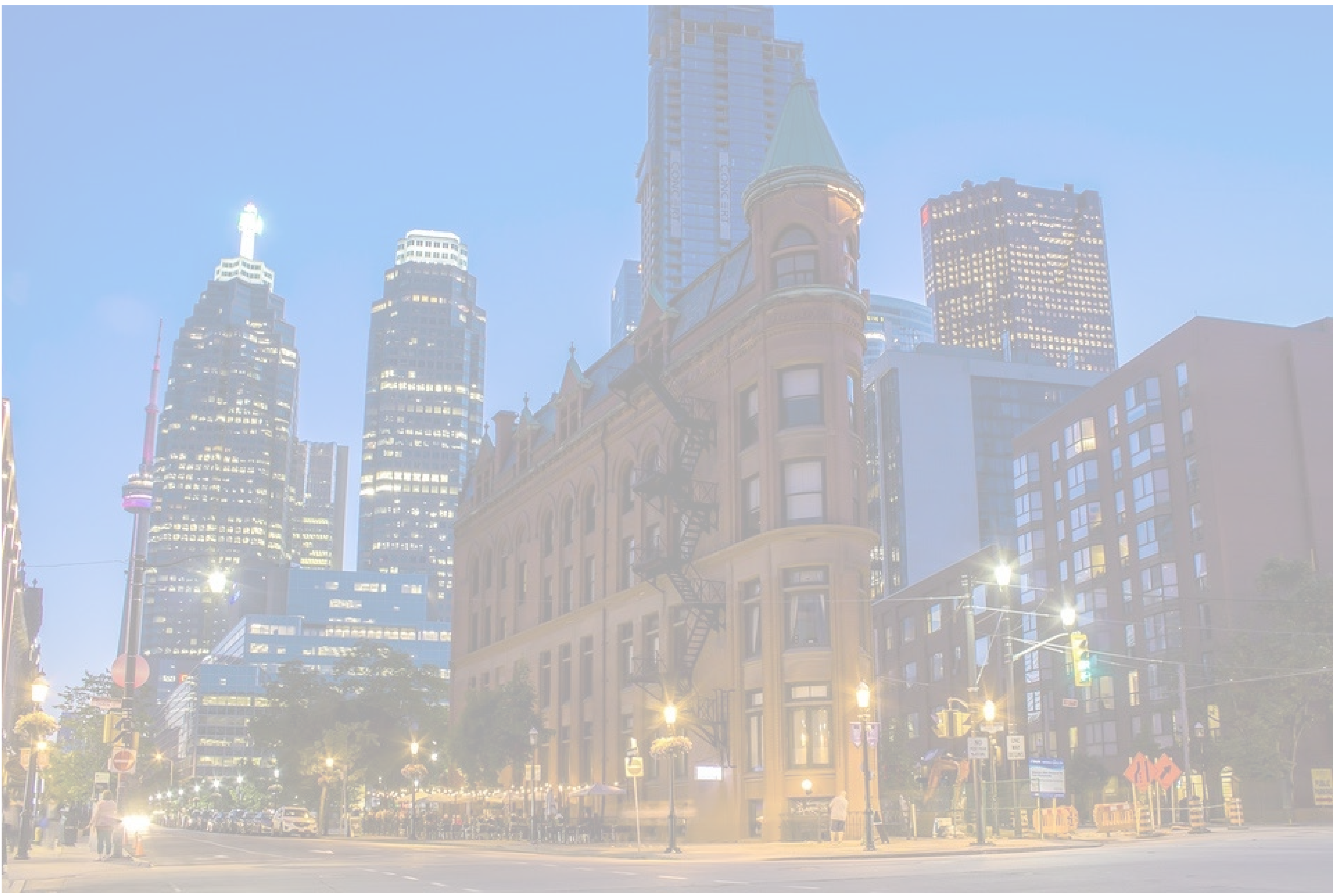
August 2024

Cost Effective Energy Pathways Study for Ontario

Deliverable 9 – Final Report

For Ontario Ministry of Energy and Electrification (Canada)



ESMIA Energy Super Modelers and International Analysts

dunsky Energy + Climate

The Ministry of Energy and Mines made minor changes to this report received from ESMIA and Dunsky Energy + Climate Advisors to link to data tables, posted on the Ontario Data Catalogue for accessibility: https://data.ontario.ca/dataset/data-tables-for-cost-effective-energy-pathways-study-final-report.

About ESMIA

ESMIA offers a solid expertise in 3E (energy-economy-environment) integrated system modelling for strategic decision-making at city, regional, national and global scales. We specialize in economy-wide energy system optimization models. We have participated in the development of turnkey large scale energy system models using a large variety of platforms. Many high-profile public and private organizations worldwide have called upon our expertise, in both developed and developing countries. Additionally, we offer advisory services using our proprietary models that focus on analyzing complex and long-term problems such as energy security, electrification, energy transitions, and climate change mitigation.

About Dunsky

Dunsky Energy + Climate Advisors supports leading governments, utilities, corporations and non-profits across North America in their efforts to accelerate the clean energy transition, effectively and responsibly. Founded in 2004, Dunsky assesses, designs, and evaluates clients' decarbonization strategies, programs, and plans, drawing on our deep expertise across technologies, industry practices, and innovative market strategies across Canada and the United States. Our expertise is focused primarily on buildings/industry, energy, and mobility. Our work covers all market sectors and segments, as well as innovative and cross-cutting (enabling) strategies.

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List of Abbreviations

ACC	Abatement Cost Curve
ASHP	Air-Source Heat Pump
BECCS	Bioenergy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
CAT	Catenary System
CBA	Carbon Border Adjustment
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CER	Clean Electricity Regulations
CFR	Clean Fuel Regulations
DAC	Direct Air Capture
DES	District Energy System
DER	Distributed Energy Resources
EU	European Union
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FIT	Feed-in Tariff
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GSHP	Ground-Source Heat Pump
HD	Heavy-Duty
ICE / ICEV	Internal Combustions Engine Vehicles
IP	Integrated Pathway
ITC	Investment Tax Credit
LDES	Long-Duration Energy Storage
NET	Negative Emission technology
NIR	National Inventory Report
NZ	Net-zero

OER	Ontario Electricity Rebate
PHEV	Plug-In Hybrid Vehicle
PRC	Project Review Committee
RNG	Renewable Natural Gas
RPP	Refined Petroleum Products
SA	Sensitivity Analysis
SC-CH4	Social Cost of Methane
SC-CO2	Social Cost of Carbon Dioxide
SC-GHG	Social Cost of Greenhouse Gas
SC-N2O	Social Cost of Nitrous Oxide
SMR	Small Modular Nuclear Reactor
T&D	Transmission and Distribution
ZEV	Zero Emission Vehicle

For a list of abbreviations of integrated pathways and sensitivity analyses, see Table 1-1 and Appendix B.

List of Units

B$ CAD2022	Billion real Canadian 2022 dollars
B$ CAD2022/y	Billion real Canadian 2022 dollars per year
CAD2022	Real 2022 Canadian dollars
CAD2022/y	Real 2022 Canadian dollars per year
GJ/m^2	Gigajoules (10^9 joules) per square meter
GW	Gigawatts (10^9 watts)
GWh	Gigawatt-hours (10^9 watt-hours)
GWh/y	Gigawatt-hours (10^9 watt-hours) per year
M$ CAD2022	Million real Canadian 2022 dollars
M$ CAD2022 (2019 to X)	Cumulative million real Canadian 2022 dollars from 2019 to year X
M$ CAD2022/y	Million real Canadian 2022 dollars per year
Mt CO2eq	Million tonnes of carbon dioxide equivalent
Mt CO2eq/y	Million tonnes of carbon dioxide equivalent per year
MW	Megawatt (10^6 watts)
pkm	Passenger kilometers
TJ	Terajoules (10^{12} joules)
TJ/y	Terajoules (10^{12} joules) per year
tkm	Tonne kilometers
TWh	Terawatt-hours (10^{12} watt-hours)
TWh/y	Terawatt-hours (10^{12} watt-hours) per year

SUMMARY

Executive Summary

Study context

ESMIA Consultants, in collaboration with Dunsky Energy + Climate Advisors, has been commissioned by the Ontario Ministry of Energy and Electrification to conduct an independent Cost-Effective Energy Pathways Study that identifies least-cost pathways to decarbonizing the province’s energy system by 2050.

This report, as one of the final outcomes of the Study, consolidates and summarises the key insights from the research, modelling and analysis conducted to provide insights to decision-makers, stakeholders, and communities (including Indigenous communities) on where Ontario is today, pathways for decarbonizing Ontario’s energy system, the potential impacts of and barriers to these pathways, and key solutions to ensure that Ontario seizes the opportunity of the energy transition and secures a prosperous, competitive, net-zero future.

Ontario is making progress and is positioned for success in the global energy transition

The global energy transition is well underway, driven by declining clean technology costs, increasing demand for energy services, and ambitious policy commitments. For Ontario, transitioning to a net-zero economy offers benefits such as attracting investment, creating skilled jobs, and driving innovation in clean technologies. Failure to act beyond 2030 to achieve climate goals could impact Ontario’s competitiveness, increase costs of the transition, and lead to significant environmental and health damages.

Ontario has experienced economic growth with stable energy consumption and declining GHG emissions over the past decade. Key milestones include the phase-out of coal-fired electricity generation in the province, as well as a significant increase in solar and wind capacity, which has quadrupled since 2010. Despite these positive trends, achieving net-zero by 2050 will require further significant reductions across all sectors.

Achieving net-zero by 2050 in the different pathways will involve integrating new fuels and technologies, each with associated costs and uncertainties. Key fuels and technologies will vary by sector. Nuclear, particularly small modular reactors (SMRs), as well as onshore wind and long-duration energy storage (LDES) will play key roles in decarbonizing and growing electricity generation; while electrification of space heating and water heating will be crucial to decarbonizing the province’s buildings sector.

A major energy system transition is required to reach net-zero

The study leverages three sophisticated models: an energy systems optimization model, a rate impacts model, and a macroeconomic model (NATEM, RateVision, and NAGEM)[1]. Multiple integrated pathways (IPs) are modelled to identify least-cost pathways for Ontario's energy future, including a **Reference Case** (REF IP) business-as-usual trajectory that includes committed policies; ten **Net-Zero Integrated Pathways** (NZ IPs) with a net-zero GHG emissions constraints in 2050; and eight **Sensitivity Analyses** (SAs) that capture the impact of key uncertainties around the pace of cost declines and availability of new technologies. Results from this study should not be interpreted as forecasts or most likely outcomes, but rather represent least-cost optimal solutions.[2]

Across NZ IPs, four key pillars are needed to enable a least-cost pathway for Ontario to achieve net-zero in 2050.

- **REDUCING** total final energy consumption, e.g., by 31% in the NZ50 IP in 2050 (compared to 2019) (Figure ES-1);
- **SWITCHING** more than 80% of fossil fuel use to emission-free electricity, with targeted use of clean fuels from 2019 to 2050;

Electrification of end-uses in the transportation, buildings and industrial sectors is a key enabler of this transition, and total demand for electricity is expected to increase to 2-3x across NZ IPs, to 320-467 TWh/y.

- **GROWING** electricity generation capacity, e.g. to over 2x from 2019 to 2050 in NZ50, primarily through new additions of wind, nuclear (mainly SMRs), energy storage and solar, and growing the associated transmission and distribution capacity.

Ontario's electricity supply will need to expand significantly – on the order of to double to triple today's system across all NZ IPs– to power the province's economy. In 2050, 87-115 GW of installed capacity will be needed to meet the province's electricity demand in the NZ IPs, (e.g. Figure 5-8 shows the NZ50 IP). The growth in electricity supply in NZ IPs is largely dominated by growth in wind and nuclear capacity, 12-26 GW and 12-31 GW respectively, between 2019 and 2050, as well as rooftop PV and storage. Significant investment will be required to support growth of capacity and transmission and distribution infrastructure.

- **SEQUESTERING** remaining GHG emissions (e.g., 20 Mt CO2 per year in the NZ50 IP in 2050) using CCS and DAC, and (~12Mt CO2eq per year in the NZ50 IP in 2050) using NETs.

[1] NATEM, NAGEM, and RateVision are developed and operated by ESMIA (www.esmia.ca)

[2] For example, the modelling has limited consideration of market barriers and economically irrational decisions and does not represent the behavior of individual economic agents or consumers.

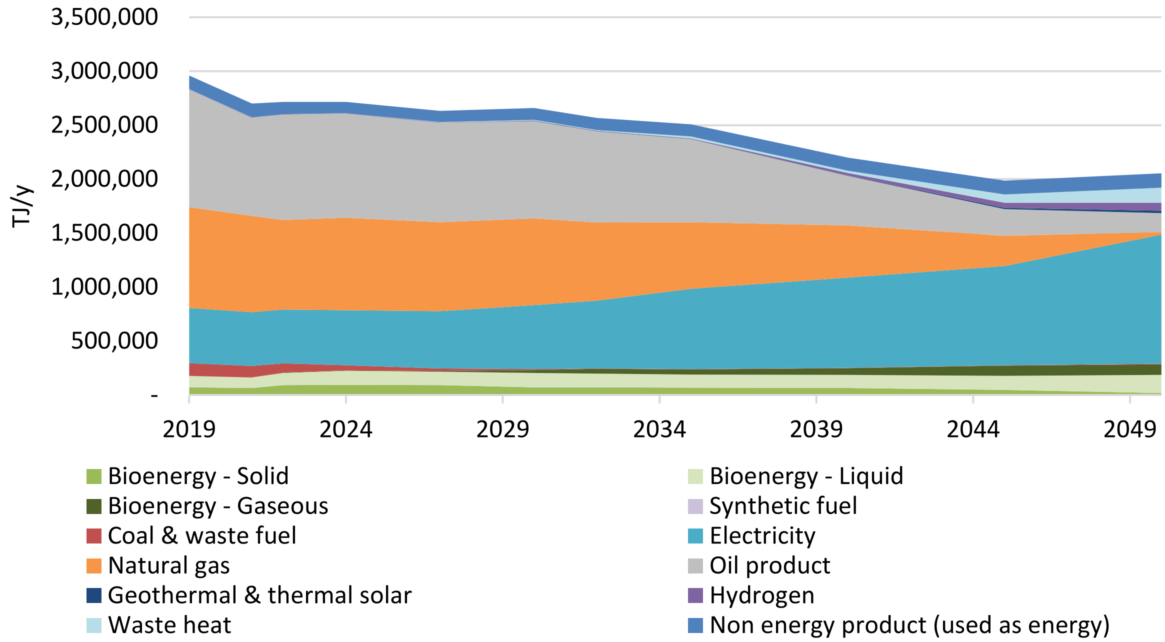


Figure ES-1. Final energy consumption (TJ/y) by fuel type from 2019 to 2050 for the NZ50 IP

Despite the directional alignment of these four pillars across the modeled integrated pathways, the results also highlight specific nuanced considerations and uncertainties around: the role of clean fuels, the magnitude of electricity growth, the trade-offs between the magnitude of wind and nuclear deployment, and the potential of CCS and negative emissions. Future government policies, innovations, and climate impacts (not modelled) are also key uncertainties.

Significant action and investments are required to reach net-zero

Achieving net-zero in 2050 will require significant action. In the least-cost REF pathway, Ontario would reach its 2030 greenhouse gas (GHG) emissions target if all assumed policies and actions materialize. However, business-as-usual policies, including committed policies (in the REF pathway), fall short of net-zero in 2050.

To close the gap and achieve net-zero GHG emissions in 2050, there is a need for significant emissions reductions across all sectors in the NZ IPs: residential and commercial sector emissions are completely eliminated in 2050; transportation sector emissions are reduced by 90% (compared to 2019); industrial and electricity sectors become net-negative emitters, through carbon capture and storage (CCS) and negative emissions technologies (NETs) (Figure ES-2).

