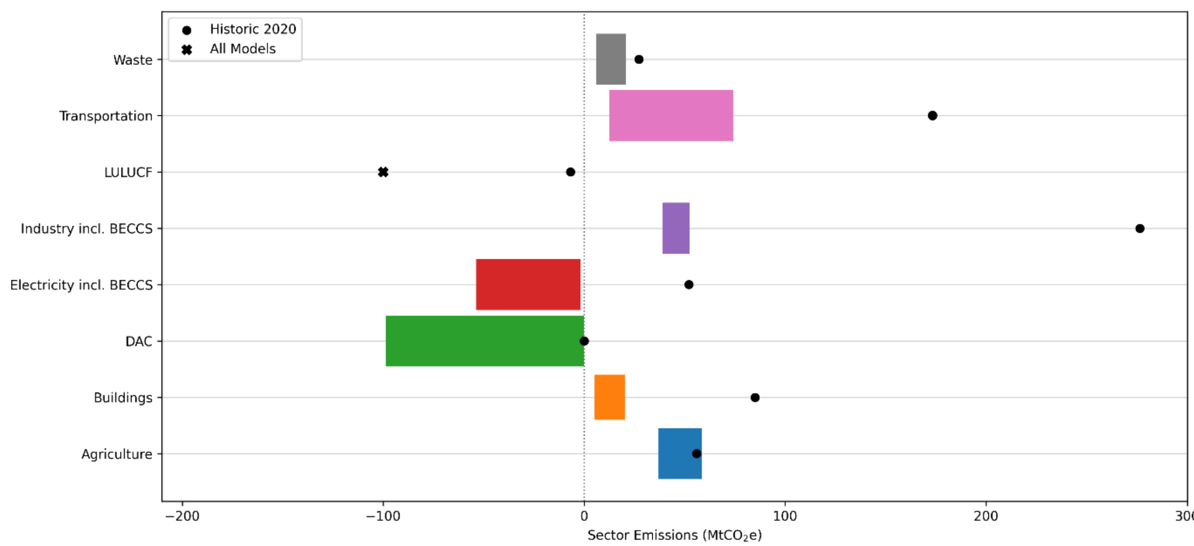


3.5. Scenario 3: High Use of Renewable and Alternative Fuels

This scenario illustrates a pathway to net-zero emissions through the increased use of renewable and alternative fuels, such as low-carbon hydrogen and bioenergy fuels. In this scenario, resources like hydrogen complement widespread electrification, particularly in the harder-to-electrify areas of industry, as well as heavy-duty transport, such as aviation, freight trucks, and shipping. To achieve this in the modelling, this scenario assumes a cost reduction in clean hydrogen production, as well as significant developments in hydrogen end-use technologies.

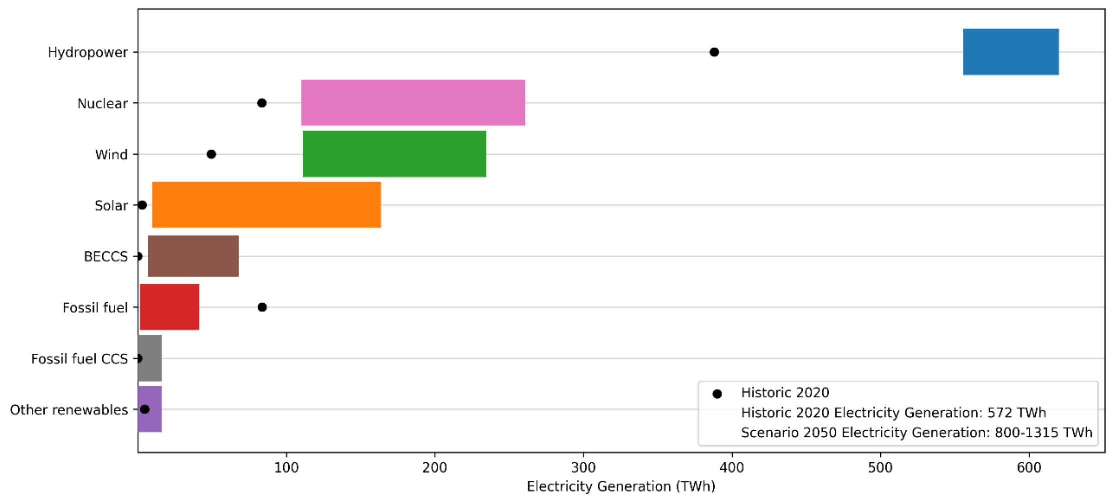
This scenario shows a similar 2050 emissions profile (shown in Figure 7) as the current assumptions scenario, with residual emissions predominantly appearing in the industry, waste and agriculture sectors, as well as the transportation sector in one model. Depending on the model, removals from BECCS, DAC, and LULUCF account for a large amount of negative emissions, a combined total ranging from -124 to -215 $MtCO_2e$.

Figure 7: Canada Emissions by Source 2050 – High Use of Renewable and Alternative Fuels Scenario



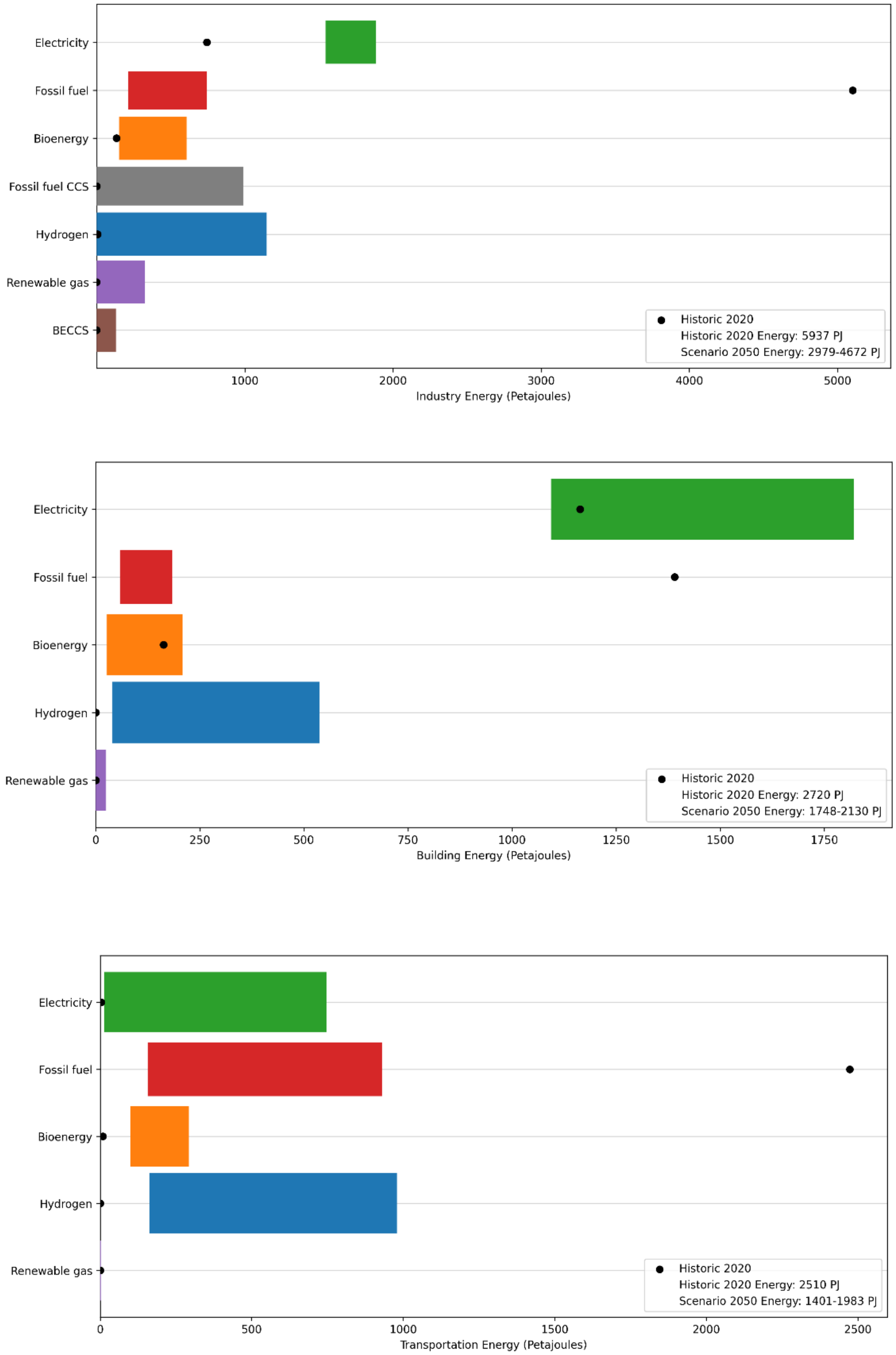
The level of electricity generation under this scenario ranges from 800 to 1315 TWh as shown in Figure 8. Overall, the electricity generation mix is similar to the other scenarios.

Figure 8: Canada Electricity Generation Mix in 2050 – High Use of Renewable and Alternative Fuels Scenario



This scenario shows a substantial increase in hydrogen demand in 2050, (shown in Figure 9), by a range of 29 to 339% relative to the current assumptions scenario. Similar to the current assumptions scenario, the building sector has low levels of residual emissions and relies predominantly on electricity. By contrast, the transportation sector sees significant increases in hydrogen and biofuel consumption, with an increase of 31 to 60% compared to the current assumptions scenario.

Figure 9: Canada Final Energy Use by Sector in 2050: High Use of Renewable and Alternative Fuels Scenario

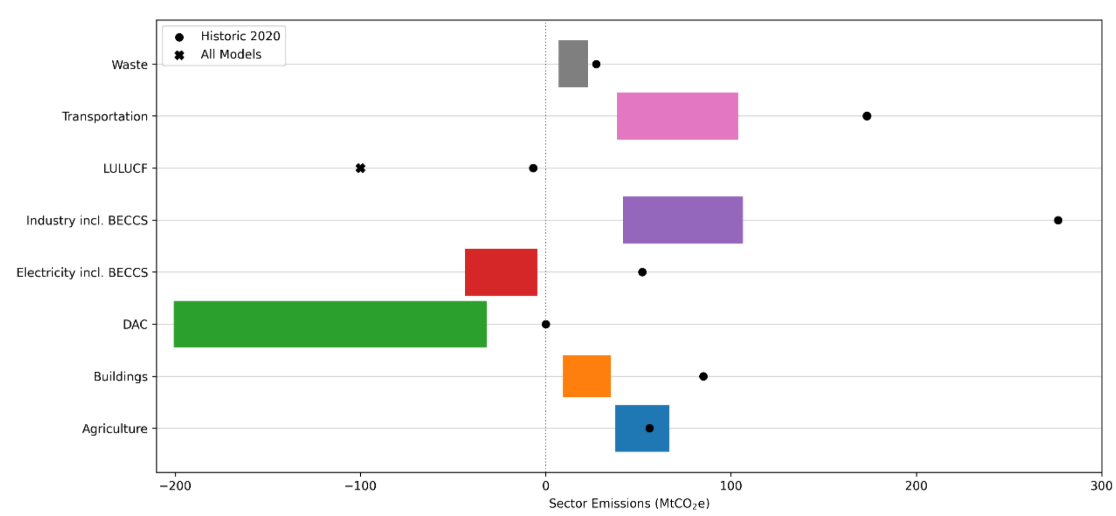


3.6. Scenario 4: High Use of Engineered CO_2 Removal Technologies

The high use of CO_2 removal technologies scenario explores the impact of more rapid technological change and a greater use of carbon capture technologies, including CCS and DAC. This scenario assumes that CO_2 removal technologies become more affordable and cost-effective, leading to an increased deployment in various industry sectors, electricity generation, and the oil and gas sector.

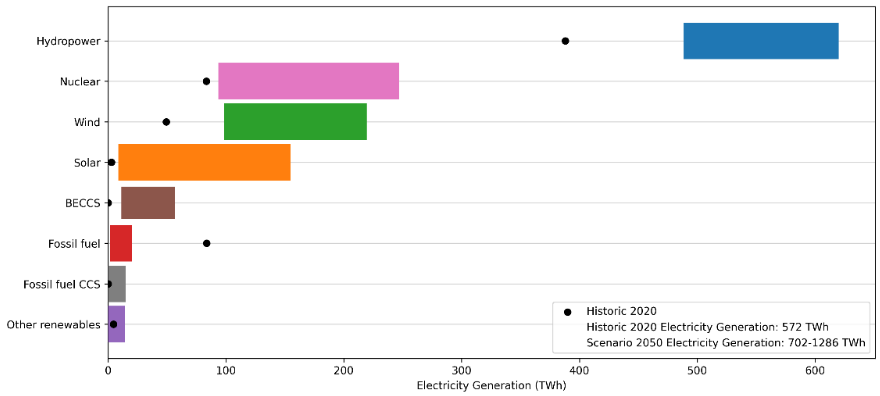
As depicted in Figure 10, this scenario illustrates CO_2 removals (DAC, BECCS, and LULUCF) contributing -177 to -326 $MtCO_2e$ in removals. In comparison to the current assumptions scenario, DAC increases significantly, though the relative contribution varies due to assumptions around the respective competitiveness of the technologies.