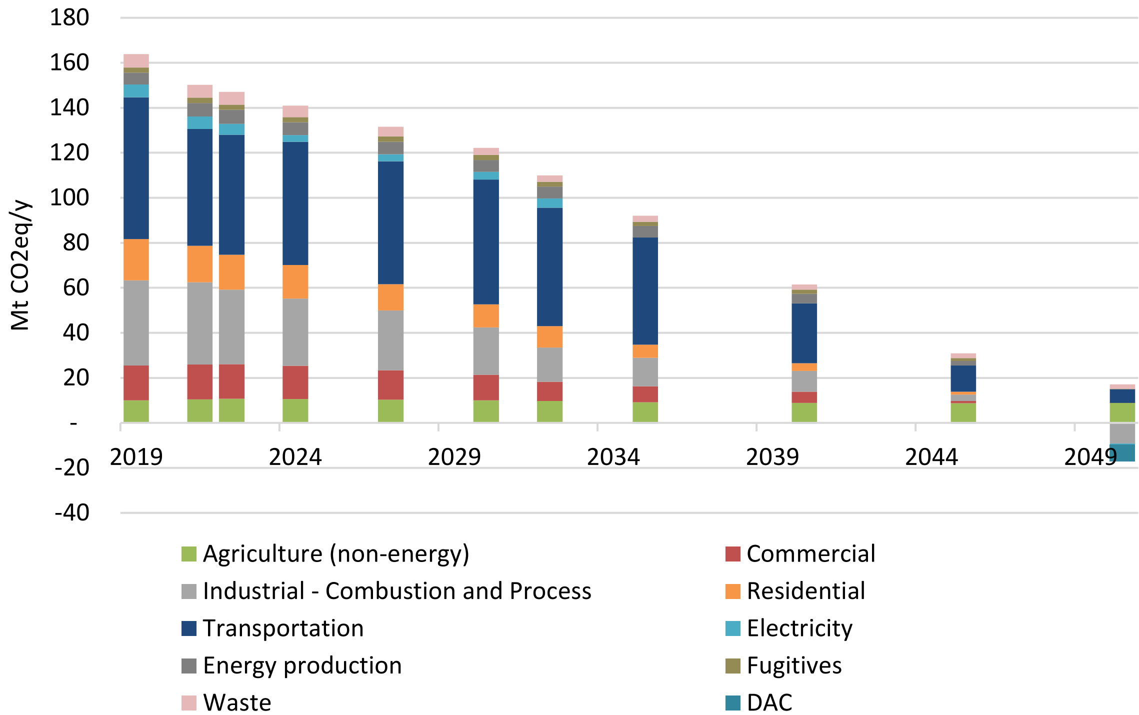


Figure ES-2. Total annual GHG emissions by sector (Mt CO2eq/y) from 2019-2050 for the NZ50 IP (Economy-wide GHG emissions covered by the NIR)

Steering Ontario's economy onto a pathway to achieve net-zero in 2050 will require additional cumulative investments in the order of CAD2022 $173B (in the NZ50 IP) beyond what might occur in the REF IP (Figure ES-3) from 2019 to 2050. **Incremental investment will be primarily concentrated in the electricity sector,** due to the high need for emissions-free electricity supply as well as transmission and distribution infrastructure. Incremental investment in the transportation sector is relatively small, as current policies and technology cost trends already drive significant decarbonization of transportation in REF – however, it should be noted that keeping Ontario on track to achieve the GHG emissions reductions in the REF IP will require significant investment.

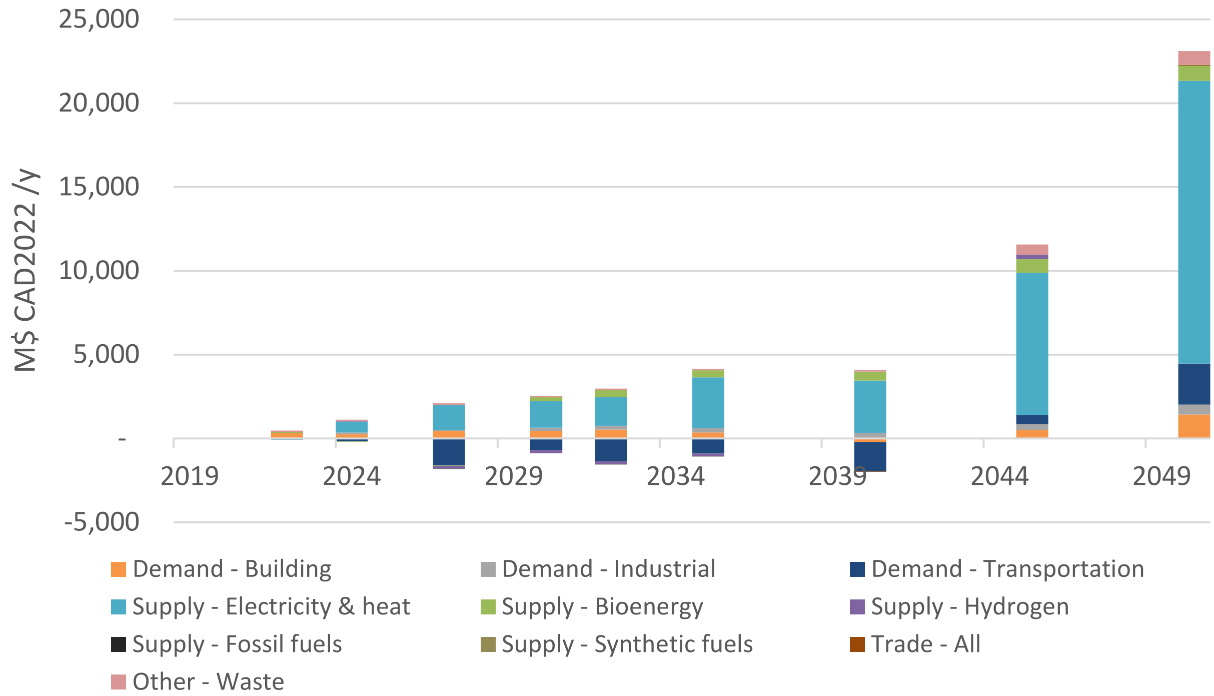


Figure ES-3. Annual incremental investment cost (M$ CAD2022/y) of the NZ50 integrated pathway compared to the REF IP in 2019 to 2050

The transition's positive outcomes on energy affordability and societal co-benefits will offset energy investment costs and GDP impacts

The net-zero transition will have minor impacts on gross domestic product (GDP) and labor demand in comparison to REF, with GDP growth continuing. The incremental impacts of Ontario's energy transition on GDP will be 0.04 percentage points per year[3] lower in NZ50 and off-set by numerous co-benefits. The NZ50 pathway is expected to require more highly skilled workers compared to REF, while demand for lower skilled workers is smaller.

At the same time, average ("normalized") household energy bills are expected to decline substantially, e.g. 47% from 2022 to 2050 in NZ50[4], due to fuel switching and energy savings. However, there is a risk of high energy bills for households remaining on natural gas due to a large drop in consumers in 2045-2050 in NZ IPs.

Additionally, the transition is anticipated to bring significant co-benefits, such as improved health and avoided impacts on agricultural productivity and economic activity, and reduced risk of disruption of energy systems, with cumulative (2019-2050) benefits from avoided damages

[3] Difference in average real annual growth (%/y) (2019-2050) between REF and NZ50.
[4] Without OER and with the legislated carbon price

estimated between CAD2022 $245 billion and $874 billion across NZ IPs (incremental to REF), far outweighing the incremental investments required.

A number of immediate no-regret actions will be critical for the success of Ontario's energy transition

There are nine solutions for 2030 that appear in almost all of the NZ IPs and exhibit little to no variability in the magnitude of uptake (i.e., are no-regret solutions) that should be supported immediately. Early success across these nine solutions will be critical to long-term decarbonization. The nine solutions are:

1. Pursue full economic potential for demand reduction in the building sector through **energy efficiency and building controls**,
2. Pursue the rapid **electrification of residential and commercial space heating** with ASHPs,
3. Pursue the rapid **electrification of light-and medium duty vehicles as well as buses**,
4. Continue to deploy **electricity storage technologies** to meet near-term (before 2030) capacity requirements and peak demand,
5. Deploy **onshore wind** as a solution to meeting near-term 2030 system needs and monitor the need for additional growth by 2050,
6. Build out **electricity transmission and distribution (T&D) infrastructure** within Ontario.
7. Deploy rooftop PV and other distributed energy resources to meet system needs,
8. Continue exploration and **development of SMRs** to reduce first-of-kind deployment risks and work with federal government to ensure that its regulatory processes facilitate timely and safe deployment, to achieve economies of scale and enable significant growth in SMR capacity by 2050,
9. Ramp up the sustainable **utilization of forests** to fulfill the growing demand for biomass.

Other solutions required by 2030 have variability in the magnitude of uptake but appear in almost all of the NZ IPs (i.e., are least-regret solutions) or show less consistency across NZ IPs (i.e. are wild card solutions). However, this does not indicate that no action is required. These solutions will also require action before 2030 if Ontario wishes to pursue modelled least-cost net-zero pathways.

Key **barriers** include lack of awareness, public acceptance, skilled labor shortages, investment uncertainty in new markets i.e. "chicken-and-egg" dynamics, and regulatory challenges. Addressing these barriers will be critical for scaling the necessary fuels and technologies. Further, many solutions for 2050 require significant infrastructure development to support their implementation. Early exploration and developments in some technologies will be key to ensuring that learnings can enable achievement of future cost reductions associated with Ontario-specific barriers.

Advanced planning, decisions, and actions between now and 2030 will have important implications for the success and cost-effectiveness of solutions for 2050.

In the absence of timely decision-making, the cost of implementing solutions for 2050 may become higher, and the risk of not meeting net-zero in 2050 will increase. Inaction or failure to act in a timely manner also risks incurring significant costs on the order of CAD2022 $245 billion and $874 billion by 2050 due to climate change related damages (across NZ IPs, incremental to REF, cumulative from 2019-2050, as quantified by the social cost of GHGs (SC-GHG)), and may have other consequences to health, competitiveness, and affordability.

This study should serve as a starting point for more refined planning by sector. In particular, some areas that warrant further work include assessing the resource adequacy, operability and transmission and distribution requirements for the electricity sector, and regional infrastructure planning. Almost all long-term solutions have initial uptake in the modelled IPs before 2050 and require actions before 2030, including developing regulatory frameworks, encouraging technology adoption and early investment, beginning infrastructure development, developing stable supply chains, and re-training of skilled workers. The design of new policies was out of scope of this study; but constitutes an important next step to direct Ontario’s economy towards further emission reductions.

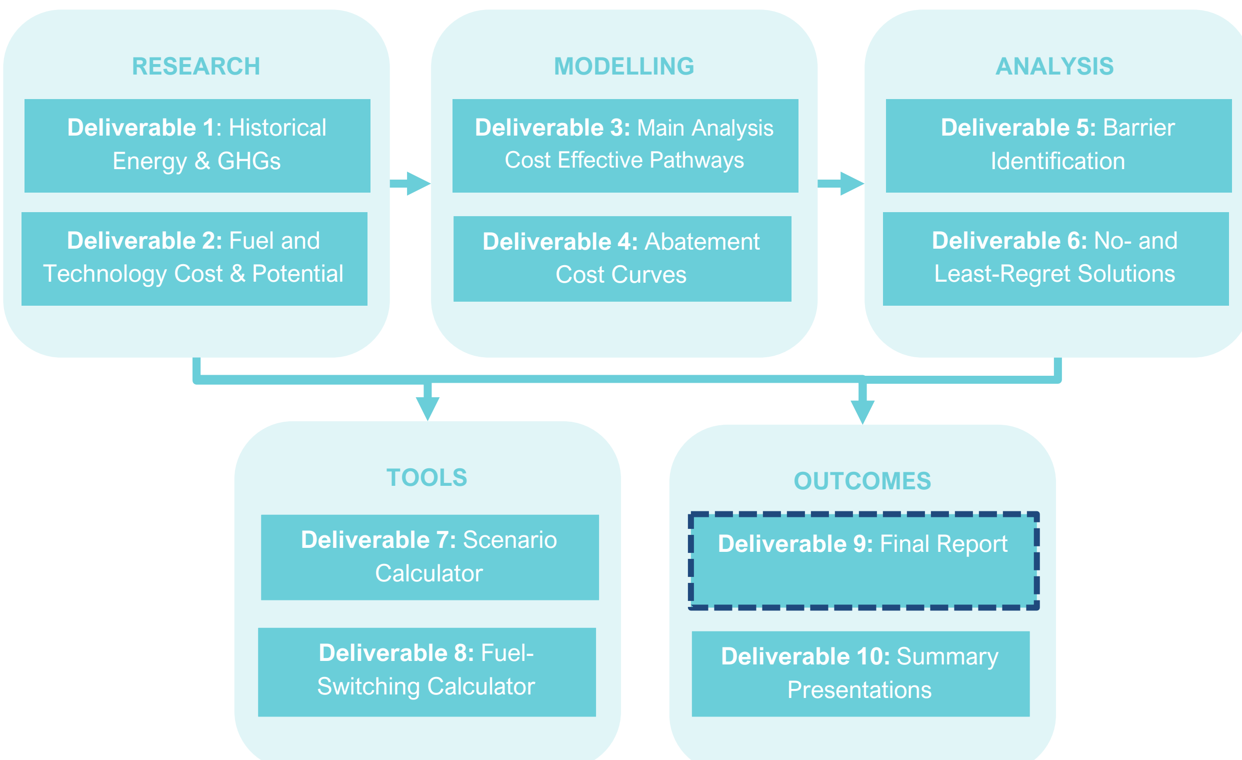
SECTION 1

1. Introduction

1.1 Study Overview

ESMIA Consultants, in collaboration with Dunsky Energy + Climate Advisors, has been commissioned by the Ontario Ministry of Energy and Electrification to conduct an independent Cost-Effective Energy Pathways Study that identifies least-cost pathways to decarbonizing the province's energy system by 2050. The study is intended to provide decision-makers, stakeholders, and communities (including Indigenous communities) in Ontario with insights as to how Ontario's energy sector can best support electrification and the energy transition. In addition to contributing to long-term energy planning in the province, the study has also supported the work of the Electrification and Energy Transition Panel (Panel) and is intended to inform future policy decisions and discussions in Ontario.

As illustrated in the figure below, the study is comprised of 10 key deliverables, each of which is linked through three key project phases, and the tools and outcomes that will be the final outputs of this study.



1.2 Approach

Research

Historical Energy and GHG Emissions

To understand the current state and trajectory of Ontario's energy system and GHG emissions, as well as fine-tune the model and enable comparison of the modelled integrated pathways with historical trends, historical information on energy and GHG emissions in Ontario over the past 10 years was collected for key sectors, fuels, and end-uses. The exercise leveraged publicly available data from federal and provincial governments and their agencies, as well as targeted data requests to key stakeholders (e.g., Independent Electricity System Operator (IESO), Enbridge Gas). This data was then used to analyze key trends in energy and GHG emissions in Ontario over the past 10 years by sector and end-use.

Fuel and Technology Cost and Potential

Key technical and economic parameters (e.g., cost, efficiency, lifetime, achievable supply) for 34 fuels/technologies key to Ontario's energy transition were characterized. This provided data, insights and forecasts of cost, performance (e.g. efficiency) and achievable supply / deployment tuned to the Ontario context to inform the modelling conducted in this study as well as future work by the Ministry.

An initial list of over 60 potential solutions was compiled, focusing on high-value, high-potential options, including high-certainty measures expected to be critical, and high-potential measures with significant uncertainty, and those targeting large emitters.

Based on these criteria and through engagements with the Ministry and the Project Review Committee (PRC), a subset of 34 fuels and technologies were selected, along with a relevant comparator for each. Credible industry and academic resources[5] as well as internal technology databases were leveraged to characterize each fuel and technology.

Where available, Ontario-specific data was leveraged to characterize the fuels and technologies. Where it was not available, the best available data from other representative jurisdictions or regions (for example, Canada) was used. The team conducted targeted engagements with industry stakeholders to gather the Ontario-specific information, data, and insights on the cost, performance, and achievable supply of fuels and technologies, as well as to review key assumptions.

The research provides projections for fuel and technology characteristics out to 2050. Where applicable, three scenarios were characterized that reflect uncertainty in technical performance, costs, or other attributes, comprising a central case that represents the most likely trajectory and low/high cases representing alternative trajectories for technology development. Some of these

[5] Detailed references used are documented in the Deliverable 2 excel workbook appendix.

low/central/high cases for specific technologies were used in the pathways modelling, depending on the IP/SA. Note: some of the results from Deliverable 2 were overridden for the model; where this is the case, the data can be found in the appendices for Deliverable 3.