Figure 10: Canada Emissions by Source in 2050 – High Use of Engineered CO_2 Removal Technologies Scenario



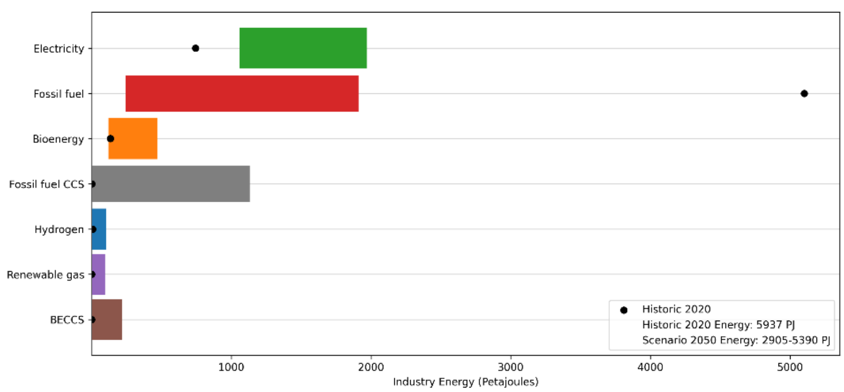
As presented in Figure 11, renewable technologies dominate electricity generation expansion. CCS technologies are still present in electricity generation, however even with the high use of engineered CO_2 removal technologies scenario's assumptions, CCS is still not deployed on a large scale relative to the current assumptions scenario. The electricity sector remains as a net negative sector of the Canadian economy and contributes by removing GHG emissions from others that are harder-to-abate.

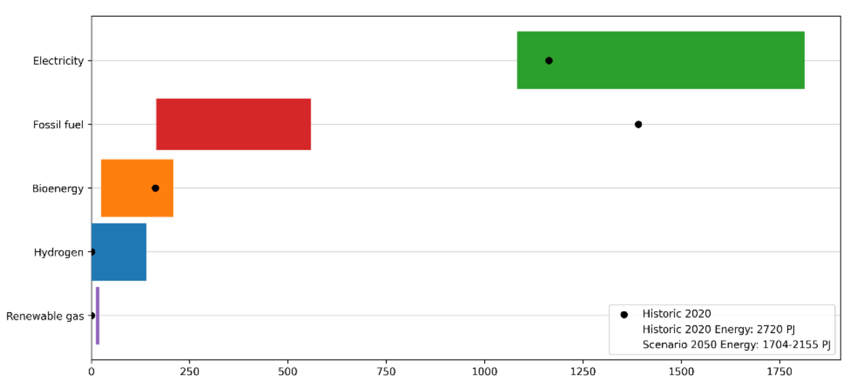
Figure 11: Canada Electricity Generation Mix in 2050 – High Use of Engineered CO_2 Removal Technologies Scenario

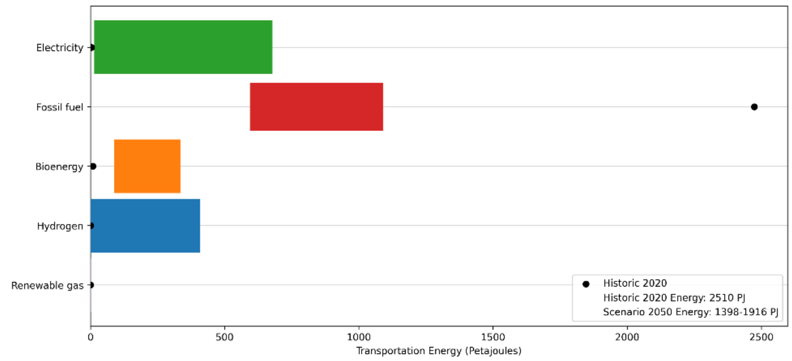


Compared to the current assumptions scenario, CO_2 removal technologies influence the energy mix in end-use sectors considerably, though electrification still plays a key role. As shown in Figure 12, fuel switching is less prominent in this scenario, and fossil fuel with and without CCS are more present than in the current assumptions scenario.

Figure 12: Canada Final Energy Use by Sector in 2050 – High Use of Engineered CO_2 Removal Technologies Scenario







Third Party Modelling Results- the Trottier Foundation and Canadian Climate Institute

As a complement to this LTS' modelling results, publicly available pathways analysis done by the Trottier Foundation and the Canadian Climate Institute are shown in Table 2.

In the modelling by the Trottier Institute—Canadian Energy Outlook 2021: Horizon 2060-- various net-zero emissions scenarios were explored, but only one pathway focused on achieving net-zero emissions by 2050 (NZ50). Key findings include:

- Similar to Canada's scenario results, significant residual emissions were observed in the pathway results, indicating the necessity of CO_2 removal technologies, with most of the residual emissions coming from transportation, agriculture and waste.
- Industry as well as electricity sectors can contribute to the abatement of remaining emissions, compared to Canada's LTS scenario results where electricity sector is the only net-negative sector.
- Consistent with Canada's LTS scenario results, increased production of hydrogen led to an increased use in both the transportation and industrial sectors, and electricity demand is shown to grow sharply

In the modelling by the Canadian Climate Institute, a total of 62 net zero pathways were explored with the only implemented "policy" being a cap on emissions at net zero in 2050 across scenarios. As a result, all pathways reach the same level of emissions reductions, but vary in the mitigation actions used to achieve those reductions. Key findings include:

- Across all scenarios, a growing share for electricity, hydrogen, and biofuels was observed, similar to Canada's scenario results.
- Within the industry sector, reliance on negative emissions was seen in all pathways.
- Similar to results from the Trottier Institute and Canada's LTS modelling, negative emissions are found to be necessary to achieve Canada's net zero by 2050 target, such as through the deployment of DAC and BECCS.
- However, CCI's analysis found that Canada can reach net zero by 2050 without relying on engineered negative solutions, with nature-based solutions playing a larger role. This conclusion is unlike Canada's LTS scenario results, which assumed a specific emission reduction from LULUCF across all scenarios and models.

Table 3: Canada Emissions by Sector in $MtCO_2e$ – Government of Canada Modelling and Third-Party Results

Sector	2020[a]	2050		
Scenarios	Historic	Government of Canada LTS scenarios	Trottier Institute	Canadian Climate Institute (CCI)[e]
Agriculture	69	37 to 86	41	58 to 73
Building	88	5 to 35	3	3 to 22
Electricity[b]	56	-54 to -1	-55	-12 to 6
Industry[c]	273	30 to 107	-30	10 to 99
Transportation	159	13 to 104	51	11 to 65
Waste	27	6 to 23	9	5 to 6
Total (excluding DAC and LULUCF)	672	100 to 301	19[d]	75 to 271
DAC	-	-201 to 0	-15	-166 to 0
LULUCF	-7	-100	-	-105

- a: Source: 2022 National Inventory Report
- b: Includes BECCS
- c: Includes BECCS and Oil and Gas industry
- d: Numbers are shown as in Canadian Energy Outlook
- e: These results are based on the 62 net zero scenarios from Canada's Net Zero Future. Here, the Institute reports the 80th and 20th percentiles of the scenarios. The DAC range

3.7. Summary of Scenarios

Across all models and scenarios, there are some similarities in terms of 2050 emissions by sector, however in other sectors there is a greater range of possible outcomes (Table 4).

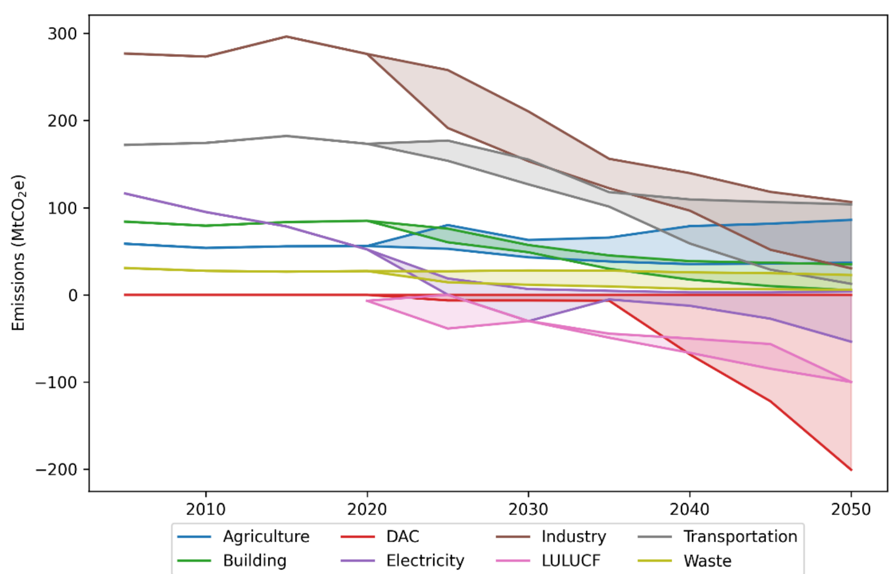
Table 4: Canada Emissions by Sector in 2020 and 2050 in $MtCO_2e$ – All Scenarios

Sector Scenarios	2020[a] Historic	2050 Current Assumptions	2050 High Electrification	2050 High Use of Renewable and Alternative Fuels	2050 High Use of Engineered CO_2 Removal Technologies
Agriculture	69	37 to 66	37 to 86	37 to 59	38 to 67
Building	88	7 to 27	6 to 20	5 to 20	9 to 35
Electricity[b]	56	-40 to -1	-38 to -3	-54 to -2	-44 to -4
Industry[c]	273	52 to 64	30 to 74	39 to 53	42 to 107
Transportation	159	18 to 81	15 to 59	13 to 74	39 to 104
Waste	27	6 to 0	6 to 20	6 to 21	7 to 23
Total (excluding DAC and LULUCF)	672	100 to 233	100 to 233	100 to 199	131 to 301
DAC	0	-133 to -20	-133 to 0	-99 to 0	-201 to -32
LULUCF	-7	-100	-100	-100	-100

a: Source: 2022 National Inventory Report
b: Includes BECCS
c: Includes BECCS and Oil and Gas industry

The pathway each sector takes to 2050 in all modelled scenarios is shown in Figure 13, with shaded parts representing the bands in emission pathways. As seen in the figure, there are numerous pathways with a wide range of possibilities to achieving net-zero emissions in Canada. While these bands in emission pathways do not represent an exhaustive list of possible pathways, they are helpful in identifying general trends.

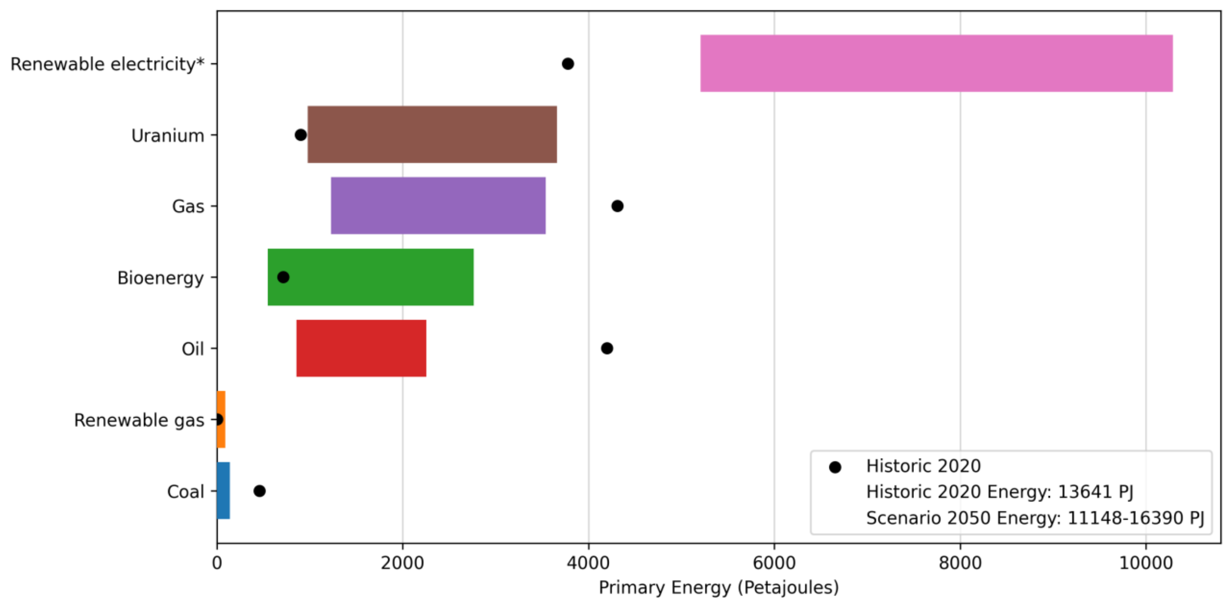
Figure 13: Canada Emissions 2005-2050 – All Scenarios



Possible Energy Pathways

Canada's LTS scenario analysis also provides insight into the key technologies that could drive Canada's transition to net-zero emissions. This is important because the future structure of Canada's economy will be highly dependent on the energy pathway that Canada takes to 2050. For example, if CO_2 removal technologies are deployed rapidly and at a large scale, fossil fuel production and consumption could remain higher than in other scenarios, whereas if electricity and hydrogen are heavily relied upon, Canada's economic structure could look very different. Primary energy use is shown in Figure 14 where horizontal bars represent the range of results from all modelled scenarios. Modelling results show renewable electricity dominating other energy sources, representing a minimum value of 36% of total primary energy (TPE). For the purposes of this modelling analysis, renewable electricity includes hydropower, wind, solar, and geothermal. Uranium and natural gas also represent a significant portion of TPE with a maximum share of 31 and 28%, respectively.