Modelling

Cost-Effective Pathways

Representing the core component of the study, integrated pathways (IPs) were modeled using an integrated energy system optimization modelling framework to identify the least-cost pathways to meeting energy service demands in Ontario, while respecting resource limitations and energy and climate policy objectives.

Three key models[6] were used to obtain the results and insights presented in this study: (1) the North American TIMES Energy Model (NATEM), the most technologically comprehensive economy-wide energy system optimization model in Canada, covering the entire energy chain from primary production to end-use demand; (2) the North American General Equilibrium Model (NAGEM), a new generation dynamic macroeconomic model; and (3) RateVision, used to evaluate the impact on tariffs[7] for distribution connected gas and electricity consumers. Detailed energy system results from NATEM are soft-linked to the other two models, ensuring coherence in the modelling approach. Detailed model descriptions are available in Appendix A.

Appendices B & C of Deliverable 3: Cost-Effective Pathways provide detailed documentation of the assumptions used in the study, including a list of modeled technologies / fuels and corresponding key assumptions (e.g., costs), demand projections, a list and description of modeled policies, and other key variables.

The models were used to produce projections of different cost-effective energy pathways for Ontario:

- **A reference case** integrated pathway (REF IP) that reflects Ontario's trajectory under business-as-usual, including committed policies;
- **10 Net-Zero Integrated Pathways (NZ IPs)**, of which 9 reflect plausible future pathways for Ontario's energy system under different market and policy conditions, and each with a GHG constraint of net-zero GHG emissions in 2050;
    - **One NZ IP, the H2+ IP,** is a favourable hydrogen pathway which exceeds the level of plausibility used in the other integrated pathways. A production tax credit for electrolytic hydrogen was added to get to material levels of hydrogen uptake above and beyond what is seen in the other NZ IPs. Due to this, the IP is often an outlier compared to other pathways, and should be interpreted with care;

[6] NATEM, NAGEM, and RateVision are developed and operated by ESMIA (www.esmia.ca)
[7] The term "tariffs" refers to both fixed charges and variable rates.

- **8 Sensitivity Analyses (SA)** that capture the impact of key uncertainties around the pace of cost declines and availability / supply for new technologies on targeted IPs.

The choice of pathways and sensitivities was determined based on guidance from the Ministry, with input from the Project Review Committee. Table 1-1 below provides brief descriptions of the IPs modeled in the study. Detailed assumptions for the IPs, as well as a list of SAs modeled, are presented in Appendix B.

The results presented in the report are largely focused on the reference (REF) and the NZ50 IP. Insights from other IPs and SAs are presented where notable trends that deviate from REF or NZ50 are observed.

Table 1-1. Description of Integrated Pathways Modeled in the study.

IP Number	Label	Description
IP0	**REF**	"Business-as-usual" including committed policies.
IP1	**NZ50**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies.
IP2	**ELC +**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to committed policies. Favourable electrification conditions.
IP3	**ELC HP**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to committed policies. Unfavourable electricity cost conditions.
IP4	**2030-30%**	GHG reduction of 30% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies.
IP5	**H2 +**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to committed policies. Favourable hydrogen conditions and production tax credit for electrolytic hydrogen.
IP6	**2030-50%**	GHG reduction of 50% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies.
IP7	**BIO +**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. Favourable biomass conditions.
IP8	**ELC -**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. Unfavourable electrification conditions.

IP Number	Label	Description
IP9	**CCS -**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. Unfavourable CCS and NET conditions.
IP10	**TRADE +**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. Favourable energy trade conditions.

Abatement Cost Curves

Building on the pathways modelling results, abatement cost curves (ACCs) were generated to analyze the cost-effectiveness of various GHG reduction measures across different sectors of the economy. The curves highlight the cost per tonne of carbon dioxide equivalent (“abatement cost”, CAD2022/t CO2eq) resulting from different levels of GHG emissions reductions. Each point on the curve represents different abatement measure(s), with their corresponding cost. In contrast to typical marginal abatement cost (MAC) curves, in this study, the ACCs were developed using a system approach, by using NATEM e.g., the full energy value chain and cross-sectoral interactions across the economy are accounted for. Short-term (2030) and long-term (2050) ACCs were developed, focusing on the incremental costs needed to achieve GHG reductions of 40% by 2030, and net-zero by 2050.

Analysis

Barrier Identification

Based on the pathways modelled, barriers to scaling key fuels and technologies in Ontario were identified. Fuels and technologies were selected based on their: significant increase in use in the IPs and SAs, high uncertainty across IPs and SAs, or unique deployment conditions. Technologies with less than 1% contribution to Ontario’s supply or demand were excluded. Engaging with the Ministry and PRC, 28 fuels and technologies were selected for barrier identification.

Recognizing the IPs represent a least-cost future state based predominantly on economic optimization, it is important to acknowledge that various barriers may impact their feasibility and realization. Key barriers affecting the fuels and technologies were identified along the following six critical dimensions: market, technical, financial, regulatory, social/cultural, and environmental.

While many of the barriers may be cross-jurisdictional and pertain to technology risks, global economic conditions, or other considerations, the analysis focused on key barriers along these six dimensions and Ontario-specific challenges to scaling the use of the selected key fuels and technologies.

No-and Least-Regret Solutions

Based on modelling results, solutions for achieving net-zero in Ontario were divided into three categories: no-regret, least-regret, and wild cards. This categorization was based on three criteria: significance (degree of uptake relative to other technologies), consistency (appearance across all IPs, excluding REF and H2+), and variability (magnitude of contribution variance across IPs with significant uptake).

A long list of potential solutions was developed based off fuels and technologies that appear across the modelled IPs. The threshold for "significant uptake" (e.g., capacity of electricity generation, percentage of vehicle stock, percentage of useful heat supplied, MtCO2eq/y sequestered) was determined on a case-by-case basis for each fuel and technology.

Solutions that were deemed to have significant uptake in at least one NZ IP were then assessed for their consistency and variability across the NZ IPs and subsequently classified as either no-regret, least-regret, or wild card solutions.

This Report

This report, as one of the final outcomes of the Cost-Effective Pathways Study, consolidates and summarises the key insights from Deliverables 1-6. It presents critical findings from the research, modelling and analysis phases regarding where Ontario is today, cost-effective pathways for Ontario's future energy system, potential impacts of and barriers to these pathways, and key solutions for Ontario's energy future.

In assessing cost-effective pathways to net-zero, this study **provides insight into the essential fuels, technologies and solutions for Ontario to seize the enormous opportunity of the energy transition and secure a prosperous, competitive, net-zero future.**

SECTION 2

2. Why Net-Zero?

2.1 Global View

A global energy transition is underway, driven by declining clean technology costs, increasing consumer and investor demand, and ambitious policy commitments from over 140 countries pledging to achieve net-zero GHG emissions.[8]

Net-zero commitments now cover 88% of global emissions and 90% of global GDP.[9] These commitments align with the scientific consensus that reaching net-zero emissions by 2050 is necessary to limit global warming to 1.5°C and mitigate the worst impacts of climate change.[10]

Global investment in clean energy has surged in recent years, with global investment in clean energy now almost double that of fossil fuels.[11] In 2024, global energy investment is projected to reach a record US$3 trillion per year (nominal), with nearly two-thirds directed towards clean energy technologies and infrastructure.[12]

Major economies are exploring Carbon Border Adjustment (CBA) mechanisms to maintain economic competitiveness while reducing emissions, and the European Union (EU) has a CBA that transitions into effect in 2026.[13] This global alignment towards decarbonization presents both a challenge and an opportunity for economies worldwide to transition to cleaner energy systems and foster economic growth through innovation and decarbonization.

2.2 Ontario's Opportunity

Ontario is positioned for success in the global energy transition

The province's electricity grid is largely emissions-free, thanks to historic investments in hydropower and nuclear energy, and previous initiatives to phase out coal-fired generation. As of 2023, 87.5% of Ontario's electricity output is emissions-free, positioning it favorably compared to many advanced economies and major trading partners.[14] Ontario's low emissions intensity and reliable, cost-competitive energy supply provide a strong foundation for future growth.

In 2023 the province launched a Clean Energy Credit (CEC) registry, designed to facilitate the tracking and trading of clean energy credits, which can be purchased and retired by businesses to meet their environmental and sustainability goals, positioning Ontario to respond to increasing commitments from companies to procure clean energy.

[8] International Energy Agency. World Energy Outlook 2023
[9] United Nations. Climate Action; International Energy Agency. World Energy Outlook 2023
[10] United Nations. Climate Action;
[11] IEA. World Energy Investment 2024.
[12] *Ibid.*
[13] European Commissions. Carbon Border Adjustment Mechanism;
[14] Ontario Energy Board (OEB). 2024. Ontario's System-Wide Electricity Supply Mix: 2023 Data

For Ontario, transitioning to a net-zero economy offers multiple benefits beyond mitigating climate change. By pursuing net-zero, Ontario can attract investment, create new green jobs (not modelled), and drive innovation in clean technologies (not modelled). This transition also provides an opportunity to improve public health (not modelled), reduce energy costs, and reduce energy-related trade deficits.

2.3 Risks of Inaction

There are economic, environmental, and social consequences that would result from failing to move beyond a business-as-usual pathway, which includes committed policies and actions. Inaction or failure to act in a timely manner risks incurring significant cumulative costs (2019-2050) on the order of CAD2022 $245 billion and $874 billion due to climate change related damages (as quantified by the SC-GHG, across NZ IPs, incremental to REF, see section 6.3) in addition to other consequences related to health, competitiveness, and affordability.

Economic

Without proactive measures, Ontario faces significant risks to affordability. Delaying investments in key technologies and infrastructure will lead to higher costs in the long run. Early planning and investment are crucial for cost-effective pathways to net-zero; hesitation will only increase costs and complicate the transition. For instance, the uptake of Heavy-Duty Zero Emission Vehicles (HD ZEVs) is contingent on supporting infrastructure. Development timelines for these technologies span 5+ years, and delays will slow down market penetration, increasing the eventual costs of adoption and reducing Ontario's competitiveness (not modelled) in the global market.

Inaction will also impact household energy affordability. Zero emissions energy sources could be less expensive than fossil fuels and adopting clean technologies, such as electric vehicles (EVs) and heat pumps, can generate significant cost savings for Ontarians. If done right, the energy transition will save households money by reducing reliance on fossil fuels and taking advantage of more efficient, cleaner technologies.

Failing to act could hinder Ontario's ability to manufacture and trade goods globally (not modelled). As major economies like the EU implement CBAs, Ontario's products could become less competitive if they are not produced with low-carbon methods. This shift towards greener products, driven by both regulatory requirements and changing consumer preferences, could lead to job losses and diminished economic growth if Ontario fails to adapt.

Building out clean energy infrastructure efficiently is critical for attracting investment in sectors essential to Ontario's low-carbon economy (not modelled). Businesses and industries globally are increasingly prioritizing reliable and affordable clean electricity to power their operations. If Ontario fails to build out and decarbonize its electricity grids, crucial investment in sectors such as green steel production and EV manufacturing may flow elsewhere. Ontario has made early progress towards this with Powering Ontario's Growth Plan as a first step, and further efforts are needed.

Health and Environmental

Without achieving net zero or negative GHG emissions for its own economy and imports, Ontario will continue to contribute to global climate change, facing more frequent and severe weather events. These changes will have direct impacts on agriculture, infrastructure, and overall quality of life. Increased occurrences of extreme weather, such as floods and heatwaves, will strain public resources and lead to higher costs for disaster response and recovery. Both changing weather patterns and extreme weather events can jeopardize Ontario's ability to produce, transport, and distribute energy, with significant societal costs. Investments to increase infrastructure resilience to weather events will increase costs, e.g. for ratepayers or taxpayers. Without action to reduce GHGs, these costs will continually increase.

Health impacts are also a concern. Continued reliance on fossil fuels and increases in forest fires will result in higher levels of air pollution, which is linked to respiratory and cardiovascular diseases. Increasing frequency and severity of heatwaves will also result in an increased risk of heat stroke and heat-related deaths.

Indigenous communities, and particularly those in northern and remote regions of Ontario experience disproportionate impacts of climate change. Extreme weather events can exacerbate existing inequities including respiratory, cardiovascular, water, foodborne, chronic and infectious diseases, as well as financial strain and food insecurity.

The transition to a net-zero economy offers a chance to improve public health by reducing pollutants that contribute to chronic illnesses. Failing to make this transition will maintain, if not exacerbate, current public health challenges.

Cascading Effects of Global Inaction

If other regions do not take sufficient action to address climate change, impacts including trade disruptions, transboundary pollution, impacts to food security, climate refugees, increased climate risks and increased risks of conflict may cascade onto Ontario.

Ontario's economy is highly integrated with global markets. If other jurisdictions fail to act on climate change, supply chains may be disrupted due to climate-related events such as extreme weather, impacting the availability and cost of goods. This could lead to increased production costs for Ontario's industries, reducing their global competitiveness.

Air and water pollution do not respect borders. If neighboring jurisdictions do not reduce GHG emissions, Ontario could suffer from transboundary pollution, leading to degraded air and water quality. This would exacerbate health issues such as respiratory and cardiovascular diseases among Ontario's population.

Climate change also poses significant risks to food security. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events disrupts food production processes and can lead to decreased crop yields and increased prevalence of pests and diseases. Ocean warming, acidification and deoxygenation also threatens to degrade marine ecosystems, impacting fisheries and aquaculture. Extreme weather events can also affect the stability of food supply, for example through impacts to infrastructure and disruption of transportation.

Failure to act on climate change globally could result in increased migration from areas severely affected by climate impacts. Ontario may face an influx of climate refugees, which could strain social services and infrastructure, requiring substantial public investment to accommodate and integrate these populations.

Global failure to mitigate climate change will likely result in more severe and frequent weather events. Ontario could experience heightened risks of floods, droughts, and heatwaves, which would impact agriculture, infrastructure, and overall public health and safety. These events would lead to increased costs for disaster response, recovery, and adaptation measures.

SECTION 3

3. The History

3.1 Historical Energy & GHG Trends in Ontario

Over the last decade, Ontario has experienced economic growth with relatively stable energy consumption and GHG emissions.

In 2019, Ontario emitted 166 million tonnes per year of GHGs, measured in carbon dioxide equivalent units (Mt CO2eq/y)[15] and consumed 3,047 PJ/y of energy. Energy demand grew by less than 1% per year on average between 2010-2019, and GHG emissions decreased by 0.5% per year on average (Figure 3-1).[16] GHG emissions had a consistent decline from 2010 to 2017 (by 1.2% per year on average), followed by a 5% increase from 2017 to 2018, then declined through 2019. Between 2019 and 2020, many of these historic trends were disrupted due to the COVID-19 pandemic, discussed further below.

While Ontario's energy demand and GHG emissions remained relatively stable from 2010-2019, the province's emissions intensity decreased as activity metrics increased (population, employment, travel, floor space, and GDP). Per capita GHG emissions have trended down, (declining from 13 t CO2eq per person per year in 2010 to 10 t CO2eq per person per year in 2019, a 23% decline) (Figure 3-2).[17] Similarly, annual energy use per capita declined by 6%. These trends show that **Ontario could be moving towards an era where GHG emissions are decoupled from economic and population growth.**

This section summarizes key highlights and findings from Deliverable 1: Historical Energy and GHG Emissions. For further details, readers can refer to Deliverable 1.

[15] GHG emissions in this section, and in the majority of the report reflect the reporting scope of Canada's official GHG inventory, also known as the National Inventory report ("NIR", Government of Canada, 2022) but excluding impacts of Land-Use, Land-Use Change and Forestry (LULUCF). The study scope for energy and emissions is slightly larger than the NIR as explained below but the difference is small and using NIR data avoids potential data misalignment.

[16] Government of Canada, "Environment and Climate Change Canada data : Canada's official greenhouse gas inventory," 2022. [Online]. Available: https://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/?lang=en.
Statistics Canada, "Table: 17-10-0005-01 Population estimates on July 1st, by age and sex," [Online]. Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710000501&pickMembers%5B0%5D=1.7&pickMembers%5B1%5D=2.1&cubeTimeFrame.startYear=2010&cubeTimeFrame.endYear=2022&referencePeriods=20100101%2C20220101. [Accessed 2023].
Statistics Canada, "Table: 36-10-0222-01 Gross domestic product, expenditure-based, provincial and territorial, annual (x 1,000,000)," [Online]. Available: https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3610022201 . [Accessed 2023].
NRCan - Natural Resources Canada, "Comprehensive Energy Use Database," 2019. [Online]. Available: https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm.

[17] All values are annual for year shown, GDP is in 2022 CAD.

Activity is increasing at a faster pace than energy consumption and GHG emissions.

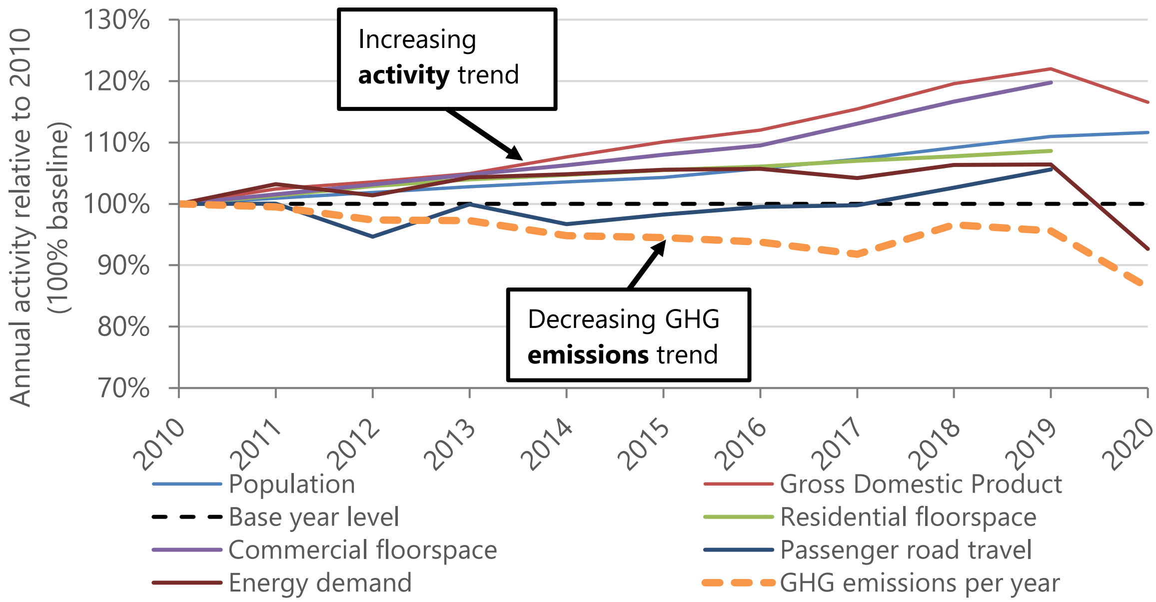


Figure 3-1. Annual activity for years 2010 to 2020, relative to 2010, which is the baseline of 100%

Energy demand and GHG emissions intensity is declining.[18]

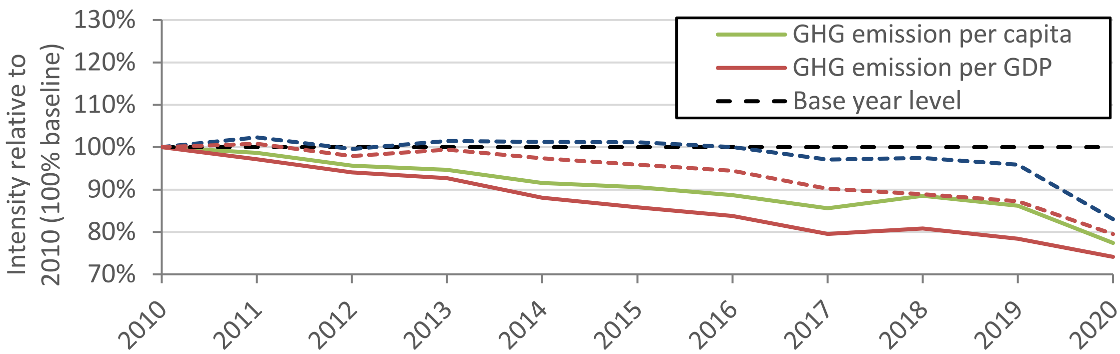


Figure 3-2. Index changes (per capita and GDP) relative to 2010, which is the baseline of 100%

[18] Government of Canada, "Environment and Climate Change Canada data : Canada's official greenhouse gas inventory," 2022. [Online]. Available: https://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/?lang=en.
Statistics Canada, "Table: 36-10-0222-01 Gross domestic product, expenditure-based, provincial and territorial, annual (x 1,000,000)," [Online]. Available: https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3610022201 . [Accessed 2023].

At a high level, Ontario's GHG and energy demand trends have remained relatively consistent over the past decade.

Historically, from 2010 to 2020, most of Ontario's GHG emissions are due to energy use, including fossil fuel combustion for transportation (35% to 38% of total emissions) and heat (stationary combustion, 36% to 42% of total) (Figure 3-3). Over this same timeframe, industrial processes and products use[19] account for between 12% to 16% of total emissions, agriculture accounts for 5% to 7%, waste accounts for 4% to 5%, and fugitives (emissions released during oil and gas exploration, production, transportation, and distribution) represent approximately 1%.

Since 2010, total GHG emissions have decreased by 23 Mt CO2eq/y. [20]

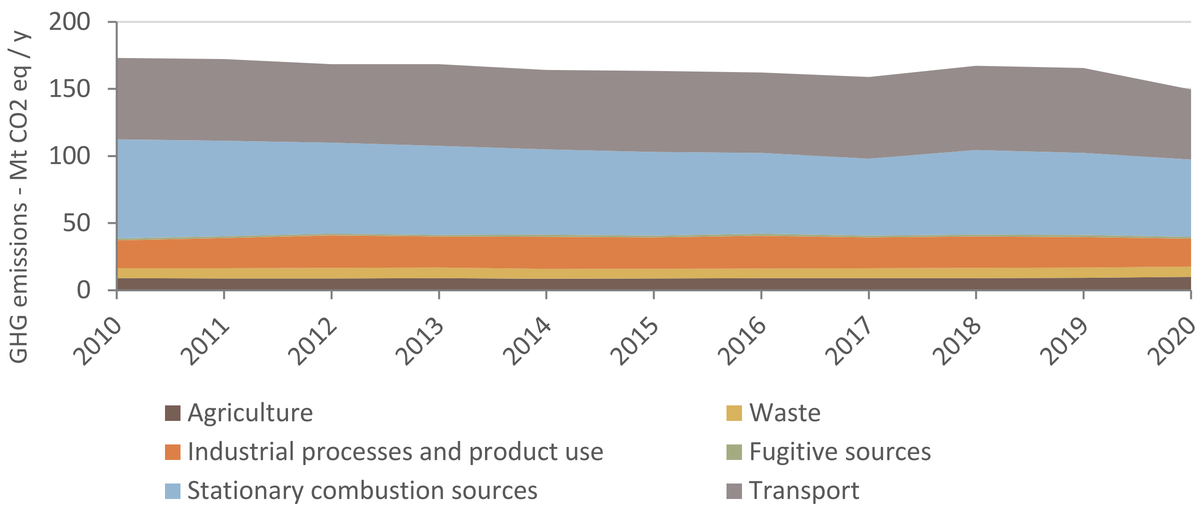


Figure 3-3. Ontario GHG emissions by source (IPCC category), NIR scope (Mt CO2eq/y) from 2010 to 2020

Refined petroleum products (RPP) and natural gas have historically made up the majority of Ontario's secondary energy demand (40% and 33%, respectively), followed by electricity (18%) in 2021. The "other" category – which includes coke and coke oven gas, natural gas liquids, steam, wood waste and pulping liquor – makes up 9% in 2021 (Figure 3-4).

[19] This category includes non-combustion emissions resulting from the production of cement, lime, minerals, metals, and chemicals. It also includes consumption and use of halocarbons, solvents, non-energy use of fossil fuels, and other product use and manufacture.

[20] Government of Canada, "Environment and Climate Change Canada data : Canada's official greenhouse gas inventory," 2022. [Online]. Available: https://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/?lang=en.

RPP and natural gas made up 73% of Ontario's secondary energy demand in 2021. [21]

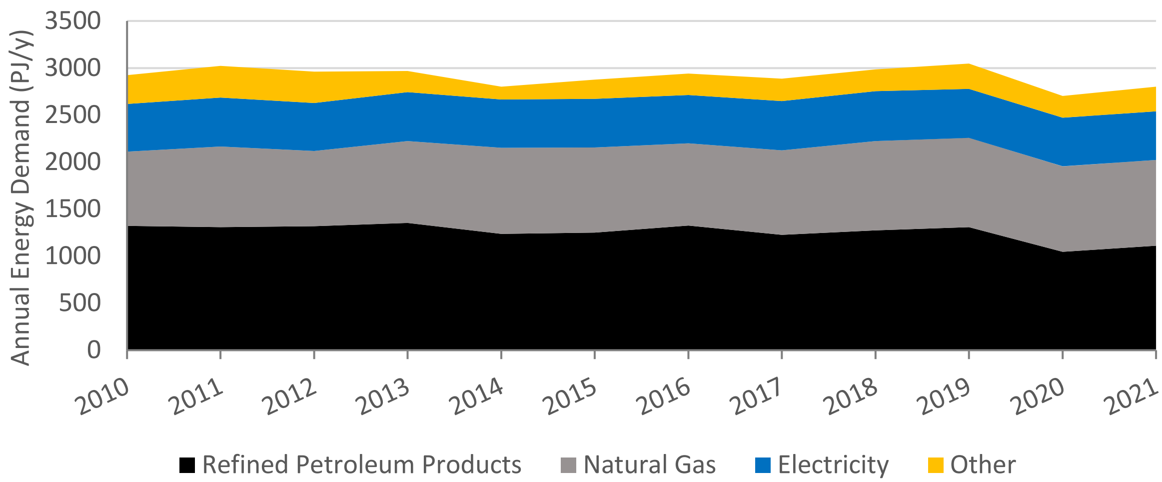


Figure 3-4. Ontario secondary energy demand (PJ/y) by energy type in 2010-2021

Other key trends and inflection points

There are several key trends and inflection points illustrated by the energy and GHG emissions data collected for this study.

Phase-out of coal-fired electricity generation: In 2001, the Government of Ontario committed to stop burning coal at the Lakeview Generating Station, and appointed the Select Committee on Alternative Fuel Sources, which advised to phase out coal-fired electricity generation. In 2003, the government committed to closing the province's four remaining coal-fired power plants. Ontario succeeded in phasing out coal-fired electricity generation, from >12 TWh/y in 2010 to zero in 2014. Due to this phase-out, GHG emissions from electricity generation decreased from 20 Mt CO2eq/y in 2010 to 6 Mt CO2eq/y in 2014, while in-province electricity generation increased from 152 TWh/y to 158 TWh/y, leading to a steady decline in the carbon intensity of Ontario's electricity.

Increased Capacity of Solar and Wind: Since 2010, Ontario's fleet of solar and wind electricity generators increased from less than 2 GW of installed capacity in 2010 to 8.7 GW in 2021. Consequently, the percentage of Ontario's electricity generated from solar and wind has also

[21] Statistics Canada, "Table 25-10-0029-01 Supply and demand of primary and secondary energy in terajoules, annual," 2022. [Online]. Available: https://doi.org/10.25318/2510002901-eng. [Accessed 2023]. "Secondary energy" refers to energy after all energy to energy conversions, e.g. electricity made using natural gas is secondary energy, but not the natural gas used to produce that electricity. Secondary energy includes demand for fuels for non-energy uses, such as lubricants and petrochemical feedstocks. "Secondary energy demand" is used interchangeably with "final energy demand".

increased from <2% to approximately 9%. The Feed-in Tariff (FIT) program was a significant driver of this, with most of these increases occurring between 2010 and 2016.[22]

Rate relief policies and programs: Electricity rates and residential bills in Ontario have varied significantly in response to rate relief policies and programs implemented by the government, in particular the Fair Hydro Act of 2017, which reduced prices by approximately 25% and limited price increases in 2018 and 2019. The Ontario Electricity Rebate and other special COVID-19 pandemic measures, as mentioned previously, also impacted rates post-2019.

EV Incentives: Although EVs still make up a small share of Ontario's overall transportation market, the sales of light-duty BEVs and plug-in hybrid electric vehicles (PHEVs) have been increasing since 2010. Increases in sales have been highly correlated with access to incentives and rebate programs – for example, the introduction of a provincial EV rebate program in 2010 contributed to increasing sales, and there was a notable decrease of 42% in sales between 2018 and 2019 when the provincial EV rebate program was terminated. The introduction of a federal rebate program (along with the influence of other pressures such as post-COVID-19 pandemic recovery and increasing gasoline prices) caused sales to increase again in 2021.

Annual GHG intensity in the residential, industrial, and personal transportation sectors declined during the past decade[23]. While it is difficult to link these overall declines to a single particular policy, several policies implemented by the government and other actors over the past decade have likely contributed, including the renewable content requirements for gasoline and diesel[24], the Ontario Building Code, various demand side management programs, the Green bond program, nuclear refurbishment programs, Provincial energy efficiency standards for products, appliances, and equipment, and regulatory changes and investments for reducing the use of coal in energy-intensive industries.[25]

Energy intensity of the residential buildings, passenger transportation, and freight transportation sectors has also declined during the past decade – while both energy and activity have been generally increasing (with the exception of COVID-19 pandemic impacts), the growth in activity (such as building floor space, passenger-kilometers per year, and tonne-kilometers per year) has outpaced growth in energy consumption.

[22] While the FIT program significantly increased renewables capacity, it also faced criticism for contributing to increased electricity costs due to the high rates guaranteed to renewable energy producers which were passed on to consumers through the Global Adjustment Fee.
[23] Percent decline is calculated as intensity in 2020 relative to intensity in 2010.
[24] Current regulation is the Cleaner Transportation Fuels regulation (O. Reg. 663/20), but versions of the renewable content requirements for transportation fuels have been implemented in Ontario since 2005.
[25] This analysis focused on historical trends between 2010-2021 (or 2020, depending on data availability). However, it is worth noting that in 2022 the Government of Ontario, in a joint effort with the federal government, further committed to reducing the use of coal in energy-intensive industries, providing funding for the phase-out of coal fired furnaces at two steel plants, Algoma Steel and ArcelorMittal Dofasco. These plans were included in the pathways modelling.

Ontario is among the leading jurisdictions in a jurisdictional comparison of energy and emissions benchmarks for reducing GHG emissions

Compared to other jurisdictions, Ontario has made strong progress towards decarbonization in the last 10 years, with the coal phase-out policy being key to reducing the GHG intensity of electricity generation.

Overall, the province has a lower electricity GHG intensity and higher electricity use than many Canadian provinces, California and New York, but lags behind Norway, Quebec, and British Columbia on current GHG intensity (Figure 3-5, Figure 3-6).