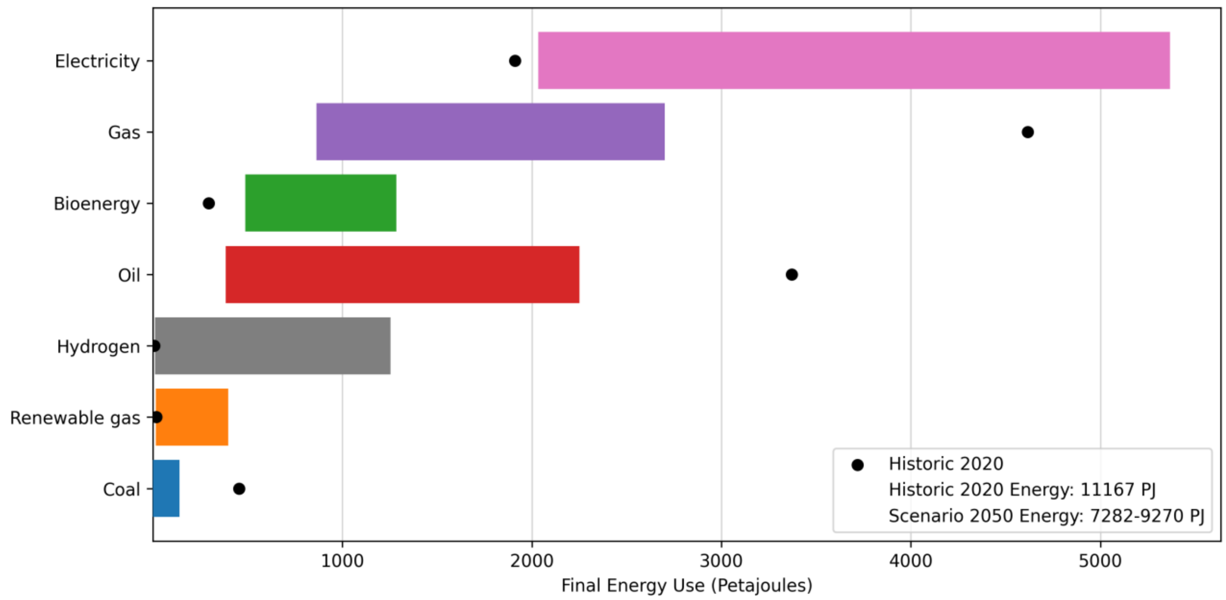
Figure 14: Scenarios for Canada Primary Energy Use by Source 2050



* Electricity generation from renewable sources is converted with a 42% efficiency rate

Figure 15 shows the range in modelling results of Canada's final energy use mix in 2050. Similar to the primary energy use breakdown in Figure 13, electricity dominates all other forms of energy with a maximum value of 5 367 petajoules (PJ) across all scenarios. This widespread use of electricity can be distributed over all end-use sectors of the economy. Following electricity, natural gas also represents a significant share of total final energy demand with its share ranging from 12 to 41%. The larger end of the range represents a case where there is high use of CO_2 removal technologies, allowing a higher consumption of natural gas in 2050. The lower end of the spectrum represents other cases where there is either high levels of electrification or clean fuels such as hydrogen and biofuel, resulting in a lower consumption of natural gas. Clean fuels, like bioenergy and hydrogen, could play a significant role in 2050 depending on the deployment of CCS and DAC technologies to abate emissions from remaining fossil fuels like natural gas and oil. As expected from federal regulations to phase-out coal-fired electricity, coal appears in small amounts of less than 140 PJ in all scenarios.

Figure 15: Scenarios for Canada Final Energy Use by Fuel Type 2050



Sector-by-Sector Analysis

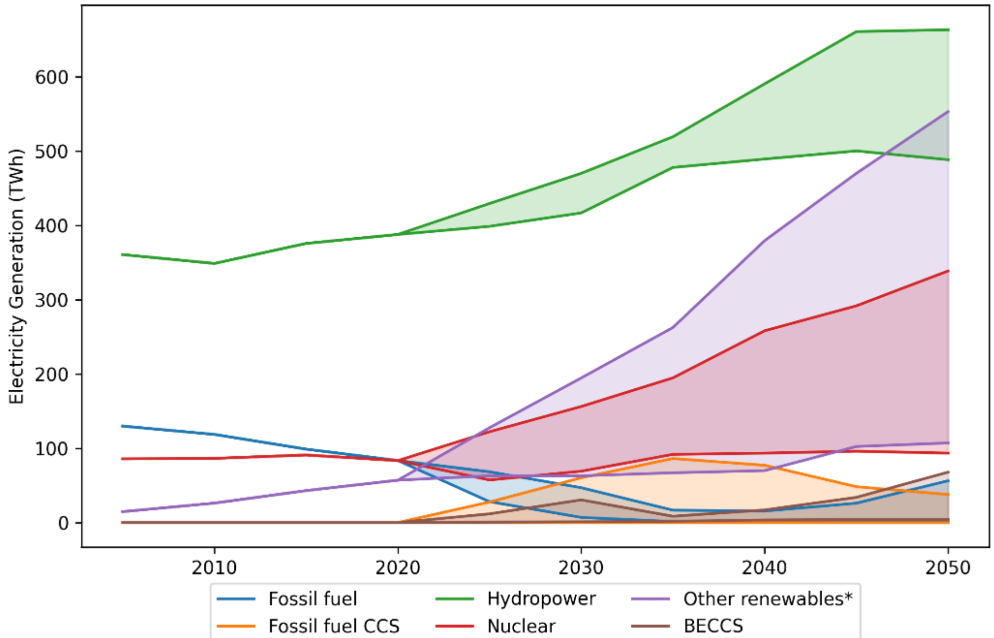
The different models and scenarios describe different pathways for each sector. The four sectors with biggest impact on emissions (i.e., electricity, industry, buildings, and transportation) are described in detail below.

Electricity Generation

Electricity generation results from all modelled pathways are shown in Figure 16. In all scenarios, total electricity generation is found to increase from 2020 levels by 23% up to a maximum of 178%, and electricity produced from hydropower plays a very important role. In 2020, Canada already had a large hydroelectric capacity of close to 400 TWh[10], but reaches some 600 TWh in 2050 in many of the net-zero emissions scenarios. Wind and solar photovoltaic see significant increases in generation from 2020 to 2050 of 136% to 657% and 51 to over 3613%, respectively. Nuclear shows a comparatively smaller increase from 2020 to 2050 but is still a major contributor to total energy generation. While there is a small portion of electricity generated from fossil fuels with a maximum of 4% without CCS and 5% including CCS by 2050 in general, all types of fossil fuels represent minimal amounts of total generation in all modelled scenarios to net-zero emissions.

[10] Ibid

Figure 16: Scenarios for Canadian Electricity Generation Mix 2005 to 2050



* Other renewables includes biomass, wind, solar PV, geothermal, and waste.

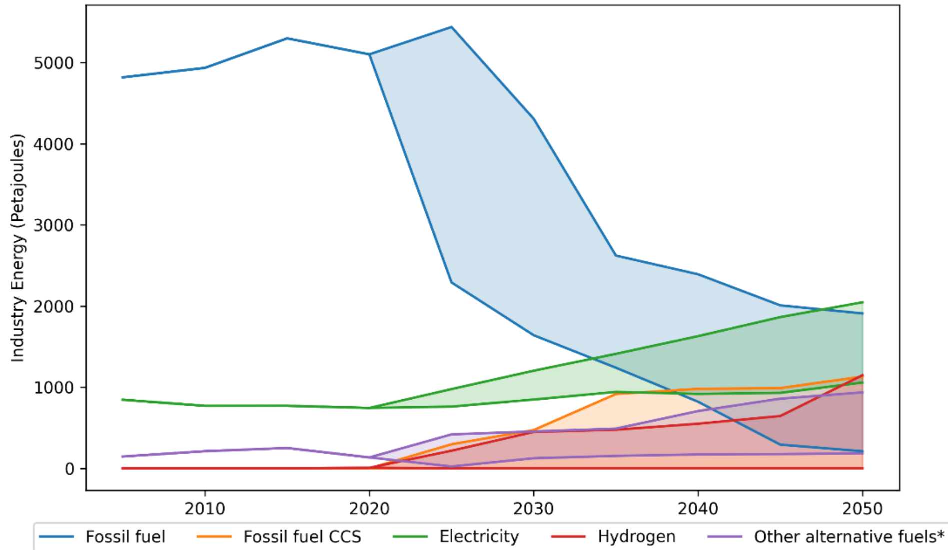
Industry

Decarbonization opportunities vary from industry-to-industry as each has differing heat and energy requirements, process emissions, and technological barriers. Some industries could benefit greatly from electrification, energy efficiency improvements, fuel switching, or alternative processes, while the harder-to-abate industries may require CO_2 removal technologies.

Across all scenarios, as shown in Figure 17, there is a reduction in final energy use in 2050 compared to 2020 for Canada's industry sector[11], with a decrease in final energy use of 9% to 52% from 2020 levels, pointing to the significance of energy efficiency for this sector. Canada's modelling results also suggest a significant and rapid decrease in fossil fuel usage in the industry sector beginning in most scenarios near 2025, and leveling off near 2045. Hydrogen is found to be important in some, but not all, scenarios, with its 2050 share ranging from close to 0% to 34% of industry's final energy use. Other clean fuels such as bioenergy and renewable natural gas are also shown to grow in share, but play less important roles, with up to 22 and 7%, respectively.

[11] Ibid.

Figure 17: Scenarios for Final Energy Use in Industry 2005 to 2050



* Other alternative fuels includes BECCS, bioenergy, and renewable gas.

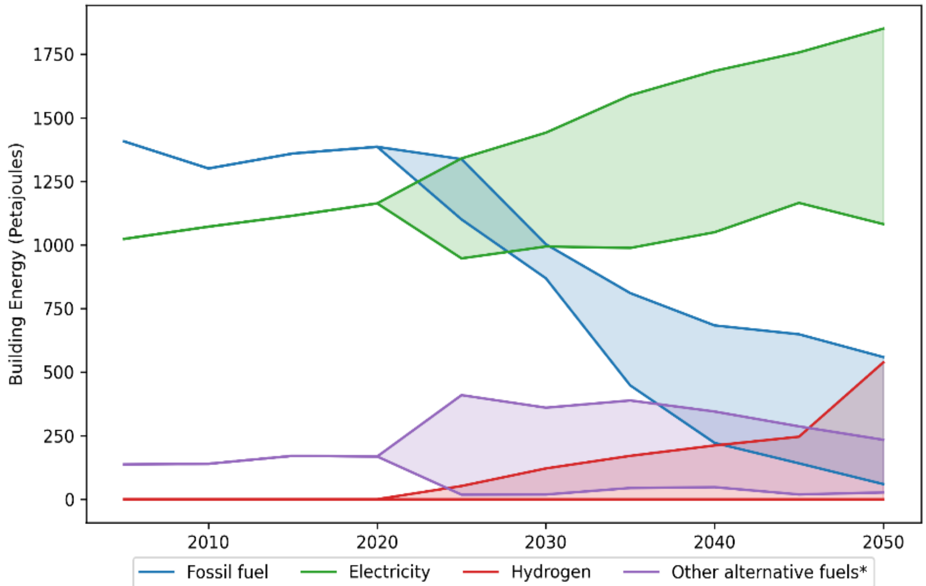
Buildings

A unique feature of the buildings sector is the long lifetime of many buildings, meaning that retrofitting and energy efficiency are expected to be vital features on the road to decarbonization. Electricity could also play a key role in helping this sector achieve emission reductions, as many services within buildings could be electrified, such as heating, cooling, appliances, and other services. Furthermore, electricity can be much more energy efficient than fossil fuels (e.g. heat pumps), and has the potential to reduce the total amount of energy needed to provide the same services.

Modelling results (shown in Figure 18) show the historical data and transition pathways in electricity, hydrogen, fossil, and other alternative fuels until 2050 in the buildings sector. Similar to the industry sector, total energy use in the buildings sector is projected to decrease across all scenarios, with reductions in 2050 ranging from 21% to 40%, compared to 2020 levels[12]. Fossil fuels usage in the buildings sector is shown to fall in all scenarios and decrease by at least 60% in 2050 compared to the 2020 level. Electricity is projected to be the dominant energy source in all scenarios with its overall share increasing from approximately 40% in 2020 to a range of 63% to 88% in 2050. Other fuels such as hydrogen and alternative fuels (e.g., renewable natural gas and bioenergy) play less significant, but still important roles, with shares of up to 31% and 13% in 2050, respectively.

[12] Ibid.