Ontario's GHG intensity of the economy decreased by 26% in 10 years. [26]

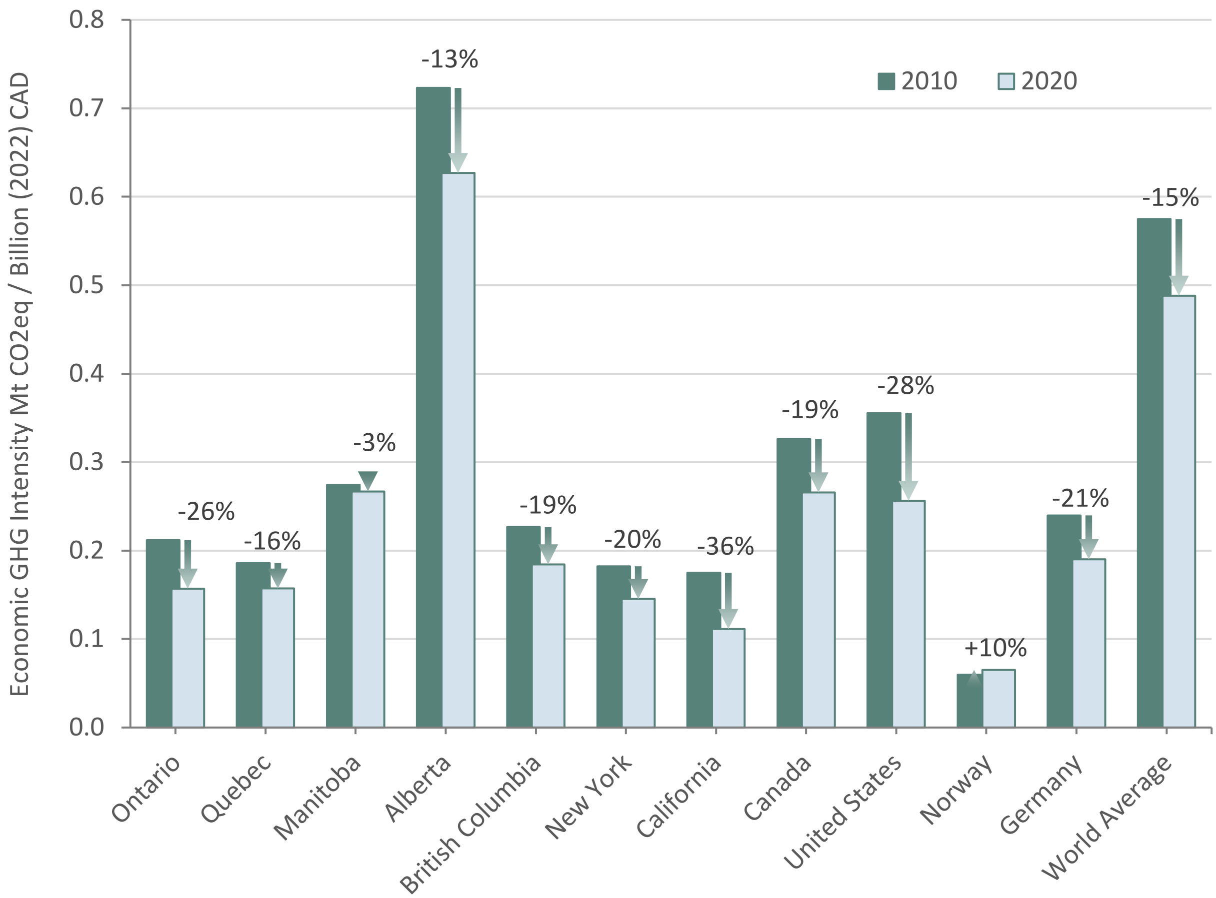


Figure 3-5. GHG intensity of the economy by jurisdiction (Mt CO2eq/y / Billion CAD2022 GDP/y) for 2010 and 2020

[26] Several sources were used to compile this figure. Refer to Deliverable 1 for details.

Ontario's electricity grid GHG intensity dropped by 81% in 10 years.[27]

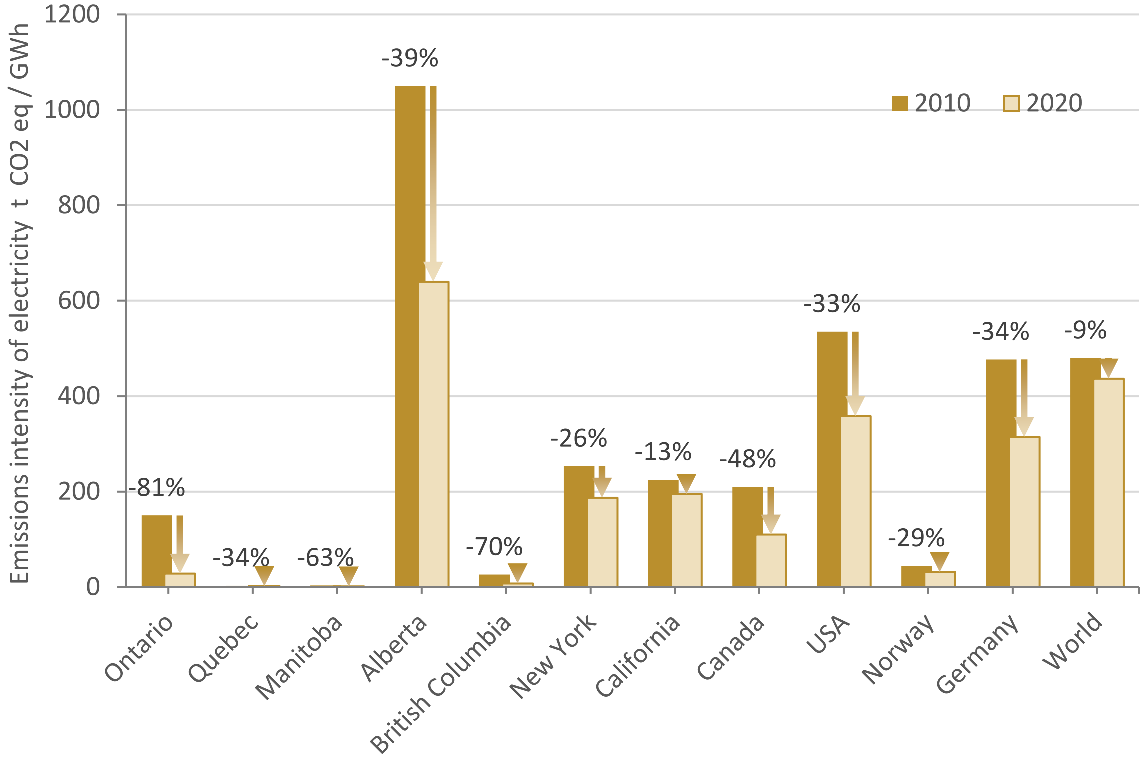


Figure 3-6. Electricity grid intensity by jurisdictions (t CO2eq/y / GWh/y) for 2010 and 2020

To reach net-zero, Ontario must build on past successes

Achieving net-zero by 2050 will require further significant GHG emissions reductions across all sectors. Ontario has made great progress to date in decoupling GHG emissions from economic growth and decarbonizing its electricity system. These efforts have positioned Ontario for success in the global energy transition. To reach net-zero and capitalize on the economic opportunities of the energy transition, the province will need to build on its progress to date by advancing rapid decarbonization across all sectors of the economy.

[27] Several sources were used to compile this figure. Refer to Deliverable 1 for details.

SECTION 4

4. The Tools

4.1 Key Fuels & Technologies for Ontario's Energy Future

Several fuels and technologies will be critical for a cost-effective energy transition

Achieving net-zero GHG emissions by 2050 in Ontario will involve the integration of new fuels and technologies, each with their own set of costs, uncertainties, and infrastructure requirements. There is inherent uncertainty regarding future technology mix, however, certain fuels and technologies can be expected to play a key role in Ontario's cost-effective energy transition. This section provides a description of these key fuels and technologies, as well as an overview of uncertainties and considerations for their integration into Ontario's energy system.

This section summarizes key highlights and findings from Deliverable 2: Fuel and Technology Cost & Potential. For further details, readers can refer to Deliverable 2.

Growing and decarbonizing Ontario's electricity generation

In the electricity sector, electricity demand is expected to grow significantly to 2050, with electricity generation capacity anticipated to more than double by 2050.[28] Several technologies are expected to play a role in meeting this future demand:

- **Small Modular Reactors (SMRs):** Over 50% of Ontario electricity generation is currently from conventional nuclear power. With 18 reactors in 3 locations, Ontario owns a net-capacity of 13 GW which corresponded to 79 TWh generated in 2023.[29] Nuclear power generation is in general well accepted and there are no major constraints for nuclear generation expansion.

In the transition to net-zero, SMRs are projected to play a role in providing low-emission, reliable electricity. These advanced nuclear reactors are designed to be smaller and more flexible than traditional nuclear power plants, offering scalable deployment potential. SMRs come in multiple designs, with no single dominant design, and investment costs are extremely high and highly variable. Types of SMRs include light-water small modular reactor, gas-cooled small modular reactor, molten salt small modular reactor, and liquid metal cooled reactor. There are over 50 SMR designs, most of which are still in the early stages of prototyping[30], and among them a wide range of power levels, designs, and end-user applications, making site-specific design more complex

[28] Independent Electricity System Operator. Pathways to Decarbonization.
[29] Independent Electricity System Operator. Supply Overview.
[30] IESO. 2022. Pathways to Decarbonization.

and time-consuming. Cost declines are uncertain and will depend on technological advancements in the coming years.

Given these and other uncertainties, the role of SMRs in Ontario's clean energy transition is subject to uncertainty relative to more proven, mature technologies.

Despite these uncertainties, Ontario is a global leader in SMRs. While there are no SMRs currently operating in Ontario, the province is currently building four first-of-a-kind grid-scale SMRs at the Darlington nuclear site. The first of these is expected to enter commercial operation in 2029 (assumed to be 2028 in the model).

- **Onshore wind** turbines have blades that convert the kinetic energy in wind to electricity. Onshore wind is a mature and low-cost technology with significant potential for reducing GHG emissions.

However, several factors may constrain wind development in Ontario. For example, there are acoustic constraints related to regulations on maximum allowable noise levels for wind energy projects in Ontario. Siting and permitting, transportation limitations, and community concerns are considered the primary constraints for onshore turbines. Additionally, interconnection policies, processes, and costs often delay or limit the potential and pace for deploying onshore wind resources. The limited availability of skilled labour, installation and assembly equipment (hoists, cranes) can pose a constraint.

- **Long-duration energy storage (LDES)** refers to technologies that can be used to store electricity and dispatch stored energy for an extended period, typically longer than 8 hours. Numerous technologies exist today or are under development. These technologies are critical for supporting grid stability and integrating intermittent renewable energy sources. They offer low-cost solutions with limited technical and financial barriers. Longer-duration storage (e.g., pumped hydro, 8-hour vs. 4-hour batteries) will be important for ensuring resource adequacy needs. As of 2024, Ontario has recently completed the largest battery storage procurement in Canada's history, including a mix of both short- and long-duration battery storage projects.

Electrifying and improving efficiency of Ontario's buildings

In the buildings sector, aligning with net-zero GHG emissions will require electrifying building systems, while also taking further action to improve building efficiency. Several technologies are expected to play a key role in this sector:

- **Air Source Heat Pumps (ASHPs)** are electrically driven devices that provide heating and cooling by extracting heat from a low temperature place (a source) and delivering it to a higher temperature place (a sink). In heating mode, the heat pump draws heat from the outside air and delivers it inside the home. In cooling mode, it operates in reverse, drawing heat from air inside the home and rejecting it outside.

ASHPs are expected to play a central role in decarbonizing space heating (while also replacing air conditioners and providing space cooling). Their efficiency and potential to significantly reduce GHG emissions make them a critical technology for Ontario's building sector. ASHPs are approaching cost parity on a total cost of ownership basis with traditional heating systems, which is anticipated to drive their widespread adoption. Barriers to the adoption of ASHPs include workforce constraints, technical and financial barriers, and supply chain constraints.

- **Retrofit and Controls:** Retrofitting existing buildings with energy-efficient technologies and advanced controls are expected to be vital measures for improving the energy performance of Ontario's aging building stock. Despite the high upfront costs associated with retrofits, there are long-term savings and GHG emissions reduction potential. Financial incentives and increased public awareness are key to accelerating the adoption of these measures.

- **District Energy Systems (DESs)** provide heating and cooling to multiple buildings through a network of distribution pipes connected to centralized heating and cooling centres. DESs are currently available, and Ontario has systems currently operating in Toronto, Hamilton, Ottawa, London, Markham, Sudbury, Cornwall, and Windsor.

  A DES requires a high density of heating or cooling demand to be cost-effective. In areas where buildings are densely populated, less piping and trenching is required, and there are fewer losses associated with heat distribution. However, installing a DES in an existing densely populated area can be challenging and costly. Potential barriers include land constraints, disruption, congested right-of-way, lack of regulatory framework, and lack of funding and policy support. Challenges associated with DES are also highly dependent on the fuels and technologies used – for example, a DES leveraging waste heat from SMRs may face public concern associated with the perceived risks of nuclear power.

Powering Ontario's vehicles with clean energy

In transportation, electrifying and decarbonizing light-duty transportation is already well underway, while a range of options for decarbonizing medium-and-heavy-duty transportation are emerging. Key fuels and technologies expected to play a role in decarbonizing the transportation sector include:

- **Light-Duty Battery Electric Vehicles (LD BEVs):** BEVs use electricity stored in a battery pack to run an electric motor for propulsion. BEVs have no tailpipe emissions. All energy is stored in battery packs which are recharged from the grid using electrical vehicle supply equipment (EVSE), more commonly referred to as EV chargers.

  LD BEVs are nearing cost parity on a total cost of ownership basis with internal combustion engine vehicles (ICEVs) and are widely expected to be a key technology for reducing transportation GHG emissions.

Ontario-specific constraints include a lack of provincial rebates or incentives on new BEVs or associated home charging equipment. Furthermore, there may be limited supply available due to a lack of Ontario ZEV sales mandate.

- **Heavy-Duty (HD) BEVs:** BEVs are also expected to play a role in decarbonizing medium- and heavy-duty transportation. However, uptake is constrained by several factors. There are two methods of charging for long-haul trucks: depot charging and public charging networks. Currently, there is insufficient high-power charging capacity to support HD-BEVs along the traditional trucking highway corridors in Ontario (or Canada). Fleet owners looking to transition to BEVs will also need to factor in the costs of purchasing and installing charging stations within their depots to support their electric trucks. The potential installation of high-power chargers along highway corridors across the province will require necessary transmission and distribution (T&D) capacity as well as coordination with local utilities.
- **Fuel Cell Electric Vehicles (FCEVs):** HD-FCEVs are powered by hydrogen. HD-FCEVs use a propulsion system powered by electricity produced by conversion from hydrogen in a fuel cell, whereas typical heavy-duty internal combustion vehicles (HD-ICEVs) use diesel. The only tailpipe emissions from HD-FCEVs are water vapor and warm air. Hydrogen gas is stored in a tank on the vehicle that can be refueled within a similar refuelling time to a traditional ICE vehicle.

  The biggest barrier to FCEV adoption is that these vehicles depend on hydrogen refuelling stations, which Ontario currently lacks.

- **Catenary Systems (CAT)** supply electricity to heavy-duty trucks through overhead wires and a pantograph, allowing for charging while driving. The cost-effectiveness of CAT depends on the electrification of major highway corridors and the widespread adoption of electric trucks. Key barriers include high initial infrastructure costs with uncertain returns if uptake is limited, and potential inadequacies in transmission and distribution capacity in remote highway areas. Additionally, real-world pilots are more common in Europe, where freight distances are shorter compared to Canada and Ontario.

Other emerging technologies for Ontario's clean energy future

Several emerging fuels and technologies are expected to play a role in decarbonizing or offsetting hard-to-abate sectors.

- **Pyrolysis for biochar production:** Pyrolysis is the thermal decomposition of organic matter in the absence of oxygen, producing biochar, bio-oil, and syngas. Slow pyrolysis is a simple and cost-effective method for carbon capture and sequestration compared to conventional CCS methods. Biochar, a stable carbon-rich byproduct, is highly porous and primarily used for soil amendments and long-term carbon sequestration. It is also utilized as activated carbon in the automotive industry.

At time of writing, there is no industrial biochar production for carbon sequestration in Ontario. Biomass feedstock supply is limited by existing agricultural and forestry practices, impacting availability and cost. Developing robust supply chains and optimizing feedstock processing methods are essential to ensure a steady and affordable biomass supply for pyrolysis and improve cost-effectiveness.

- **Hydrogen:** clean hydrogen technologies for industrial applications, including electrolyzers, turbines, and boilers, are expected to play a key role in decarbonizing hard-to-abate sectors and applications. The lack of hydrogen infrastructure and the high costs associated with production and storage are significant barriers.
- **CCS and other negative emission technologies (NET)** (direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS)), are expected to play a key role in addressing GHG emissions from hard-to-abate sectors. However, they are characterized by high uncertainty and low technological readiness.

SECTION 5

5. The Pathways

5.1 Introduction: Modelling Cost-Effective Pathways

This section summarizes key results and insights from modelling cost-effective pathways to identify the least-cost trajectories for Ontario to achieve net-zero GHG emissions in 2050.[31] This modelling represents the core component of the study, leveraging an integrated energy system optimization model to find the least-cost pathways while respecting resource limitations and energy and climate policy objectives.

Specifically, this analysis sought to answer three key questions:

1. **GHG Emission Reductions:** Where will GHG reductions come from?
2. **Energy Demand:** How will energy demand change in key sectors and for key fuels?
3. **Energy Supply:** What resources will be used to supply Ontario's future energy needs?