Figure 18: Scenarios for Energy Use in Buildings 2005 to 2050



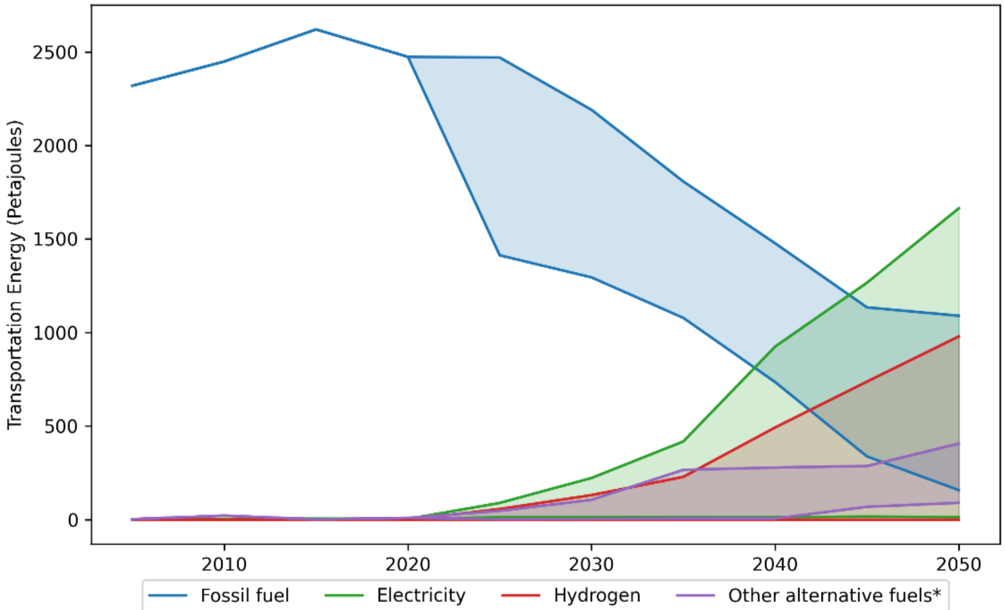
* Other alternative fuels includes bioenergy and renewable gas.

Transportation

The transportation sector includes transportation of both passenger and freight, which covers light-duty vehicles, medium-and-heavy-duty vehicles, rail, aviation, marine, off-road vehicles and pipelines. Each mode of transportation has varying energy requirements and ability to electrify. Where electrification is not possible, low-carbon fuels, such as hydrogen and biofuels, can support decarbonization. Similarly to the building sector, electricity is more energy efficient than fossil fuels for many modes of transport.

Modelling results in Figure 19 show the historical data and projected changes in fossil fuel, hydrogen, electricity, and other alternative fuels up to 2050 in the transportation sector. In all pathways, total energy use is projected to decrease at least 8% compared to 2020 levels. In all modelled scenarios, fossil fuels are projected to drop from being the main energy source to a minimum value of 8% of total energy use in this sector by 2050. Electricity plays a growing role in the modelled scenarios with a maximum of over 1600 PJ in 2050, or 72% of total energy use. In scenarios where hydrogen is cost-effective and scalable, this fuel can represent up to 49% of total energy, while biofuels reach up to a 30% share.

Figure 19: Scenarios for Energy Use in Transportation 2005 to 2050



* Other alternative fuels includes biofuel and renewable gas.

Contribution of CO_2 Removal

All scenarios reflect the potential of negative emissions that remove CO_2 from the atmosphere (e.g., LULUCF, DAC, BECCS). However, depending on the scenario, modelling results show that emissions are primarily reduced through electrification, alternative technologies (with greater efficiencies or less emissions-intensive processes), or fuel switching rather than through negative emissions technologies.

In each scenario, LULUCF was standardized to remove 100 $MtCO_2e$ by 2050 which allowed for more residual emissions to appear across the economy in the modelling. However, even with the 100 Mt of removals, in all but two modelled runs, DAC was projected to be necessary in reaching the net-zero emissions target. On top of this, BECCS appeared across all scenarios with a range of 16 to 73 Mt of removals. In the two scenarios that did not rely on DAC, higher levels of BECCS appeared.

Key Takeaways

Canada's LTS modelling demonstrates first, that widespread electrification of sectors—such as industry, buildings, and transportation—will likely be essential for reaching net-zero emissions. To achieve this, large increases in electricity generation from non-emitting sources (e.g., hydropower, wind, solar, and nuclear) would be required. Second, energy efficiency measures beyond electrification across the economy are likely to be crucial, with total energy use in the industry, buildings, and transportation sectors decreasing in all scenarios, despite a growth in population and output. Third, clean, alternative fuels such as bioenergy and hydrogen could play important roles in the pathway to net-zero emissions, especially in areas that are difficult to electrify, but electricity would likely dominates these fuels in most scenarios. Fourth, fossil fuel demand in Canada is found to decrease across all scenarios. Lastly, modelling results suggest that the usage of negative emissions technologies have a role to play in a net-zero emissions context. Residual emissions are likely to occur in sectors like transportation and industry, which are more challenging to decarbonize. To account for these emissions, removals from a combination BECCS and DAC are found to play key roles in all modelled scenarios, with the exception of two modelled runs where it is projected that net-zero emissions could be achieved without DAC.

Canada's Next Steps to Net-Zero Emissions

These illustrative scenarios show there are many different ways Canada can achieve its goal of net-zero emissions by 2050. However, some enabling conditions, such as renewable energy, electrification, and energy efficiency play a key role in all scenarios, and Canada is working to advance these through a number of measures and strategies. Looking ahead, there are many domestic and international factors that could change the course of Canada's pathway to net-zero emissions. For example, Canada's population and GDP growth will both play a large role in determining Canada's pathway to net-zero emissions. International factors, such as the scale of collective global action on climate change, global oil demand and price, and the rate of technological advancements, will also greatly impact Canada's trajectory.

Canada's Net-Zero Advisory Body

The Net-Zero Advisory Body (NZAB) is a legislated group of experts with relevant backgrounds that provide forward-looking independent advice to current and future governments with respect to achieving net-zero emissions over the next three decades. It is also mandated to conduct engagement activities related to achieving net-zero emissions. The NZAB is committed to transparency around its activities and its independent advice, and must submit an annual report with respect to its advice and activities, which must be made public.

Members of the NZAB bring together a diverse range of expertise in climate science, Indigenous Knowledge, social sciences and economics, clean technology, energy markets, and climate policy. The inaugural group of members, who come from across Canada, has been actively developing advice since February 2021. In June 2021, the NZAB released a summary of initial observations on transition pathways that the NZAB considers are the most likely for Canada to achieve net-zero emissions by 2050. The report identifies five foundational values (seize the upsides, put people first, motivate and empower Canadians, collaborate every step of the way, and recognize and respect regional differences and circumstances) and five design principles (Act early and urgently, be bold and proactive, acknowledge there is more certainty than uncertainty, don't get caught in the "net", and beware of dead-ends) to guide the development of net-zero emissions pathways.

In February 2022, the NZAB provided advice on Canada's 2030 ERP. It focused on four key areas: oil and gas, transportation, buildings, and governance. The advice from the NZAB was incorporated into the 2030 ERP and continues to guide federal climate efforts.

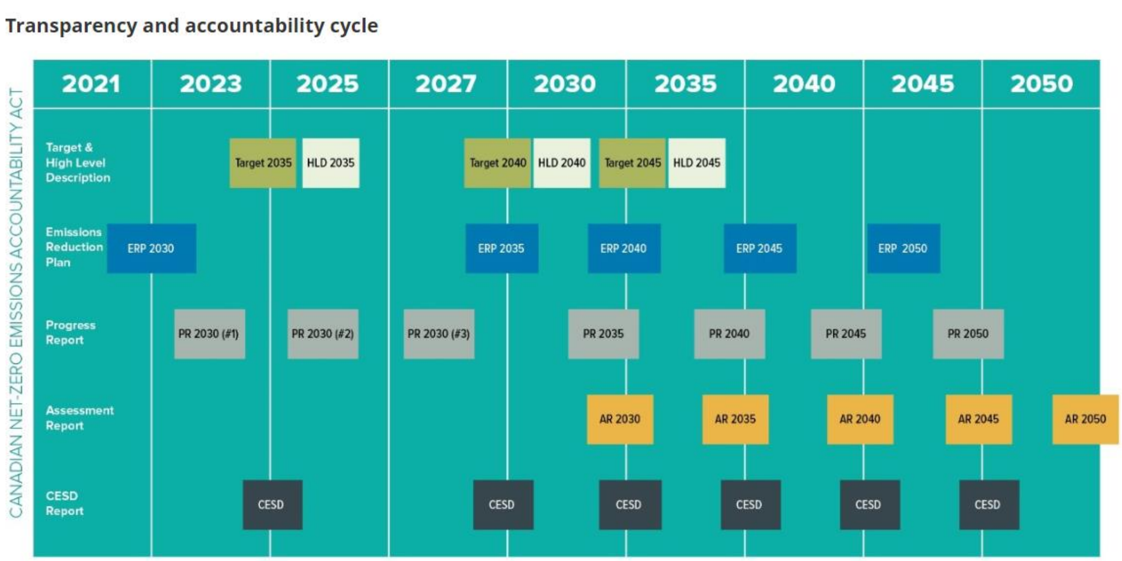
In the next phase of its work, the NZAB will delve deeper into the complex considerations needed to inform more specific policy advice moving forward. In particular, the NZAB's work is to be structured along specific "Lines of Inquiry", which may include certain sectors or thematic opportunities. Further information on the NZAB's current activities and forward-looking plans can be found on its website: https://nzab2050.ca/

Canada has taken steps to enable its achievement of net-zero emissions by 2050. In June 2021, Canada committed in law to reducing emissions to net-zero levels by 2050, through the *Canadian Net-Zero Emissions Accountability Act* (the Act). The Act codifies the process for setting national emissions reduction targets and introduces planning and reporting mechanisms to promote transparency and accountability in achieving those targets. In addition, the Act establishes the independent Net-Zero Advisory Body, a group of experts with a mandate to engage with Canadians and provide advice to the Minister of Environment and Climate Change on pathways to achieve net-zero emissions by 2050.

The Act requires the establishment of successively deeper emissions reduction targets for 2030, 2035, 2040, and 2045, and the tabling of an Emissions Reduction Plan (ERP) for each target, including the 2050 target. The Act requires the Minister of Environment and Climate Change to set the subsequent 2035, 2040 and 2045 targets at least 10 years in advance. Pursuant to the Act, the Government of Canada will also be required to provide updates in 2023, 2025 and 2027 through progress reports and assessment reports.

The Act also holds the Government of Canada accountable as it charts Canada's path to achieve net-zero emissions by 2050. It does so by establishing a transparent process to plan, assess and adjust the federal government's efforts to achieve, at regular intervals, national targets for the reduction of GHG emissions based on the best scientific information available, and by providing for public participation and independent advice and review with respect to those efforts. The Government of Canada will take into account this advice when setting emissions targets and emissions reductions plans. The work of the Net-Zero Advisory Body, along with additional engagement with provinces and territories, Indigenous Peoples, and the public will guide Canada's pathways to achieve net-zero emissions by 2050.

Figure 19: Canadian Net-Zero Emissions Accountability Act (CNZEAA) Milestones



The Act includes specific measures for third party review, the provision of independent advice and the public release of reports and plans to ensure Canadians have the information they need to hold the Government accountable. The Commissioner of Environment and Sustainable Development (CESD) must, at least once every 5 years, examine and report on the Government's implementation of climate change mitigation measures, including those undertaken to achieve each target. The CESD's first report is due no later than the end of 2024. All progress and assessment reports, emissions reduction plans, and the annual report of the NZAB must be made available to the public.

4. Conclusion

The science is clear: achieving deep emissions reductions by 2030 and net-zero emissions by 2050 is key to limit warming to 1.5°C and avert severe climate-related risks. Canada is taking charge and laying the foundation to support pathways to 2050, including by adopting a 2030 emissions target of 40-45 per cent below 2005 levels as its enhanced Nationally Determined Contribution and enshrining into legislation its commitment to being net zero by 2050 through the *Canadian Net-Zero Emissions Accountability Act*.

To achieve net-zero emissions by 2050, deep transformation of all sectors of the Canadian economy will be required, especially in the way that energy is produced and consumed. While much of this transition can be achieved with existing technology available today, significant investments in research, development, demonstration and deployment, and ongoing innovation are needed.

There is no one-size-fits-all approach for achieving net-zero emissions and that while the road to 2050 contains many opportunities, it is also uncertain. Canada's pathway to 2050 will be shaped by external factors, such as the availability of key emerging technologies and the global context. Decarbonizing the economy will allow Canada to support the competitiveness of traditional sectors in a global decarbonized market by taking advantage of our existing expertise and resources in areas like critical minerals.

The Government of Canada will continue to regularly review and update its path forward to consider changing circumstances and the best available science, supported by ongoing collaboration with communities, provinces and territories and Indigenous Peoples. While the pathway of transition may need to be tailored to support the unique needs of Canada's diverse jurisdictions, the direction and orientation are clear, and Canada is putting the building blocks in place for success.

ANNEX: Modelling Annex

A. Model and Assumption Details

In the modelling for Canada's LTS, there are several common assumptions regarding the international and domestic context of achieving net-zero emissions by 2050. This annex provides additional information on these contextual assumptions, as well as further technical information on each of the models used and their assumptions.

International and Domestic Assumptions

Across all scenarios and models, Canada is constrained to achieve or surpass net-zero emissions by 2050, as well as its Paris Agreement Nationally Determined Contribution (NDC) of 40 per cent emissions reduction from 2005 levels by 2030. It is assumed that land-use, land-use change, and forestry (LULUCF) will remove 30 $MtCO_2e$ in 2030 and 100 $MtCO_2e$ by 2050. These assumptions are consistent with the 2030 ERP and Annex 1 of Canada's Mid-Century Strategy study 2016. CCI assumed a similar offset potential from LULUCF in their report about reaching net-zero emissions by 2050, with 80 $MtCO_2e$ in 2030 and 105 $MtCO_2e$ in 2050. As models are illustrative to 2050, it should be noted that the LULUCF assumption is not a policy goal that reflects the anticipated impact of the LULUCF sector in meeting Canada's climate objectives. Further, the precise contribution that LULUCF will make to Canada's net-zero target is uncertain, and is likely to change as more sophisticated analysis is undertaken.

Given that Canada is a small open economy, international assumptions and frameworks have effects on Canada's industry and trade-exposed sectors. The models in Canada's LTS use other countries' NDCs as the base of international and national assumptions. Similar to Canada, countries are constrained to either achieve or surpass their NDCs. For modelling purposes, countries or regions with explicit net-zero emissions pledges achieve their target in the announced year. Most of the countries have 2050 as the net-zero emissions target year. For countries without a net-zero target, it is assumed that their post-NDC targets will be met with linear extrapolation. Table 1 shows G20 members' GHG mitigation pledges for 2030 NDCs and achieving the net-zero emissions target. Intermediate targets are also included in this exercise. In the context of reaching net-zero emissions, GHG emissions can be lower than the intermediate targets announced. In order to constrain regions to their NDCs, carbon pricing or an emissions cap by region is used.

Table 1: Summary of GHG mitigation pledges by G20 members

G20 members	NDCs Pledge	
	2030 Pledge	Net-zero Target Year
United States of America	Reduce GHG emissions by 50% to 52% from 2005 levels by 2030	2050
Canada	Reduce GHG emissions by 40 to 45% from 2005 level by 2030	2050
United Kingdom	Reduce GHG emissions by at least 68% from 1990 levels by 2030	2050
EU27	Reduce net GHG emissions by at least 55% from 1990 levels by 2030	2050
Republic of Korea	Reduce GHG emissions by 35% from 2018 levels by 2030	2050
Japan	Reduce GHG emissions by 46% from 2013 levels by 2030, with efforts to reduce by 50%	2050

China	Peak CO_2 emissions before 2030 Reduce CO_2/GDP by 65% from 2005 levels by 2030 Increase the share of non-fossil fuels in primary energy consumption to around 25% by 2030 Increase forest stock volume by around 6 billion cubic metres in 2030 Increase the installed capacity of wind and solar power to 1200 GW by 2030	2060
Australia	Reduce GHG emissions by 26% to 28% from 2005 levels by 2030	2050
Russia	Reduce GHG emissions by 30% from 1990 levels by 2030	2060
India	Reduce emissions/GDP by 33% to 35% from 2005 levels by 2030 Increase the share of non-fossil fuels in primary electricity production to 40% (conditional)	2070
Brazil	Reduce GHG emissions by 43% from 2005 levels by 2030	2050
Mexico	Reduce GHG emissions by 22% (unconditional) and 36% (conditional) from BAU by 2030	N/A
Argentina	Cap 2030 net emissions at 359 $MtCO_2e$ (unconditional)	2050
Indonesia	Reduce GHG emissions by 29% (unconditional) and 41% (conditional) relative to BAU by 2030	2060
South Africa	Limit 2030 emissions to 350 to 420 $MtCO_2e$	2050
Saudi Arabia	Annually abate up to 130 $MtCO_2e$ by 2030	2060
Turkey	Reduce GHG emissions by up to 21% from BAU by 2030	2053

Sources : climateactiontracker.org and https://www.unep.org/fr/resources/emissions-gap-report-2021

The modelling for Canada's LTS uses three international models as they reflect mitigation actions taken by the global community and linkage to the international trade impact of these actions. Given that Canada is a small open economy, endogenous modelling of how Canada's trading partners and the global community respond to the imperative to reduce emissions provides clearer insights into Canada's potential pathway.

Global Change Analysis Model (GCAM)

Global Change Analysis Model (GCAM) is an open-source integrated assessment model that captures key interactions between worldwide economic, energy, land use, agriculture, water, and climate systems. The model was created by Edmonds and Reilly in 1985.[13] GCAM is now primarily developed and maintained by the Joint Global Change Research Institute (JGCRI) and a full description of the model is available at GitHub.

GCAM represents a class of recursive dynamic partial equilibrium model runs in five-year time steps, with 2015 as the last historical period. The model divides the world into 32 regions (with Canada as a separate region) and 384 land-water sub-regions that are defined along hydrologic basins.[14] Energy and land systems are connected in the model through supply and demand for bioenergy and nitrogen fertilizer markets. Anthropogenic sources of emissions from the energy and land systems are provided in a reduced-form climate model called Hector.[15] The model uses population and labour productivity growth as main drivers of socio-economic activities that are prescribed exogenously. These socio-economic indicators influence the demand and supply mechanism for energy and agriculture (e.g. food, feed, and forestry) commodities through interactions across sectors (Joint Global Change Research Institute (JGCRI)). The sectors in GCAM cover alternative technologies that compete based on several

[13] Edmonds and Reilly, 1985
[14] Calvin et al., 2019
[15] Hartin et al., 2015

factors including their costs, efficiencies, climate-effectiveness (e.g. emissions intensity in case of climate policy), and consumer behaviour (i.e. income and price elasticities).
The model's energy system includes regional representation of both depletable (coal, oil, natural gas, and uranium) and renewable (bioenergy, solar, and wind) resources. The depletable and bioenergy resources are traded in global markets. Energy transformation sectors, such as electricity generation, liquid refining, gas processing, and hydrogen production, are used to convert primary resources to final energy carriers. These final energy carriers are used to produce energy services in the transportation, building, and industrial end-use sectors. Technology deployment in GCAM's energy and other human systems is determined by relative cost as well as consumer preferences for established technologies, which are based on historical trends. Economic decision-making is based on the discrete choice (logit) formulation, which allows a distribution of heterogeneous real-world conditions and avoids unrealistic winner-takes-all outcomes.[16] For each time step, the model seeks for equilibrium prices that balance supply and demand for energy, land, and emissions markets in each modelled region. Commodity prices and regional production levels are determined endogenously.

GCAM Database and Model Calibration

GCAM is calibrated based on a set of commodity-demand databases consistent with the supply data for every historical period and all specified regions. The model uses this balanced supply-demand commodity data along with a set of cost and price assumptions to solve for market equilibrium, in each historical time step. Given its recursive nature, GCAM uses the last base year's solution as initial values to calibrate its first future period, and then repeats this same mechanism for the subsequent periods.

While JGCRI provides detailed information on databases and assumptions applied in the released version of the GCAM model, a brief description of the data and sources used in the model calibration is indicated in Table 2. Canada's LTS has used a modified version of GCAM v5.3 by incorporating the Canadian historical energy demand and supply balance aligned with Environment and Climate Change Canada's reference case 21 (i.e. Ref21), which is prepared by the E3MC model (Table 2). ECCC's GCAM version has also incorporated some additional features related to hydropower electricity generation,[17] and the Canadian unconventional oil supply technologies.[18] Using 2015 (the last historical year) as the base year, the model calibrates for future periods at 5-year time steps until 2100.

[16] Clarke and Edmonds, 1993; McFadden, 1980; Train, 1993
[17] Arbuckle et al., 2021
[18] Bergero et al., 2022

Table 2: GCAM Database and Parameters' Information

GCAM System	Region	Indicators	Source/References
Socio-economic	Other regions	Population GDP	• United Nation, Maddison, SSP database • USDA, World Bank, IMF, SSP database, OECD Model • http://jgcri.github.io/gcam-doc/inputs_economy.html
	Canada	Population GDP	• Statistics Canada Table 17-10-0057-01 (M1: medium growth scenario: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710005701) and E3MC population projection • Statistics Canada Table 36-10-0222 (https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610022201) and E3MC reference case (Ref21)
Energy (Historical data)	Other regions	Energy supply and demand balance	• International Energy Agency (IEA) 2019 data used for history with last historical model year 2015 • http://jgcri.github.io/gcam-doc/inputs_demand.html
	Canada		• Environment and Climate Change Canada's E3MC reference case (Ref21) – https://publications.gc.ca/collections/collection_2022/eccc/En1-78-2021-eng.pdf
Food, Feed, and Forestry	All regions	Historical database for agriculture and livestock commodities and forest products	• http://jgcri.github.io/gcam-doc/inputs_demand.html#food--feed--forestry
Land	All regions	Historical Land Use and Land Cover data	• Moirai Land Data System (Moirai LDS) • http://jgcri.github.io/gcam-doc/inputs_land.html • https://github.com/JGCRI/moirai
Electricity generation	All regions	Capital cost	• Annual Technology Baseline 2019 • http://jgcri.github.io/gcam-doc/inputs_supply.html#energy
		Other costs, efficiency, and capacity factors	• Muratori, M., Ledna, C., McJeon, H., et al. 2017. Cost of power or power of cost: A U.S. modeling perspective. Renewable and Sustainable Energy Reviews 77, pp. 861-874
Hydrogen	All regions	Hydrogen production structure	• U.S. Department of Energy. 2015. DOE H2A Production Analysis, DOE Hydrogen and Fuel Cells Program • http://jgcri.github.io/gcam-doc/v5.3/energy.html#doe2015 • Argonne National Laboratory, 2015, Hydrogen delivery scenario analysis model (HDSAM), Argonne National Laboratory • http://jgcri.github.io/gcam-doc/details_energy.html#anl2015
Building	All regions	Heating and cooling system, and energy demand	• Clarke, L., Eom, J., Hodson Marten, E., et al. 2018. Effects of long-term climate change on global building energy expenditures. Energy Economics 72, pp. 667-677 • http://jgcri.github.io/gcam-doc/v5.3/energy.html#clarke2018
	All regions	Historical building sector demand by energy type	• International Energy Agency (IEA) 2019
	Canada		• Aligned with Environment and Climate Change Canada's E3MC reference case 21
Industry	All regions	Historical industrial energy demand	• International Energy Agency (IEA) 2019 • http://jgcri.github.io/gcam-doc/v5.3/energy.html#clarke2018
	Canada		• Aligned with Environment and Climate Change Canada's E3MC reference case 21
Transport	All regions	Transport input data assumptions	• Mishra, G.S., Kyle, P., Teter, J., Morrison, G.M., Kim, S., and Yeh, S. 2013. Transportation Module of Global Change Assessment Model (GCAM): Model Documentation, Research Report UCD-ITS-RR-13-05, Institute of Transportation Studies, University of California, Davis. • http://jgcri.github.io/gcam-doc/v5.3/energy.html#mishra2013
	All regions	Historical energy	• International Energy Agency (IEA) 2019

	Canada	demand by fuels and mode	• Aligned with Environment and Climate Change Canada's E3MC reference case 21
Non-CO2 emissions	All regions	Non-CO2 Marginal Abatement Cost (MAC)	• US EPA, 2013, Global Mitigation of Non-CO2 Greenhouse Gases: 2010-2030. EPA-430-R-13-011, United States Environmental Protection Agency, Office of Atmospheric Programs • https://www.epa.gov/sites/default/files/2016-06/documents/mac_report_2013.pdf, http://jgcri.github.io/gcam-doc/v5.3/emissions.html#epa2013

Key Model and Sectoral Assumptions

Socio-Economic Parameters

Socioeconomic Indicators for Canada used in GCAM

Indicators	2020	2025	2030	2035	2040	2045	2050
GDP (MER) in USD 2015 billion*	2.12	2.46	2.70	2.97	3.30	3.60	3.93
Population in million	38.01	40.11	42.29	44.36	46.36	47.50	48.64

** Conversion from US$1990 to US$2015 IS TAKEN FROM https://fred.stlouisfed.org/series/USAGDPDEFAISMEI*

Power Generation Sector

Capital Cost Assumptions for Electricity Generation Technologies (2015 US$/kW)

Technology	2020	2030	2040	2050
Biomass (conv)	3657	3513	3397	3303
Biomass (IGCC)	5384	4994	4675	4415
Biomass (conv CCS)	6886	6352	5914	5556
Biomass (IGCC CCS)	7844	7104	6503	6009
Coal (conv pul)	3506	3411	3334	3271
Coal (IGCC)	3692	3485	3334	3218
Coal (IGCC CCS)	5984	5472	5096	4819
Coal (conv pul CCS)	5370	5222	5089	4966
Gas (CC)	920	825	779	762
Gas (CC CCS)	2025	1885	1783	1709
Gas (steam/CT)	839	800	776	765
Refined liquids (CC)	920	825	779	762
Refined liquids (steam/CT)	839	800	776	765
Refined liquids (CC CCS)	2397	2218	2085	1983
Gen_II_LWR	5980	5980	5980	5980
Gen_III	5879	5682	5503	5345
CSP_storage	6440	4640	3766	3345
PV_storage	5380	3759	2885	2411
CSP	3755	2632	2144	1930
PV	1678	1056	842	765
Wind	1425	1211	1081	1004
Wind_offshore	3338	2530	2050	1762
Wind_storage	5005	3776	3043	2604
Rooftop_pv	2678	1628	1260	1134
Geothermal	4391	3955	3668	3475
Hydropower	2239	2239	2239	2239