These IPs reflect plausible future pathways for Ontario's energy system under different market and policy conditions, including one business-as-usual, including committed policies, pathway (the reference case integrated pathway, or REF IP), and ten pathways with a constraint of net-zero GHGs in 2050 (NZ IPs).

The results presented in this report are largely focused on the REF IP and the NZ50 IP. Insights from other IPs and SAs are presented where notable trends that deviate from REF IP or NZ50 are observed. In general, the H2+ IP is not analyzed in this report unless specifically noted because it does not test a plausible future under current conditions but rather looks at where hydrogen uptake would occur *if* there were a significantly larger amount of cost-effective supply. For the list of IPs and SAs and their abbreviations, see Table 1-1 and Appendix B.

This section summarizes key highlights and findings from Deliverable 3: Cost-Effective Pathways (Main Analysis) and Deliverable 4: Abatement Cost Curves. For further details, readers can refer to Deliverables 3 and 4.

[31] For most IPs and SAs, unless otherwise specified, the GHG constraint is based on National Inventory Report (NIR) scope.

Modelling Approach: Key Considerations and Caveats

NATEM, as an optimization model, provides the least-cost system solution under a given set of constraints. Results from this study for all pathways (including REF) **should not be interpreted as forecasts, rather they represent least-cost solutions based on cost optimized pathways,** which are not necessarily the most likely outcomes. They can be interpreted as projections of what may happen in a given scenario, under certain conditions. The modelling uses relaxed market shares and there is limited consideration for market barriers or economically irrational decisions.

As an economy-wide optimization model, there are inherent trade-offs that must be made in the complexity and granularity of the modelling, the time horizon and time periods resolved, and the solving time of the model. NATEM is one of the most technologically rich models of the energy system and it is very detailed in its representation of the energy sector. To solve such a model over a long time horizon requires selection of sub-annual time periods. In this study, a time period definition of 16 sub-annual time periods was used. More granular time modelling (e.g., at hourly level) was out of scope. Given the time period granularity and agreed upon scope of the study, assessing electricity system reliability and operability was also outside of scope and will need to be conducted to better understand electricity supply requirements. Nevertheless, modelling constraints are used where possible to represent certain operational constraints.

In terms of spatial granularity, NATEM models the 13 Canadian jurisdictions as independent regions. In this study, results are presented for Ontario, while the model was run for all Canadian jurisdictions to ensure that trade flows and other interactions are well represented nationally. There are limitations associated with modelling Ontario as a single region, particularly when it comes to electricity and gas T&D infrastructure that is largely dependent on spatial distribution of production and consumption. While more refined spatial disaggregation is possible, this typically implies greater complexity and longer solving time and was not in the scope of this study.

Given these factors and other study limitations, additional analysis beyond the study will be needed to assess the feasibility and specific requirements for a plan along with other specific implications for long-term planning. The study is a first-of-a-kind study for Ontario and should be considered a starting point for discussions and future work regarding the future of Ontario's energy systems. For example, future work building on this study should include detailed analysis of resource adequacy and transmission and distribution requirements.

It should also be noted that costs associated with investments made in 2021 or earlier, including any amortized costs that would extend into the future, are not modeled.

Due to data availability, NATEM is calibrated using 2016 to 2021 data. The modelled year 2022 and onwards are modelled, so actual (historical) numbers for 2022 may differ from the modelled results.

For additional detail on key considerations and caveats related to the modelling approach, please refer to Deliverable 3: Cost-Effective Pathways.

5.2 GHG Emissions

Overview

If all the actions implied by the modelled policies in the REF IP materialize,[32] Ontario is on track to reach its 2030 GHG emissions target (e.g., 30% reduction relative to 2005 levels) (Figure 5-1). However, in the REF IP, a significant gap remains to achieving net-zero emissions in 2050, and GHG emissions start to increase post 2040 as the increase in final energy consumption in the province outweighs the impact of the modeled policies; in particular, as some key policies are phased out post-2030 or have decreasing effect (e.g., investment tax credits (ITCs), and the federal carbon price in real dollars).

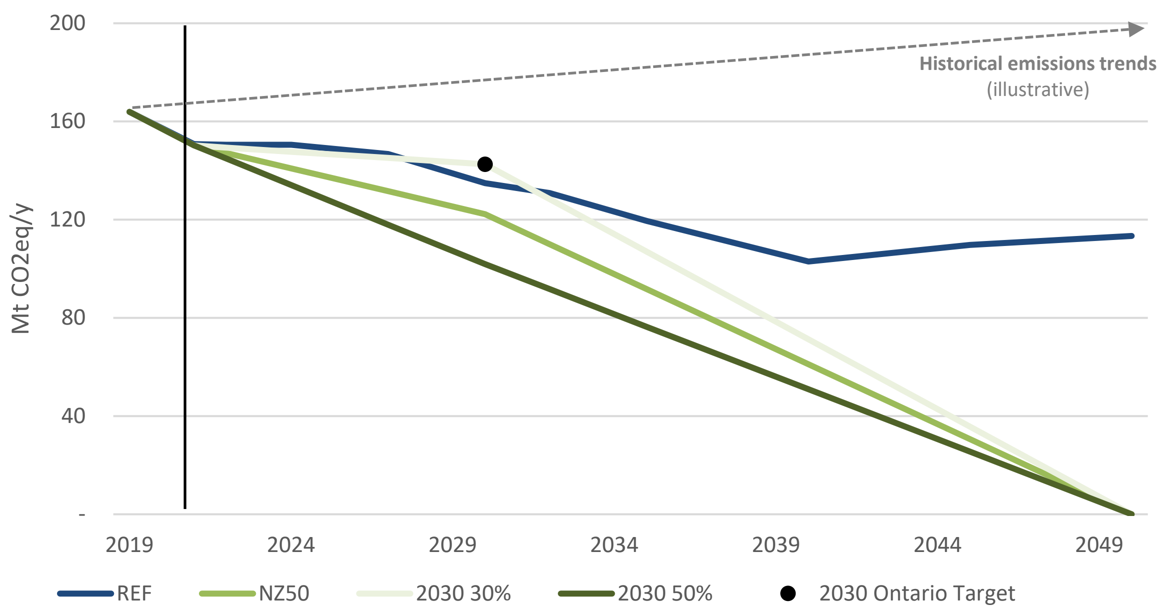


Figure 5-1. Annual GHG emissions (Mt CO2eq/y) from 2019 to 2050 for select integrated pathways (Economy-wide GHG emissions covered by the NIR)[33]

[32] The reference case should not be interpreted as a no-action pathway. It assumes a significant level of action, as per the modeled announced federal and provincial policies and additional restriction on new natural gas generation. Similar to the decarbonization pathways, it has limited consideration of market barriers and irrational economic decisions.

[33] Throughout report, "Economy-wide GHG emissions covered by the NIR" exclude GHGs from international aviation and marine. See Deliverable 3, Appendices E and F for emissions including international marine and aviation and for emissions by greenhouse gas.

GHG Emissions by Sector

To close the gap and achieve net-zero GHG emissions in 2050, there is a need for significant emissions reductions across all sectors, as well as the introduction of negative emission solutions after 2030 to compensate for remaining GHG emissions in sectors where full decarbonization is challenging or costly. Specifically, in the NZ50 IP (Figure 5-2):

- **Residential and commercial sector GHG emissions are completely eliminated in 2050.**
- **Transportation sector GHG emissions are reduced by 90%** compared to 2019.
- Over **50% of remaining GHG emissions in 2050 are from the agriculture sector**, driven by non-energy emissions related to soil management, fertilizer application and livestock.
- To offset the GHG emissions that do remain in 2050, the **industrial and electricity sectors become net-negative emitters**, through the use of CCS and NETs, including bioenergy with carbon capture and storage (BECCS) and biochar production (whose negative emissions are allocated to the industrial sector), **and DAC is used**.

  Using an optimistic estimate of Ontario's geologic sequestration potential, at the 2050 rate of sequestration, if all geologically sequestered CO2 was done within Ontario, the province's capacity will be exhausted between 2074-2081 across NZ IPs and SAs, except in CCS- and CCS- NZ-, which run out in 2233 and 2232 respectively. To maintain net zero in the long-term, while waiting for other technologies to develop, it may prove more cost-effective to preserve geologic sequestration space for the longer term and pursue earlier electrification and decarbonization efforts. The IPCC has also indicated that to stabilize global temperatures, or in a scenario where global temperature overshoots 1.5°C of warming, the world would need to become carbon negative to maintain temperatures in the long term or even bring temperatures back down. If Ontario were to use carbon sequestration to become carbon negative, either more space needs to be conserved, or space will run out faster.

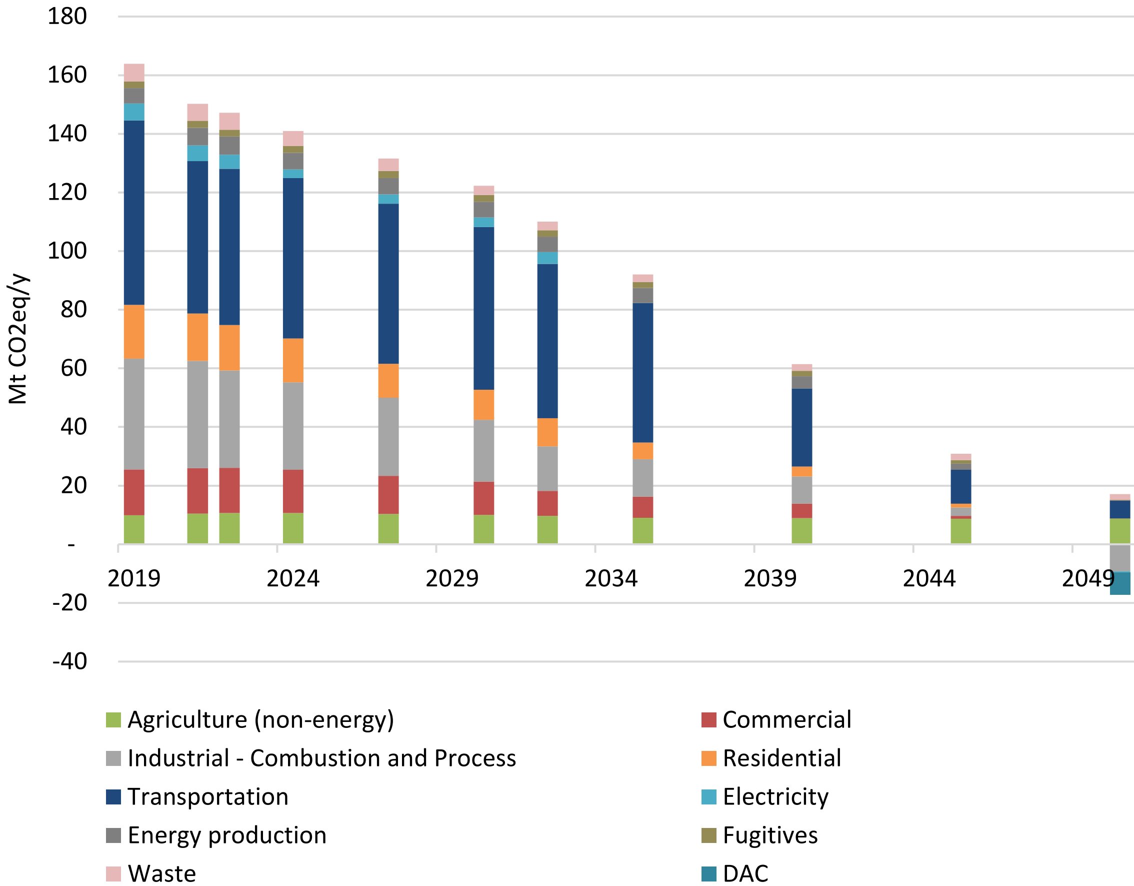


Figure 5-2. Total annual GHG emissions by sector (Mt CO2eq/y) from 2019-2050 for the NZ50 IP (Economy-wide GHG emissions covered by the NIR)

The Impact of Abatement Cost on GHG Emissions Reductions by Sector

Abatement Cost Curves (ACCs) can highlight insights into the cost-effectiveness of abatement in various sectors and of various measures, and their potential impact on achieving GHG targets. All measures up to a desired amount of GHG reductions, e.g. net zero in 2050, must be implemented; if certain measures are not implemented, more expensive alternatives are required to meet the desired GHG reductions.

GHG emissions reductions relative to the reference case required to get to net-zero in 2050 can be broken down into progressive phases, including:

Phase 1, the first step of the curve;

Phase 2, between the first step and 50% of the IP end-point GHG emissions reductions;

Phase 3, between 50% and 80% of the IP end-point GHG emissions reductions;

Phase 4, between 80% and 100% of the IP end-point GHG emissions reductions;

For analysis on **Phase 5** (showing measures beyond the end point), please see Deliverable 4.

The REF IP, which served as the starting point for the ACC curves, **already incorporates substantial GHG emissions reductions in 2050 compared to 2019,** notably in light-duty transportation, due to ambitious policies modelled as well as the low total cost of ownership of EVs, as well as in the buildings sector due to energy efficiency, ASHPs, district energy systems (DES) and ground-source heat pumps (GSHPs).

Phase 1: Low-cost abatement opportunities in industry and agriculture. Initially, low-cost solutions such as reducing enteric fermentation and improving manure and soil management in agriculture, introducing biochar production and industrial process CCS, and increasing wind capacity while reducing natural gas generation (without CCS) in the electricity sector are most cost-effective.

Phase 2: Gradually increasing GHG emissions reductions across all sectors other than agriculture. Non-energy agriculture GHG emissions stabilize, but gradually increasing GHG emissions reductions are achieved across all other sectors as the abatement cost increases. Additional decarbonization in the residential and commercial sectors occurs relatively early on (at lower abatement costs), with the increasing use of DES. Electricity generation from natural gas (without CCS) continues to steadily decrease and generation from increasing wind and solar capacity takes its place. Water heating electrification, commercial dual heating systems and the use of RNG are also introduced.

Phase 3: Further GHG emissions reductions in industry and transportation. At this stage, the electricity and buildings sectors are largely decarbonized, and there are fewer abatement opportunities in these sectors. BECCS hydrogen production, hydrogen use in industry, and hydrogen turbines for electricity generation are introduced materially in this phase.

Phase 4: Higher-cost solutions, including DAC. The remaining 20% of NZ50 IP emissions reductions are achieved largely through DAC, as well as deeper decarbonization across all sectors, with industrial decarbonization being another major contributor.

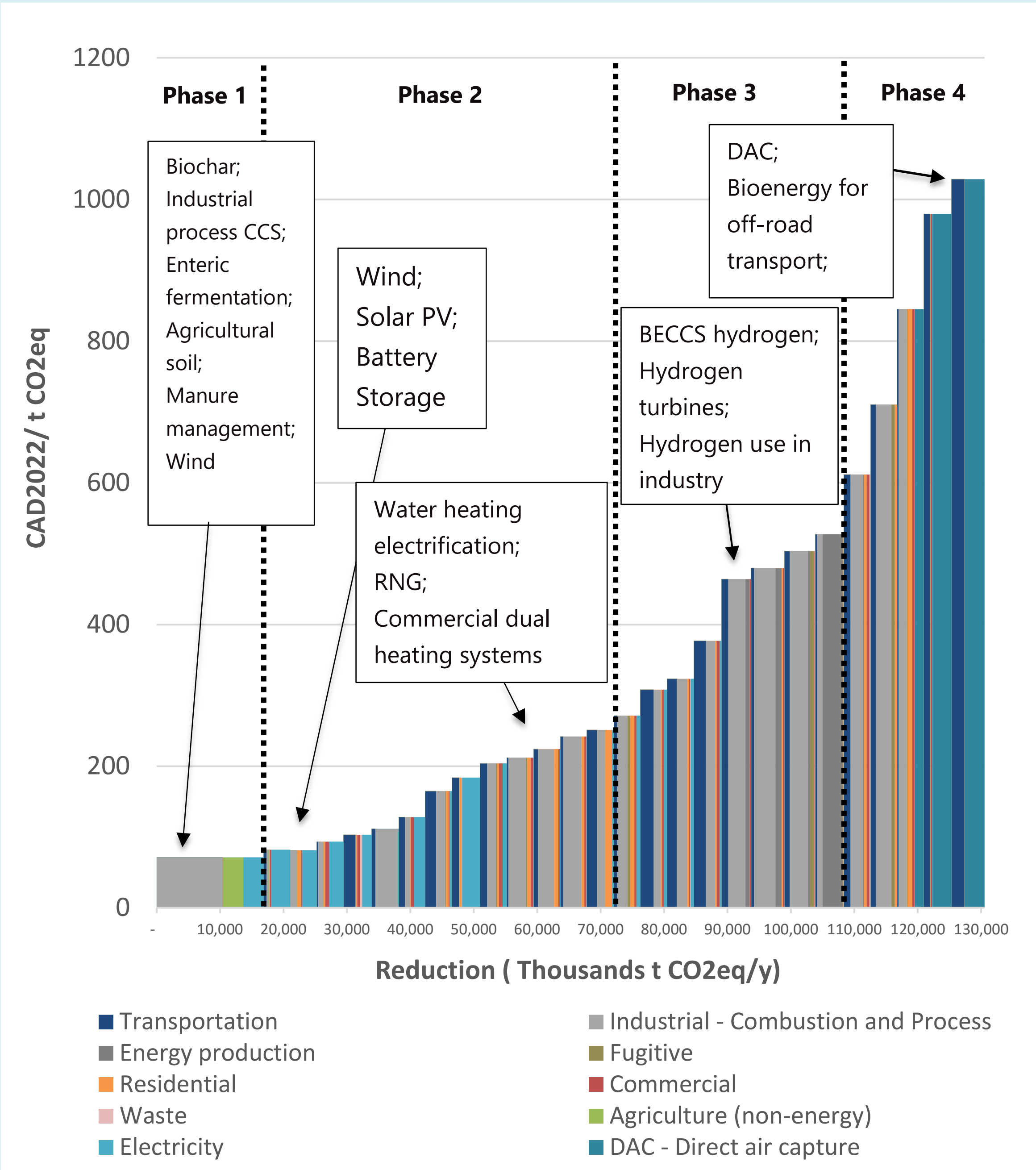


Figure 5-3. 2050 ACC (CAD2022/t CO2eq) with GHG emissions reductions by sector (t CO2eq/y) (NZ50 IP)

The Net-Zero Effect

Certain solutions which reduce, but do not eliminate, GHG emissions – such as dual fuel space heating systems using fossil natural gas and production (and use) of blue hydrogen – appear cost-effective at intermediate abatement costs. However, as the marginal abatement cost escalates moving towards net-zero, widespread use of these solutions may not remain economically viable compared to alternatives, as the remaining GHG emissions become costly to manage.

Note that the sector-level analysis presented for ACCs only looks at decreases in GHGs from one step of a GHG constraint to the next; the increases are ignored. So, the total GHG reductions in the sector-level graphs exceed the total of economy-wide GHG reductions.

5.3 Energy Demand

Overview

While fossil fuels currently account for the majority of Ontario's final energy consumption, **across NZ IPs, electricity becomes central to Ontario's energy system,** accounting for the majority (56-64%) of final energy consumption in 2050 (Figure 5-4). Other key takeaways for Ontario's final energy consumption across NZ IPs include:

- **Energy consumption decreases between 2019 and 2050**, despite increasing population, GDP, and demand for energy services. This is partly driven by electrification (electric technologies can be greater than three times more efficient than the equivalent fuel-based technology), as well as other energy efficiency and conservation measures, such as improved building envelopes.
- **Clean fuels such as liquid biofuels, renewable natural gas (RNG) and clean hydrogen[34] are used strategically** in sectors where electrification is expected to be more challenging or costly and make up 13-19%[35] of Ontario's final energy consumption combined in 2050.

[34] Throughout the report, whenever hydrogen is referred to as "clean hydrogen", this is in reference to electrolytic, blue, or biogenic hydrogen. Grey hydrogen (produced from natural gas without CCS) is not considered "clean".
[35] Comprises solid, liquid and gaseous biofuels, hydrogen and synthetic fuels.

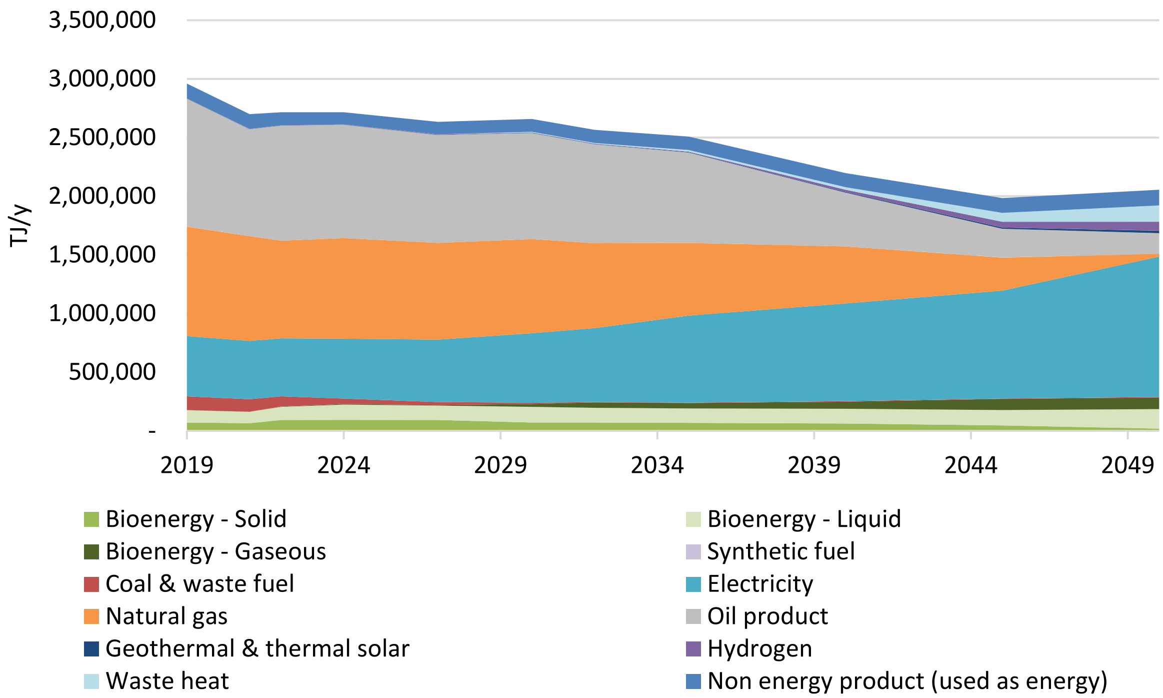


Figure 5-4. Final energy consumption (TJ/y) by fuel type from 2019 to 2050 for the NZ50 IP

Buildings

Across all IPs including REF, buildings are largely electrified, and electricity accounts for the vast majority (62-80%, depending on the pathway) of final energy consumption in 2050 (Figure 5-5). This is driven by electrification of space heating and water heating in both residential and commercial buildings – electric heat pumps (including air-source heat pumps, ground-source heat pumps, and dual systems[36]) supply more than 50% of Ontario's useful space heating demand in 2050 in all IPs including REF.[37] Other notable trends for NZ IPs include:

- **Final energy consumption decreases significantly between 2019 and 2050**, driven by electrification, improved envelopes for both new and retrofit buildings, and controls.
- **DES is another key pathway for decarbonizing space heating**,[38] accounting for 35-37% of residential and commercial space heating across NZ IPs.

[36] Dual systems include an air-source heat pump with a gas fueled backup system. The air-source heat pump provides the majority of the heating, but the system switches to the gas backup when outdoor air temperatures are very low. The gas can be natural gas, RNG or hydrogen blend.
[37] Useful space heating demand refers to the output heat energy required to fulfill space heating needs.
[38] It should be noted that while the modelling illustrates significant potential for district energy systems, future proximity of district energy system (DES)-compatible areas and SMRs is challenging to predict, and achieving a high penetration of DES will require careful coordination and planning.

- **Waste heat and GSHPs are leveraged for space heating in DES.** [39] By 2050, across all NZ IPs, inexpensive waste heat from SMRs supplies 32-37% and 33-37% of annual useful space heating demand in the residential and commercial sectors, respectively. In earlier years, and in the REF IP, GSHPs are also used.
- The use of fossil natural gas is eliminated – however, **RNG *may* play a minor but strategic role in mitigating peak impacts of electrification through use in dual systems. However, death spiral effects[40] on the natural gas system were not modelled and could impact the feasibility of maintaining the natural gas network.**

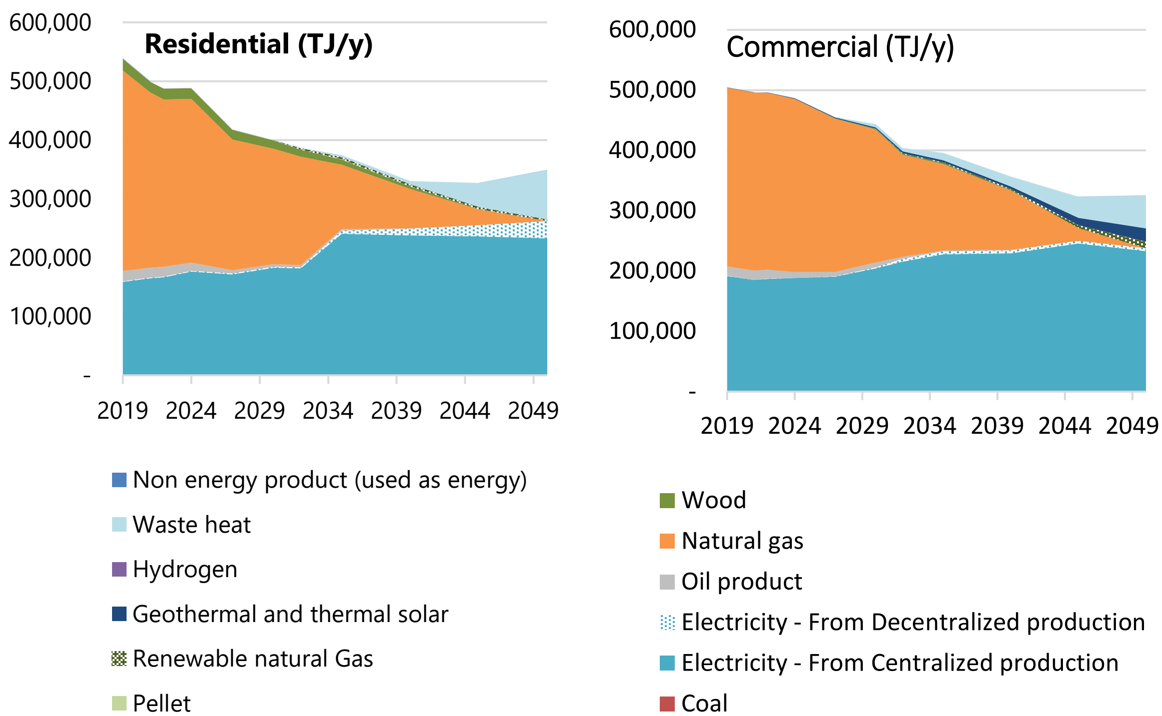


Figure 5-5. Final energy consumption (TJ/y) by fuel type from 2019 to 2050 for the NZ50 IP in the residential (left) and commercial (right) sectors

Transportation

Across all NZ IPs, electrification and the use of biofuels emerge as key pathways to decarbonization of the transportation sector, accounting for 41-50% and 14-22% of final energy

[39] Heating from DES can be supplied by a variety of sources, however, to be decarbonized waste heat should come from electric heat pumps or clean fuels. The modelling mainly sees GSHPs and, in later years in NZ IPs, waste heat.
[40] Death spiral effects refer to a decline in gas consumption and connected customers, leading to higher costs for those remaining and resulting in even higher and faster disconnections.

consumption in 2050, respectively[41] (Figure 5-6). The use of some fossil-based fuels also remains in sub-sectors which are harder or more costly to decarbonize, such as aviation and off-road. Notably, final energy consumption in the transportation sector decreases significantly between 2019 and 2050, even as annual passenger-kilometers and annual tonne-kilometers travelled continue increasing. This is driven by the much higher efficiency of electric drivetrain vehicles (~3-4x) compared to internal combustion engines.

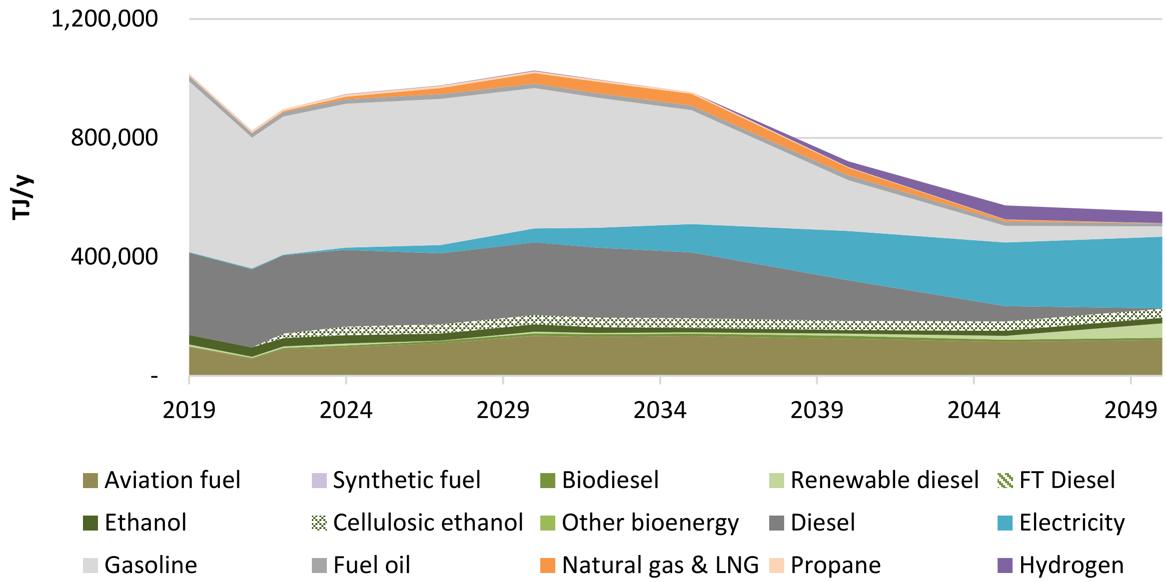


Figure 5-6. Final energy consumption (TJ/y) by fuel type from 2019 to 2050 for the NZ50 IP

The transportation sector includes many highly diverse sub-sectors and end-uses, and the extent of and pathway to decarbonization varies accordingly. Big-picture takeaways for key sub-sectors and end-uses include:

- **Light-duty road transportation is fully electrified in 2050, even in the REF IP,** for cars, passenger light-trucks and freight vehicles. This is driven by policy (federal ZEV mandate), as well as the declining total cost of EV ownership.[42]
- **Heavy-duty freight shifts towards battery electric, catenary electric and hydrogen** vehicles, with the split sensitive to the assumptions across different IPs.
- **Aviation is not decarbonized in most IPs,** but the use of synthetic fuels emerges as a potential pathway in IP/SAs requiring deeper decarbonization.
- **Buses are predominantly electrified in NZ IPs,** and hydrogen also plays a role.

[41] This excludes the H2+ IP. See section 1.2.
[42] The only form of light-duty transportation which is not fully electrified across select IPs and SAs (REF, ELC-, NZ50 NZ+) is motorcycles.

Other transportation modes – including rail, marine, and off-road transport – leverage a mix of electrification, biofuels and hydrogen.

Industry

Across NZ IPs, **the industrial sector is largely electrified**, and electricity accounts for the largest share of final energy consumption in 2050 (42-49% excluding the H2+ IP) (Figure 5-7). However, certain industries and processes are more challenging or costly to electrify – therefore, **there is also an important role for clean fuels – primarily renewable natural gas (10-15% of final energy consumption in 2050) and some hydrogen (3-9% of final energy consumption, excluding the H2+ IP).**[43] Some limited use of fossil fuels remains where lower-emitting alternatives are uneconomic or unavailable.