Fixed O&M Cost Assumptions Electricity Generation Technologies (2015 US$/kW per yr)				
Technology	2020	2030	2040	2050
Biomass (conv)	102	100	98	96
Biomass (IGCC)	146	135	128	122
Biomass (conv CCS)	123	118	114	111
Biomass (IGCC CCS)	175	161	151	144
Coal (conv pul)	27	26	26	25
Coal (IGCC)	36	34	32	31
Coal (IGCC CCS)	71	64	59	56
Coal (conv pul CCS)	52	48	45	43
Gas (CC)	11	10	10	10
Gas (CC CCS)	21	19	18	17
Gas (steam/CT)	12	10	10	10
Refined liquids (CC)	11	10	10	10
Refined liquids (steam/CT)	11	10	10	10
Refined liquids (CC CCS)	24	22	21	20
Gen_II_LWR	103	103	103	103
Gen_III	102	100	98	96
CSP_storage	65	22	52	49
PV_storage	50	46	44	42
CSP	54	47	43	40
PV	42	39	37	35
Wind	54	52	51	50
Wind_offshore	128	119	112	107
Wind_storage	64	62	60	59
Rooftop_pv	62	58	55	52
Geothermal	107	105	103	101
Hydropower	15	16	16	16

Variable O&M Cost Assumptions Electricity Generation Technologies (2015 US$/kW per yr)				
Technology	2020	2030	2040	2050
Biomass (conv)	11	10	10	10
Biomass (IGCC)	16	15	14	13
Biomass (conv CCS)	14	13	13	12
Biomass (IGCC CCS)	19	17	16	15
Coal (conv pul)	4	4	4	4
Coal (IGCC)	7	6	6	6
Coal (IGCC CCS)	10	9	9	8
Coal (conv pul CCS)	8	8	7	7
Gas (CC)	4	4	4	4
Gas (CC CCS)	7	7	6	6
Gas (steam/CT)	7	6	6	6
Refined liquids (CC)	4	4	4	4
Refined liquids (steam/CT)	6	6	6	6
Refined liquids (CC CCS)	9	8	7	7
Gen_II_LWR	2	2	2	2
Gen_III	2	2	2	2

Hydrogen Production

Technology Cost Assumptions for Hydrogen Production (2015 US$/GJ)					
Sector	Subsector	Technology	2030	2040	2050
H2 central production	Hydrobased	Electrolysis*	14	14	14

H2 central production	Biomass	Biomass to H2	10	9	9
H2 central production	Biomass	Biomass to H2 CCS	13	12	11
H2 central production	Coal	Coal chemical	10	9	9
H2 central production	Coal	Coal chemical CCS	13	12	11
H2 central production	Gas	Natural gas steam reforming	3	3	3
H2 central production	Gas	Natural gas steam reforming CCS*	4	4	4
H2 central production	Nuclear	Thermal splitting	25	25	25
H2 central production	Solar	Electrolysis	26	26	26
H2 central production	Wind	Electrolysis	26	26	26
H2 distribution	H2 distribution	H2 distribution	20	20	19
H2 forecourt production	Electricity	Electrolysis	26	26	26
H2 forecourt production	Gas	Natural gas steam reforming	21	19	18

The cost of NG-CCS and Hydrobased electrolysis are adjusted based on the "Perspectives on Hydrogen.
https://aperc.or.jp/file/2018/9/12/Perspectives+on+Hydrogen+in+the+APEC+Region.pdf
in the APEC Region"

Transport Sector

Selected Passenger Transport Sector's cost and intensity Assumptions

Mode	Technology	Load Factor (load/veh)	CAPEX and non-fuel OPEX (2015 US$/pass-km)				Energy Intensity of New vehicles (MJ/vkm)			
			2020	2030	2040	2050	2020	2030	2040	2050
Car	BEV	1.68	1.55	0.95	0.67	0.51	0.69	0.60	0.60	0.60
	FCEV	1.68		1.16	0.74	0.57		0.86	0.86	0.86
	Hybrid Liquids	1.68	1.31	1.17	1.17	1.17	1.86	0.94		
	Liquids	1.68	1.22	1.22	1.22	1.22	2.32	1.18		
Large Car and Truck	BEV	1.84	1.70	1.10	0.78	0.59	0.87	0.75	0.75	0.75
	FCEV	1.84		1.15	0.83	0.64		1.08	1.08	1.08
	Hybrid Liquids	1.84	1.38	1.34	1.33	1.32	2.33	1.15		
	Liquids	1.84	1.28	1.28	1.28	1.28	2.96	1.45		

Selected Freight Transport Sector's cost and intensity Assumptions

Mode	Technology	Load Factor (Tonnes /veh)	CAPEX and non-fuel OPEX (2015 US$/pass-km)				Energy Intensity of New vehicles (MJ/vkm)			
			2020	2030	2040	2050	2020	2030	2040	2050
Light truck	BEV	0.68		3.26	3.19	3.11		1.51	1.48	1.44
	FCEV	0.68		3.18	3.15	3.11		2.03	2.00	1.96
	Liquids	0.68	2.81	2.78	2.78	2.78	4.02	3.68		
Medium truck	BEV	4.88		3.48	3.39	3.31		3.32	3.32	3.32
	FCEV	4.88		3.38	3.35	3.31		4.47	4.47	4.47
	Liquids	4.88	3.20	2.92	2.92	2.92	9.58	8.23		
Heavy truck	BEV	10		5.00	4.42	3.85		6.54	6.36	6.21
	FCEV	10		3.95	3.82	3.70		8.36	8.27	8.17
	Liquids	10	3.35	3.35	3.35	3.35	11.66	11.52		

Building Sector

Technology Cost and Efficiency Assumptions for Commercial Building Sector

Services	Technology	Technology Cost (2015$/GJ)				Technology Efficiency			
		2020	2030	2040	2050	2020	2030	2040	2050
Heating	Wood furnace	3.47	3.47	3.47	3.47	0.40	0.40	0.41	0.41
	Coal furnace	3.47	3.47	3.47	3.47	0.50	0.50	0.51	0.52

	Gas furnace	5.39	5.39	5.39	5.39	0.79	0.82	0.84	0.86
	Gas furnace with H2 blend	0.00	8.04	7.90	7.90	0.00	2.24	2.34	2.39
	Electric furnace	4.49	4.49	4.49	4.49	0.94	0.96	0.97	0.98
	Electric Heat Pump	0.00	23.98	23.98	23.98	0.00	3.30	3.30	3.30
Cooling	Gas cooling	17.37	17.37	17.37	17.37	0.84	0.86	0.88	0.90
	Air conditioning	9.23	9.23	9.23	9.23	3.00	3.19	3.40	3.62
Others	Biomass	11.23	11.23	11.23	11.23	0.30	0.31	0.31	0.30
	Coal	7.49	7.49	7.49	7.49	0.40	0.40	0.40	0.41
	Electricity	9.20	9.20	9.20	9.20	0.98	1.01	1.03	1.03
	Gas	10.83	10.83	10.83	10.83	0.60	0.64	0.64	0.63
	Refined liquids	11.73	11.73	11.73	11.73	0.60	0.62	0.62	0.62

Technology Cost and Efficiency Assumptions for Residential Building Sector

Services	Technology	Technology Cost (2015 US$/GJ)				Technology Efficiency			
		2020	2030	2040	2050	2020	2030	2040	2050
Heating	Wood furnace	3.31	3.31	3.31	3.31	0.40	0.40	0.41	0.41
	Coal furnace	3.31	3.31	3.31	3.31	0.50	0.50	0.51	0.52
	Gas furnace	4.55	4.55	4.55	4.55	0.85	0.86	0.87	0.87
	Gas furnace with H2 blend	0.00	7.02	7.02	7.02	0.00	2.18	2.18	2.18
	Electric furnace	4.55	4.55	4.55	4.55	0.94	0.96	0.97	0.98
	Electric Heat Pump	7.10	7.10	7.10	7.10	2.67	2.74	2.77	2.77
Cooling	Gas cooling	39.46	39.46	39.46	39.46	0.84	0.86	0.88	0.90
	Air conditioning	23.56	23.56	23.56	23.56	2.89	3.07	3.27	3.48
Others	biomass	12.11	11.23	11.23	11.23	0.30	0.33	0.31	0.31
	coal	7.49	7.49	7.49	7.49	0.40	0.40	0.41	0.41
	electricity	9.03	9.03	9.03	9.03	0.98	1.02	1.05	1.08
	gas	10.64	10.53	10.53	10.53	0.61	0.63	0.64	0.65
	refined liquids	11.73	11.73	11.73	11.73	0.60	0.61	0.61	0.62

Environment Canada Integrated Assessment Model (EC-IAM)

Environment Canada Integrated Assessment Model (EC-IAM) is an integrated assessment model developed by Environment and Climate Change Canada that provides an integrated assessment framework to assess the long-term implications of global and national climate policies, in a context where damage due to climate change is considered.
EC-IAM divides the world into 15 geopolitical regions. The model runs into five-year time steps (with 2020 as the last historical period) and is built to run until the end of century (2100). EC-IAM is classified as a forward-looking model and has the capacity to assess the optimal economic pathway over the model's time horizon. The model combines a top-down description of the macroeconomic activities and a bottom-up approach of the energy system to represent the technologies and energy commodities level.

EC-IAM includes four integrated modules (macroeconomics, energy system, climate, and damages) that interact to determine optimal technological choices related to GHG policies and climate damages. The economic production module describes the macroeconomic activities, where each region is represented as an economic producer-consumer agent. Regions make optimal decisions to maximize the intertemporal discounted utility (welfare), which is calculated via consumption. The energetic module determines the optimal technology mix for energy supply and demand. Exhaustible resources (oil and natural gas) are represented by a hoteling module. The extraction level is computed endogenously considering both the amount of proven and unproven reserves associated to reserve additions and extraction costs. These resources are tradable in global markets. Over each time period, equilibrium prices are found in the international market to balance world supply and demand. Bioenergy production level is determined by cost curves influenced by the potential level of forestry resources and cropland available.

EC-IAM includes energy transformation sectors, such as electricity generation, liquid refining and hydrogen production, to convert primary resources to final energy carriers. These final energy carriers are used to produce energy services in four end-use sectors: transportation, residential and commercial building, and industrial sector. Technology choice and deployment are based on several factors such costs (energetic and non-energetic), energy efficiency, emissions intensity, capital stock, consumer preferences, learning by doing improvement rate, and more. Finally, the climate and damage modules create a dynamic between regional emissions, global concentration, temperature, and market (GDP) or non-market (welfare lost) damages.

EC-IAM Database and Model Calibration

EC-IAM projects its own reference scenario. This is heavily influenced by the 2017 International Energy Outlook (IEO) database for all regions other than Canada. For Canada, the reference scenario is calibrated to the E3MC reference scenario, Ref21, developed internally by Environment and Climate Change Canada.

These main information sources provide macroeconomic, energy supply, transformation and demand data, as well as GHG emissions. EC-IAM is built to be easily updated to IEO data updates. The model is also structured to follow a similar disaggregation to IEO available data. Both historical data and projections, from IEO and E3MC, are used in EC-IAM.

To complement these datasets and to introduce regional specifications, multiple other datasets are used as well. These are used mainly for cost definitions, GHG emissions coefficients, and climate information. This information is continually updated with new information sources available with technological developments. All these datasets and assumptions are computed into a complex and integrated structure unique to EC-IAM that has to objective to represent the reality of the energy system. The sources used to calibrate EC-IAM are show in the tables below.

EC-IAM System	Regions	Indicators	Sources/References
Socio-economic	Other regions	Population	• International energy outlook 2017 https://www.eia.gov/outlooks/archive/ieo17/ieo_tables.php
		GDP	
	Canada	Population	• E3MC reference case (Ref17)
		GDP	
Energy supply and demand	Other regions	Energy supply and demand	• International energy outlook 2017 https://www.eia.gov/outlooks/archive/ieo17/ieo_tables.php
	Canada		• E3MC reference case (Ref17)

	Other regions	Electricity generation and capacity	• https://www.eia.gov/outlooks/archive/ieo17/ieo_tables.php
	Canada		• E3MC reference case (Ref17)
Electricity generation	All regions	Capital cost, O&M cost, efficiency, capacity factor, and carbon capture and sequestration emissions intensity	• Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2021 https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capital_cost_AEO2020.pdf • Projected Costs of Generating Electricity 2020 Edition https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf • Renewables 2019 global status report https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf • Renewable Power Generation Costs in 2018 https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018
Bioenergy	All regions	Production costs, potential resources and land area	• Biomass Production and Logistics https://iea-etsap.org/E-TechDS/PDF/P09_Biomass%20prod&log_ML_Dec2013_GSOK.pdf • Global Bioenergy Supply and Demand Projections: A working paper for REmap 2030 https://www.irena.org/publications/2014/Sep/Global-Bioenergy-Supply-and-Demand-Projections-A-working-paper-for-REmap-2030 • Biofuels Issues and Trends https://www.eia.gov/biofuels/issuestrends/pdf/bit.pdf • Biofuels and agriculture – a technical overview https://www.fao.org/3/i0100e/i0100e02.pdf • Land use https://www.fao.org/faostat/en/#data/RL • OECD-FAO Agricultural Outlook 2019-2028 https://www.oecd.org/agriculture/oecd-fao-agricultural-outlook-2019/ • Bioenergy potentials from forestry in 2050 https://www.researchgate.net/publication/260171815_Bioenergy_potentials_from_forestry_in_2050
Hydrogen	All regions	Non-energetic cost and efficiency	• H2A: Hydrogen Analysis Production Models https://www.nrel.gov/hydrogen/h2a-production-models.html • IEA G20 Hydrogen report: Assumptions https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf
Direct Air Capture	All regions	Cost and energy input	• Keith, D. W., Holmes, G., Angelo, D. S., & Heidel, K. (2018). A process for capturing CO2 from the atmosphere. Joule, 2(8), 1573-1594. • https://www.cell.com/joule/pdf/S2542-4351(18)30225-3.pdf

Fossil fuel extraction	Other regions	Historical dataset for energy supply	• Statistical Review of World Energy – all data, 1965-2021 https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
	Canada		• E3MC reference case (Ref17)
	All regions	Proven and unproven resource potential	• Energy Resources and Potentials https://previous.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA_Chapter7_resources_hires.pdf • Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States https://www.eia.gov/analysis/studies/worldshalegas/pdf/overview.pdf
	All regions	Production costs	• Cost of producing a barrel of crude oil by country https://knoema.com/rqaebad/cost-of-producing-a-barrel-of-crude-oil-by-country • Barrel Breakdown http://graphics.wsj.com/oil-barrel-breakdown/
Building	Other regions	Historical and projected dataset for energy demand	• International energy outlook 2017 https://www.eia.gov/outlooks/archive/ieo17/ieo_tables.php
	Canada		• E3MC reference case (Ref17)
	All regions	Non-energetic cost and efficiency	• GCAM model https://github.com/JGCRI/gcam-core
Transport	Other regions	Historical and projected dataset for energy demand	• International energy outlook 2017 https://www.eia.gov/outlooks/archive/ieo17/ieo_tables.php
	Canada		• E3MC reference case (Ref17)
	All regions	Non-energetic cost, efficiency and share by mode of transport	• GCAM model https://github.com/JGCRI/gcam-core

Industry	Other regions	Historical and projected dataset for energy demand	• International energy outlook 2017 https://www.eia.gov/outlooks/archive/ieo17/ieo_tables.php
	Canada		• E3MC reference case (Ref17)
	All regions	Non-energetic cost, efficiency, CCS emission intensity	• GCAM model https://github.com/JGCRI/gcam-core
			• Technology readiness and costs of CCS https://www.globalccsinstitute.com/wp-content/uploads/2022/03/CCE-CCS-Technology-Readiness-and-Costs-22-1.pdf
Emissions	Other regions	CO2 emissions level	• International energy outlook 2017 https://www.eia.gov/outlooks/archive/ieo17/ieo_tables.php
	Canada		• E3MC reference case (Ref17)
	All regions	Historical LULUCF emissions	• GHG data from UNFCCC https://unfccc.int/process-and-meetings/transparency-and-reporting/greenhouse-gas-data/ghg-data-unfccc/ghg-data-from-unfccc
Non-CO2 emissions	All regions	Emissions level and Marginal Abatement Cost (MAC)	• Global Non-CO2 Greenhouse Gas Emission Projections & Mitigation Potential: 2015-2050 https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-non-co2-greenhouse-gas-emission-projections • Methane Tracker Data Explorer Methane Tracker Data Explorer – Analysis - IEA

Table 3 : Socioeconomics indicators for Canada used in EC-IAM

Indicator	2020	2025	2030	2035	2040	2045	2050
GDP (MER) in 2018 US billion $	2.39	2.61	2.85	3.12	3.40	3.70	3.85
Population in million	37.3	39.1	40.8	42.4	43.9	45.3	46.7

Table 4 : International oil and gas costs in Reference case from EC-IAM

Indicators	2025	2030	2035	2040	2045	2050
International oil cost (2018 US$)	6.25	6.72	7.10	7.82	8.40	8.90
International gas cost (2018 US$)	4.84	5.01	5.13	5.47	5.58	5.78

Environment and Climate Change Canada's Multi-sector Multi-regional Model (EC-MSMR)

Environment and Climate Change Canada's multi-sector multi-regional model (EC-MSMR) is an open-economy recursive-dynamic CGE model of the global economy. There are 23 basic commodity-producing sectors and 3 final-demand sectors (consumption, governmental spending, and investment). It captures international trade dynamics between the 17 regions modeled (Australia, New Zealand, China, Japan, Korea, India, Canada, USA, Mexico, Brazil, United Kingdom, Russia, South Africa, EU-27, OPEC countries, South America without Brazil and

Venezuela, Rest of the world). Each region in the model is represented by a single household whose objective is to maximize welfare subject to its budget constraint. Given the recursive-dynamic nature of the model, the representative household makes its investment and consumption decision in each period to maximize its welfare based on past states of the economy only.

The Recursive-Dynamic Formula of the Model

EC-MSMR distinguishes between extant capital and new capital. Extant capital is defined as the remaining capital after depreciation and is sector-specific; new capital is formatted exclusively through new investment. Investment, consumption, and production decisions are determined only by the economic situation in the current period. New capital and labour services are mobile across sectors but immobile across regions. The saving-investment is modeled through Tobin Q's response to the ratio of capital's return to the cost of investment. In EC-MSMR, the elasticity of investment to this ratio is assumed to be 0.3, which means, when the capital service price relative to the investment cost doubles, the investment would increase by 30% relative to benchmark. It is also assumed that government spending and the current account balance are fixed for policy comparison purposes.

Equilibrium Conditions

All GHG emissions including CO_2 and non-CO_2 emissions (e.g., CH_4, N_2O and FGAS (comprising of HFCs, PFCs and SF_6)) except those from land use, land-use change and forestry (LULUCF) are accounted for in the model with abatement occurring via inter-fuel substitution or energy savings (by substituting energy inputs for non-energy inputs and/or by a scaled reduction of production). Similarly, emissions can be reduced by substituting emissions-intensive commodities for less emission intensive ones in final consumption. The baseline calibration in EC-MSMR is carried out recursively based on the assumptions about economic growth and technological changes of production (automatic energy efficiency improvements (AEEI)). The detailed procedure used for baseline calibration is described in report co-authored by FæHn et al. (2019).[19]

Equilibrium in the model is characterized by market clearing in goods, factors of production, and all other markets in all regions of the model. Prices of goods and factors of production are determined endogenously, which ensures that all primary factors are fully employed, and all markets are cleared.

The oil price is exogenously given and resource scaling occurs endogenously on account of this. The model assumes that gas prices rise with oil prices and as a result does not impose gas reference prices in the final equilibrium calculation. The model computes a projected benchmark with a crude oil reference price from the US Energy Information Administration's (EIA) 2021 Annual Energy Outlook (AEO) (Table 5). Because prices are determined endogenously within the model allowing for markets to clear, the reference prices are taken as initial values with the observed prices deviating from the reference as required by the model in order to achieve an equilibrium solution.

[19] FæHn et al., 2019

Table 5: EC-MSMR Energy Commodity reference prices

Commodity (2014 USD)	2020	2025	2030	2035	2040	2045	2050
Brent Spot Price (dollars per barrel)	61.69	75.43	84.18	91.08	97	103.23	108.95
Natrual Gas at Henry Hub (dollars per mmBtu)	2.57	3.12	3.65	3.68	3.69	3.71	3.83
Coal, Minemouth (dollars per ton)	34.79	37.63	37.24	37.5	39.27	39.59	39.24
Electricity (Cents per kilowatthour)	10.77	11.33	11.51	11.22	10.86	10.59	10.28

**World oil price data is based on brent prices as reported by AEO 2021 for the years 2019-2050. Conversion from nominal dollars to 2014 USD was done using the AEO Energy Commodities and Services price index*

Restrictions on GHG emissions in production and consumption can be implemented through either exogenous emission constraints to keep emissions to a specified limit that determines the emission taxes required endogenously, or through exogenous GHG taxes that determine the reductions achieved endogenously. Revenues from emission regulation accrue from CO_2 taxes (or, equivalently, from the auctioning of emission allowances) and are recycled back to the economy in a revenue-neutral way in the respective region.

Model Input Data & Parameterization

The key sources of data used in the model is the GTAP (Global Trade Analysis Project) data version of GTAP 10,[20](and the US Energy Information Administration's (EIA) International Energy Outlook 2019.[21] GTAP 10 has the following key features: (1) base year of 2014; (2) global multi-regional input-output tables providing key values for economic transactions including production, consumption and bilateral trade for 65 sectors and 141 regions; (3) initial tax margins for inputs, output and trade; (4) fossil fuel-related CO_2 emissions by sector and fuel; (5) values of parameters, such as elasticity of substitution in value-added and trade. In a satellite table, GTAP also provides detailed data for emissions of non-CO_2 GHGs such as CH_4, N_2O and F-gas for the base year.

For Canada, the base year's economic accounts from Statistics Canada's 2014 D-level National Input-output tables are aggregated to the model's sector profile. Canada's energy and emissions including CO_2 and non-CO_2 emissions data comes from E3MC 2021 Reference case.

Table 6: MSMR real GDP according to model baseline

Indicator	2020	2025	2030	2035	2040	2045	2050
Real GDP (2014 Billion USD)	1711	1995	2182	2392	2623	2861	3098

For other global regions in Table 1, the technology and economic growth assumptions come from UNFCCC's submitted Fourth Biennial Reports (BR4);[22] for all other regions, the calibration assumptions come from USA EIA's 2019 International Energy Outlook on economy, energy and CO_2 emissions.[23] For non-CO_2 the emissions projection and bottom-up estimates of country-specific MACs across different activities come from the US Environmental Protection Agency. We use the value of elasticity parameters related to capital, labour, energy and material substitutions from the empirical estimates in Okagawa and Ban (2008), as the sectoral and regional disaggregation is similar to those in our model.[24] More importantly, these estimates were obtained for CGE use. The range of elasticity for KLE lies between 0.2 and 0.3.[25]

[20] Aguiar et al., 2016
[21] US EIA, 2019
[22] UNFCCC, 2020
[23] EIA-IEO, 2019
[24] Okagawa and Ban, 2008
[25] Cross-comparison of these values with other models finds that these are not significantly different from others.

Table 7: MSMR Database and Parameter Information

MSMR System	Region	Indicators	Source/References
Socio-economic	Canada	GDP	• Environment and Climate Change Canada's E3MC reference case (Ref21).
	USA		• US Energy Information Administration's (EIA) Annual Energy Outlook 2021 (US EIA, 2021). Available at [U.S. Energy Information Administration - EIA - Independent Statistics and Analysis].
	MSMR other regions		• US Energy Information Administration's (EIA) International Energy Outlook 2019 (US EIA, 2019). Available at https://www.eia.gov/outlooks/ieo/.
Energy	Canada	Energy supply and demand balance	• Environment and Climate Change Canada's E3MC reference case (Ref21)
	USA		• US Energy Information Administration's (EIA) Annual Energy Outlook 2021 (US EIA, 2021). Available at U.S. Energy Information Administration - EIA - Independent Statistics and Analysis.
	MSMR other regions		• US Energy Information Administration's (EIA) International Energy Outlook 2019 (US EIA, 2019). Available at https://www.eia.gov/outlooks/ieo/.
Food, Feed, and Forestry	Canada	Agriculture and livestock commodities and forest products	• Statistics Canada 2014 supply and use tables D-level. Supply and Use Tables (statcan.gc.ca)
	MSMR other regions		• Aguiar, A., Chepeliev, M., Corong, E., McDougall, R., & van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis, 4(1)*, 1-27. Retrieved from https://www.jgea.org/ojs/index.php/jgea/article/view/77
Electricity generation	All MSMR regions	Capital, labour, resource shares, and levelized generating costs	• Aguiar, A., Chepeliev, M., Corong, E., McDougall, R., & van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis, 4(1)*, 1-27. Retrieved from https://www.jgea.org/ojs/index.php/jgea/article/view/77
Commercial and public services	Canada	Services input-output data	• Statistics Canada 2014 supply and use tables D-level Supply and Use Tables (statcan.gc.ca)
	MSMR other regions		• Aguiar, A., Chepeliev, M., Corong, E., McDougall, R., & van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis, 4(1)*, 1-27. Retrieved from https://www.jgea.org/ojs/index.php/jgea/article/view/77
Industry	Canada		• Statistics Canada 2014 supply and use tables D-level. Supply and Use Tables (statcan.gc.ca)

	MSMR other regions	Industry input-output data	• Aguiar, A., Chepeliev, M., Corong, E., McDougall, R., & van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis, 4(1)*, 1-27. Retrieved from https://www.jgea.org/ojs/index.php/jgea/article/view/77
Transport	Canada	Transport input-output data	• Statistics Canada 2014 supply and use tables D-level Supply and Use Tables (statcan.gc.ca)
	MSMR other regions		• Aguiar, A., Chepeliev, M., Corong, E., McDougall, R., & van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis, 4(1)*, 1-27. Retrieved from https://www.jgea.org/ojs/index.php/jgea/article/view/77
Non-CO2 emissions	Canada		• Environment and Climate Change Canada's E3MC reference case (Ref21). Available at 22039.01 GHG and Air Pollutant Emissions Projections_Cover_V01-EN (publications.gc.ca)
	MSMR other regions	CO_2 and Non-CO_2 emission targeting for energy and emission data	• Aguiar, A., Chepeliev, M., Corong, E., McDougall, R., & van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis, 4(1)*, 1-27. Retrieved from https://www.jgea.org/ojs/index.php/jgea/article/view/77 • EPA (2019). Non-CO2 Greenhouse Gas Data Tool. Available at Non-CO2 Greenhouse Gas Data Tool | US EPA. • UNFCCC (2020). Fourth Biennial Reports (BR4). Available at Fourth Biennial Reports - Annex I | UNFCCC.

Electricity Generation Technologies in EC-MSMR

EC-MSMR model represents various electricity generation technologies that are active or become operational when it is cost effective. The electricity sector is split into power generation, transmission and distribution. The power supply sector is disaggregated into various generating technologies: (1) fossil fueled (coal, oil, gas), (2) nuclear, (3) hydro (4) wind, (5) solar, (6) geothermal, (7) biomass, (8) coal integrated gasification with carbon capture, (9) natural gas power generation with carbon capture, (10) biomass power generation with carbon capture, and (11) solar power generating with storage. The last four electricity generation technologies are backstop electricity generation technologies that may be activated in the presence of climate policy. Negative emission technologies can also play an important role on the transformation of electricity generation to abate GHGs.

Each electricity generation technology is represented by multi-level nested constant elasticity of substitution (CES) cost functions. The aggregate electricity supply is a CES aggregate of all types of generation implying the trade-off between the types of generation. These cost functions describe how capital, labour, energy and material resources respond to price changes. Disaggregation of the power supply sector is done according to the International Energy Outlook, Energy2020. Bottom-up information about input shares (capital, labour, and resources) for electricity generating technologies and levelized cost of generating technologies are taken from the Phoenix model documentation,[26] and the EIA's Annual Energy Outlook (AEO), respectively (Table 8).

Table 8: Average LCOE Assumptions for Electricity Generating Technologies (2014 USD/MWh)

Technology	2019	2040
Conventional Coal	99.3	90.4
Coal integrated gasification with carbon capture (IGCC)	120.4	103.5
IGCC with CCS	153.1	125.9
Conventional Combined Cycle (CC)	68.9	84.3
Advanced Combined Cycle	66.9	80.8
Advanced CC with CCS	94.8	107.0
Advanced Nuclear	89.4	86.2
Geothermal	46.2	65.9
Biomass	106.6	100.7
Biomass with CCS	164.3	140.3
Wind	83.4	75.9
Wind-Offshore	212.0	176.9
Solar PV	123.2	105.2
Solar Thermal	232.2	196.0
Hydropower	87.8	87.9

Backstop Technology Assumptions and Sources

1. Biomass with Carbon Capture and Storage (BECCS)

   BECCS is a backstop technology within the EC-MSMR model that generates electricity and creates negative CO_2 emissions for regions to reduce the burden of deep decarbonization pathways. The BECCS production block utilizes capital, labour, and agriculture goods as a feedstock while allowing for substitution between inputs based on the nesting structure similar to that described in Figure 2, but also produces negative carbon emissions as a by-product. The input values for BECCS are determined by the same specification as biomass electricity generating technologies, but the capital and labour inputs are increased to capture the additional facility requirements of carbon sequestration. This is done by a scaling factor calculated using the levelized cost of electricity (LCOE) of BECCS from the Phoenix model documentation.[27] This produces a value that is consistent with the recent estimate of \$100 per tonne of CO_2 sequestered.[28] The amount of carbon sequestered per unit of output differs per region based on agricultural goods' CO_2 emissions used as a feedstock, with a capturing efficiency of 90%. This specification of BECCS, however, does not account for the environmental or food security concerns that could potentially arise due to increased production of feedstock.

2. Direct Air Capture (DAC)

   A DAC backstop technology is implemented in EC-MSMR. Introducing new technologies in EC-MSMR involves defining the cost structure of various inputs going into the production activity. The DAC production block within EC-MSMR utilizes a fixed quantity of inputs across

[26] Wing et al., 2011
[27] Wing et al., 2011
[28] National Academies of Sciences, 2019

time and regions per tonne of CO_2 captured with prices that vary for the different input components by good, region, and time. The cost structure and parameter values for this block are calibrated from a report by Keith et al. (2018).[29] The physical energy units are converted using the prices from Environment and Climate Change Canada's Energy, Emissions and Economy Model Canada (E3MC) 2021 Reference case for natural gas and electricity at the national level in Canada. As DAC is a technology without any current commercialized projects, projected costs have a wide range of estimates and required input composition. The Special Report on 1.5°C estimated the cost of DAC at 200 USD per tonne as a mid-point value.[30] The EC-MSMR model assumes a range of DAC cost from 300 to 600 nominal USD per tonne of CO_2 abated by taking the cost share of capital, labour and fuel inputs. The actual price that regions will pay per tonne of CO_2 captured will vary based on regional electricity, capital, labour, and natural gas prices.

3. Backstop Fuels

Backstop fuels operate in the model by being perfectly substitutable with fossil fuels:

- Biofuel -> Refined Oil
- Renewable Natural Gas -> Natural Gas
- Hydrogen -> Coal, Natural Gas, Refined Oil

The backstop fuels inputs are parametrized by using the same input structure as the incumbent fuels and applying a scaling factor to account for the increased production costs. The scaling factor is determined by using exogenous backstop fuel price relative to the incumbent fuel to scale the costs. The relative price estimates used are adopted from the EC-Pro D-level model that has electrolysis from hydroelectric generation at 22 CAD$/GJ and natural gas at 3.8 CAD$/GJ. The fuels enter the market within the model once there is a price incentive to do so, e.g., when a sufficiently high carbon price makes the backstop fuel competitive with the incumbent fuel.

Transformative Technologies in Heavy Industry Sectors

Along with the standard conventional technologies that are operational in the baseline, the model features transformative technologies in four sectors: non-metallic mining (which includes cement), iron and steel, chemicals, and pulp, paper and printing. The production function follows a similar nesting structure but the input mix, including the factor shares are significantly different across these technologies and importantly, the new technologies use no or very little fossil fuels. As emerging and evolving technologies, these have significant potential for cost improvement through learning by doing.[31] Learning curves were introduced to account for possible technical change as a result of innovative activities. The concept of learning effect as a distinct source of technical change was presented in Wright (1936) and Arrow (1962). Technical change through learning effect is generally derived from learning curves where progress is typically measured in terms of reduction in the unit cost (or price) of a product as a function of experience gained from increase in cumulative capacity or output. Therefore, there is not an absolute or unique learning rate for a given technology. Also, due to the underlying differences, estimations of learning rates for different technologies may lend themselves to different models and specifications. This is expected as the characteristics of different technologies can vary across industries. These include technical change induced through the accumulation of experience with a given technology,[32] which can be expressed as:

[29] Keith et al., 2018
[30] Rogelj et al., 2018b
[31] Jamasb 2007; Hogan 2014; EPA 2016
[32] Wright 1936; Arrow 1962; Romer 1990

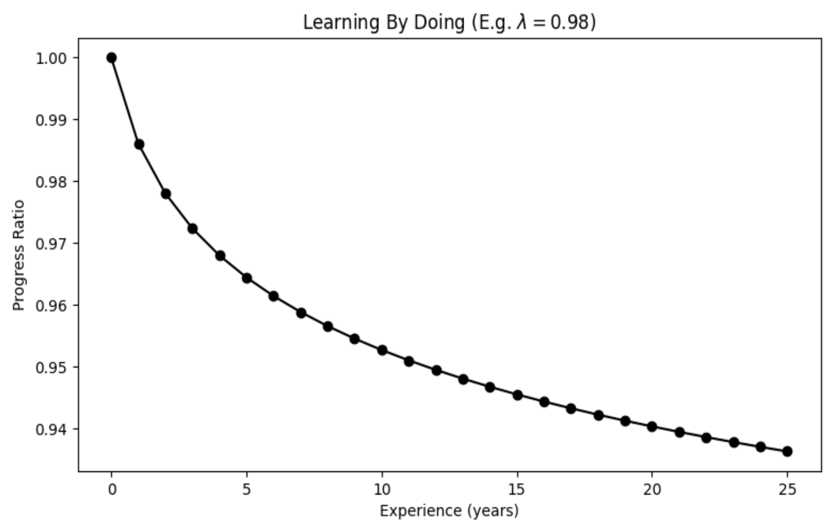
$$(1)\ PR_t = \lambda^{ln(1+Experience_{t-1})}$$

$$s.t.\ \ \lambda \le 1,\ E.g.\ \lambda = 0.98$$

$$LR_t = 1 - PR_t$$

The progress ratio (PR) represents the ratio of final to initial costs associated with experience gained from increases in cumulative output. In equation 1, λ is a constant (e.g., 0.98) that can be manually adjusted to vary the slope of the learning curve. A smaller lambda value would allow for greater cost reductions over the same period. The logged exponent characterizes the shape of the learning curve where years of past-experience with a given technology is used as a proxy for cumulative output. Once a technology in a given sector becomes cost effective and starts to produce output, the sector begins to benefit from endogenous cost reductions based on past years of experience using the advanced low-carbon technologies. The Learning Rate (LR) represents the proportional cost savings made for an increase in cumulative output or experience.

Figure 4: Learning-By-Doing



The price wedge including the cost shares of inputs for the transformative technologies in the four sectors are gathered from a comprehensive review of literature and using the GTAP input-output tables for missing information. For example, the available non-energy cost is split into detailed input shares using the input-output table. New input structures were scaled so that the difference in cost between conventional and advanced technologies is exactly equal to the break-even carbon prices. The breakeven carbon prices for these technologies were estimated using the energy mix used in the conventional versus new technologies and the required carbon price that equalizes the costs. The baseline also reflects energy efficiency improvements in conventional technology. However, information on how production cost in advanced technology evolves overtime is not available. Here the learning curve was introduced to accommodate the efficiency improvement in conventional technology. This is meant to ensure that once advanced technology kicks in, it remains active in the following years (Table 9).

Table 9: Breakeven prices and the earliest year the technology is available*

Sector	Breakeven price (2016 $/tonne of CO_2e)	Year
Chemicals	152	2030
Iron and Steel	210	2038
Non-metallic minerals (cement)	138	2029
Pulp, paper and printing	130	2028

Note: Calculations are based on literature[33] estimates and 2016 Canadian supply-use tables.

B. Oil and Gas Sector Modelling Insights

Country-specific climate ambitions suggest that there could be a global shift in fossil-fuel supply and demand since these energy sources (i.e., coal, oil, and natural gas) are major contributors to global GHG emissions. However, modelling projects that considerable fossil-fuel consumption could remain for several global regions.

For oil production, the market share of Canadian production is dependent on the models for fossil fuel supply and access to the international crude oil market. Table 10 shows that the range of supply of Canadian crude oil in the global market (i.e., beyond North America) varies. Canada's crude oil production could shrink due to technological shifts and increased climate ambitions in the US, which currently absorbs a considerable size of the Canadian crude oil and natural gas market. However, Canada's crude oil production may also be sustained if the international market becomes more accessible to certain countries outside North America (e.g., those with less ambitious 2030 and 2050 emissions targets), due to the remaining crude oil demand in these countries.

In GCAM scenarios, where assumptions constrain Canadian crude oil exports to the US market, the model estimates that Canadian global market share of crude oil supply could drop down to 2.8% in 2050. This represents a reduction of 52% in share relative to 2020. Contrary to this, in EC-IAM, where assumptions allow crude oil to be exported more easily on the global market, Canadian crude oil may increase its global share up to 9.6% in 2050, representing an increase of 65% compared to 2020 levels.

In the case of natural gas, all models estimate that Canada's share of supply could decrease. This insight is mainly reflective of the modelling limitation of natural gas exports other than the pipeline network, which constrains the export of Canadian natural gas supply beyond North America. Models project that Canada's share of natural gas global supply could change from 5.2% in 2020 to a range of 2.4% to 3.8% in 2050, depending on the scenario and model considered.

Modelling projects that Canadian demand for fossil fuels decreases across all scenarios. However, models project that rigidities in the substitution of energy inputs make it difficult for some sectors to fully eliminate fossil fuel demand, especially for uses as feedstock. Furthermore,

[33] The following literature describe the various low-carbon technologies and provide cost assumptions where available: Bataille et al. (2018); Fleiter et al. (2019); Kranenberg et al. (2016); Rissman et al. (2020); Roussanaly et al. (2017); Sluisveld et al. (2021)

modelling projects that fuel switching may not be economically or logistically feasible for some sectors (based on today's understanding of technology and resources), and these conditions may limit the feasibility of decreasing oil and gas demand.

Table 10: Oil and Gas Production and Consumption in 2020 and 2050 – All Scenarios

	Oil		**Natural Gas**	
	Exajoules		Exajoules	
	2020	2050	2020	2050
Production				
Canada	11.1	4.7-11.8	7.5	3.9-6.3
US	19.2	14.4-14.9	21.2	19.9-27.8
Europe	13.2	2.1-4.8	12.8	5.5-11.7
OPEC+	94.0	80.0-103.2	65.3	79.3-84.2
Rest of World	53.8	14.1-40.3	36.8	43.2-43.8
Total World	191.3	122.3-167.7	143.7	162.0-163.9
Demand				
Canada	4.2	0.9-1.6	4.3	1.4-2.5
US	36.2	14.4-16.2	30.6	21.4-24.5
Europe	26.7	5.5-12.6	16.5	5.8-9.7
OPEC+	36.1	35.8-42.7	42.4	44.1-50.7
Rest of World	88.2	63.5-95.2	50.0	81.8-83.9
Total World	191.4	122.3-167.6	143.7	162.0-163.9

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