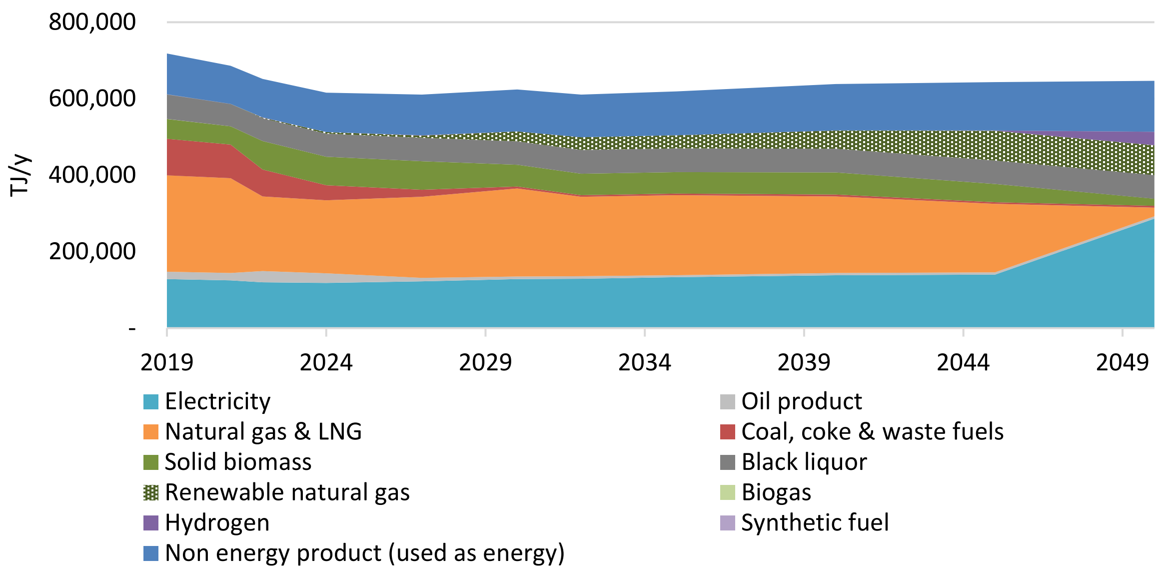


Figure 5-7. Final energy consumption (TJ/y) by fuel type in the industrial sector from 2019 to 2050 for the NZ50 IP

5.4 Energy Supply

In response to the changes in energy demand highlighted in the earlier sections, achieving net-zero in 2050 across **NZ IPs will require Ontario's energy supply to evolve to meet these shifting demands.** In particular, a significant increase and shift in electricity supply is needed to meet the growing demand for electricity as electrification plays a pivotal role in decarbonization of key end-uses in the transportation, buildings and industrial sectors. Additionally, the

[43] Hydrogen is predominantly used as pure hydrogen - blending in natural gas network for the industrial sector is negligible. The modelling considers a 5% (by energy) cap on hydrogen blending in natural gas pipelines.

contribution of clean fuels, including clean hydrogen and biofuels such as liquid biofuels and RNG, also increases.

Electricity

To meet the increase in demand for electricity (to 315 to 455 TWh/y in 2050), **Ontario's electricity supply will need to expand significantly – on the order of double to triple today's system across all NZ IPs**– to power the province's economy. In 2050, 87-115 GW of installed capacity will be needed to meet the province's electricity demand in the NZ IPs, (e.g. Figure 5-8 shows the NZ50 IP). Supply also increases significantly in the reference case (to 1.5x from 2019 to 2050), to meet the corresponding increase in demand (to 1.5x from 2019 to 2050).

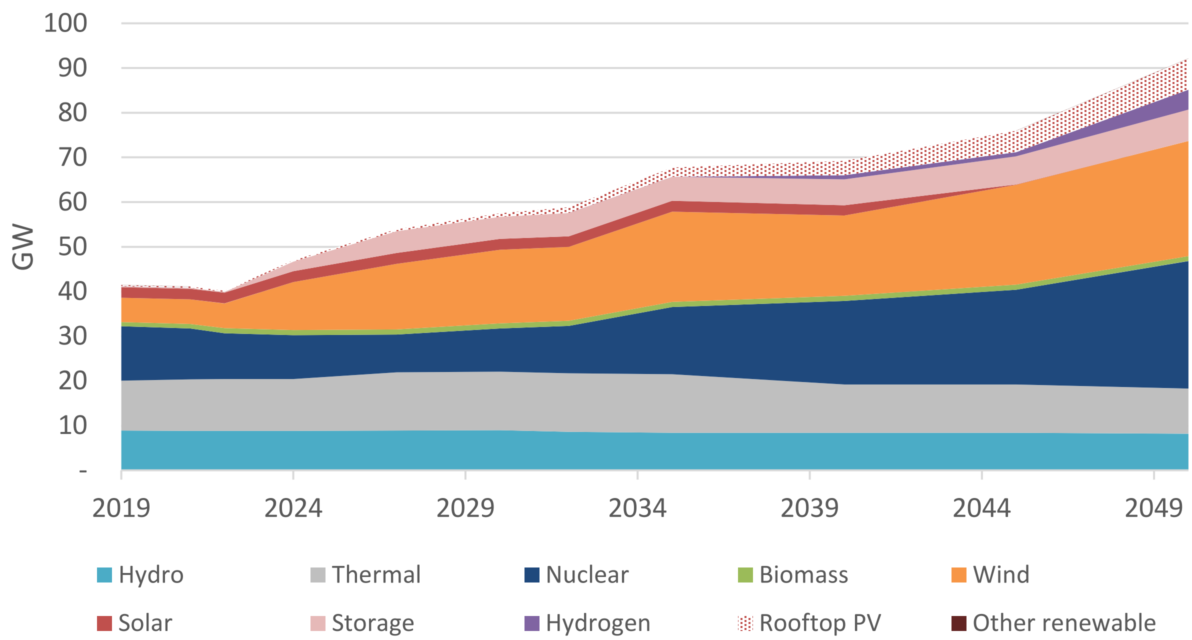


Figure 5-8. Installed capacity (GW) by technology in 2019 to 2050 for the NZ50 IP

The growth in electricity supply in NZ IPs is largely dominated by growth in wind and nuclear capacity, 12-26 GW and 12-31 GW respectively, between 2019 and 2050. Growth in conventional and advanced nuclear (GEN III+) capacity is driven by the capacity additions planned under the Powering Ontario's Growth initiative – however, additional growth in SMRs is significant, with 8-27 GW of added capacity over and above what is planned under Powering Ontario's Growth. Since SMRs only reach the required economies of scale in later years, the addition of wind capacities mid this decade is a key contributor to increasing supply. Growth in SMRs is moderate until the 2040's. While each technology offers unique benefits, across modelled IPs, there is some trade-off between the magnitude of wind versus SMR deployment – for example, if SMR cost declines are less significant, wind capacity additions may be more significant.

Beyond wind and nuclear, a notable growth in rooftop solar is observed in NZ50. Additionally, there is 7 GW of electricity storage (both batteries and pumped hydro) in 2050 to support renewables integration and/or peak needs. In 2050, the supply mix also includes a notable portion of the existing natural gas fleet as well as new hydrogen capacity to meet resource adequacy needs.

The Role of Onshore Wind and SMRs

Both wind and nuclear (SMRs) are expected to play a key role in Ontario's energy transition across all NZ IPs and SAs. Each technology offers unique benefits that are essential for an affordable and reliable emissions-free electricity system. No single generation technology can cost-effectively ensure grid stability and energy and supply resource adequacy. Instead, a diverse mix of technologies – including wind, SMRs, and others identified in the modelling results – is essential to achieve these goals in a cost-effective manner.

Wind energy, while variable, is a cost-effective option for energy production.

Despite the higher cost and uncertainty associated with SMRs, their ability to provide consistent, reliable baseload power with a high capacity factor and guaranteed contribution to peak demand mean that this technology is well-suited to meeting baseload needs.

The modelling results show that the **complementary nature of wind and SMRs implies that both are necessary for a resilient and cost-effective energy transition in Ontario.** However, the relative contributions of wind vs. SMRs to the overall mix will depend on assumptions, for example, regarding the evolution of technology costs, capacity factor and contribution to peak demand.

As an illustration of uncertainty, in 2050, the central per kW cost estimate for wind is CAD 2022 $1,142, with a range of approximately +/- 20% (from CAD 2022 $879 to CAD 2022 $1,352). On the other hand, the central per kW estimate for SMRs is approximately CAD 2022 $9,500,[44] with a range of +/- 40% (from approximately CAD 2022 $5,700 to CAD 2022 $13,300).

As an emerging technology, the cost trajectory of SMRs is less certain, which leads to some variation in deployment across modeled pathways. In contrast, onshore wind has a more predictable and narrower cost range. This comparison highlights the importance of technology assumptions for cost-effective pathways.

Bioenergy

Across NZ IPs, Ontario leverages a diverse mix of biomass feedstocks to fulfill the significant growth in demand for biomass. There is increased utilization of forest residues and roundwood, and Ontario also begins to leverage the significant potential of agricultural residues and source-

[44] With some variation depending on the type of SMR technology.

separated organics (Figure 5-9). There is also continued use of landfill gas from 2019 to 2050, and limited use of dedicated fast-growing trees and crops after 2040. The use of corn, wheat, soy and canola-based feedstocks is **already near the maximum sustainable potential in 2019**, which is limited considering these feedstocks are also in competition for land use with food crops, therefore the growth in demand for biomass is primarily fulfilled by other feedstocks.[45]

Across all NZ IPs, almost all biomass supply potential is used in 2050. This includes 97-98% of forest biomass supply, 100% of crop residue supply, and 100% of the potential for dedicated fast-growing trees and crops. Only industrial residue and corn and wheat supplies are not used up to, or near, their max potential.

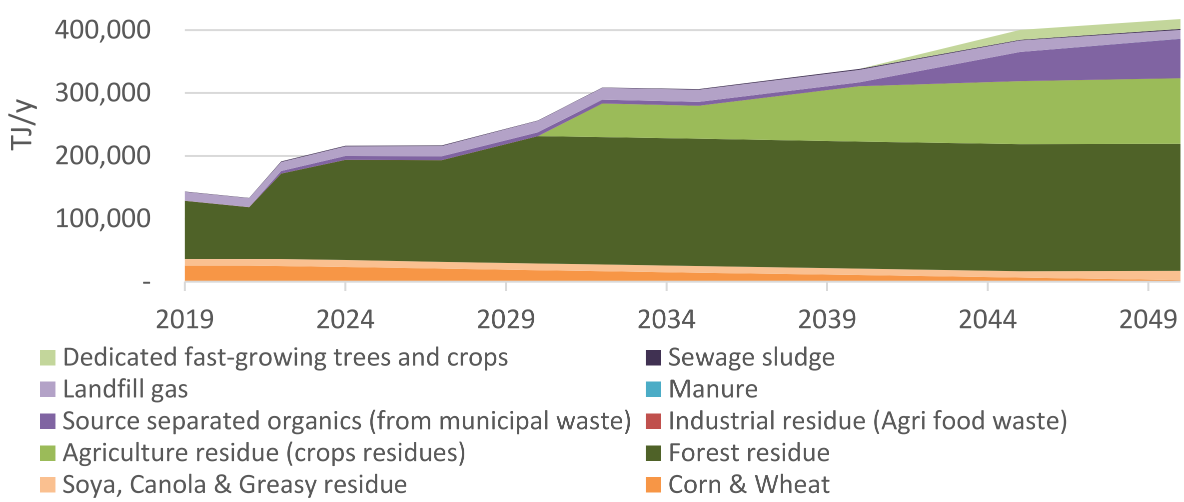


Figure 5-9. Bioenergy feedstock supply (TJ/y) in 2019 to 2050 for the NZ50 IP

Hydrogen

Across NZ IPs, hydrogen production increases significantly, particularly post-2035 (Figure 5-10). Initially, "blue" hydrogen production technologies (production from natural gas with CCS) dominate hydrogen production, ramping up significantly between 2035-2045, and production from natural gas without CCS is gradually phased out. In later years (post-2045), production from biomass with carbon capture and storage (BECCS) also supplies a portion of hydrogen demand, and BECCS production also contributes to the generation of negative emissions to meet the net-zero in 2050. Provincial imports also ensure Ontario's supply of hydrogen meets the demand in 2050 across the majority of NZ IPs.[46]

[45] In this report, biomass feedstock supply refers to potential supply used for energy, for example, it excludes food production and biomass used for other products.

[46] Except in H2+ (which is an outlier, see section 1.2) and BIO+, where additional availability of biomass leads to increased BECCS production.

Across modelled NZ IPs, hydrogen pathways exhibit some sensitivity to the modelled assumptions – for example, if electrification conditions are favourable (ELC+), the production of blue hydrogen is eliminated (and overall supply and demand for hydrogen is decreased). On the other hand, in pathways where deeper GHG emissions reductions are required (CCS- and CCS NZ-) and there is a need to produce synthetic fuels, electrolytic hydrogen is produced.[47]

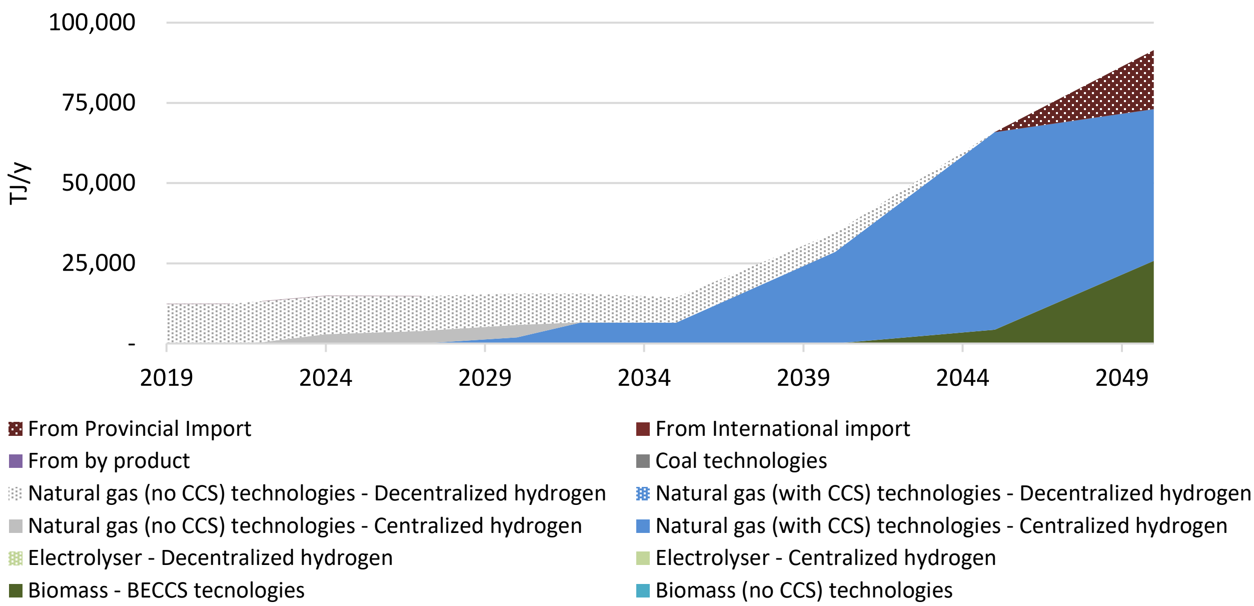


Figure 5-10. Hydrogen production (TJ/y) by technology and imports in 2019 to 2050 for the NZ50 IP[48]

The production of electrolytic hydrogen is absent (Figure 5-10) in 2050 from the majority of IPs including REF, apart from the exceptions noted above. This is likely due to the combined impact of several factors, including: (1) due to significant increase in electricity demand in other sectors, significant build-out of electricity generation capacity is already required, and electrolytic hydrogen is electricity-intensive, which would put further pressure on the electricity system and require costly build-out of capacity; (2) the total efficiency (production and consumption) of electrolytic hydrogen is relatively low, making direct electrification of end uses more cost effective in many cases. However, it should also be noted that the long-term cost-effectiveness of blue hydrogen in a NZ IP will also likely depend on the capture efficiency, assumed to be 95% in the modelling. If this capture efficiency cannot be achieved, blue hydrogen may no longer be the most cost-effective option.

[47] Electrolytic hydrogen production is also seen in the H2+ pathway which, as mentioned, is an outlier (see section 1.2) and assumes a production tax credit for electrolytic hydrogen.
[48] Hydrogen supply includes hydrogen used as a feedstock, including for energy (e.g., synthetic fuels) and non-energy (e.g., fertilizer) applications.

SECTION 6

6. The Impacts

6.1 Economic Impacts

Net-zero by 2050 will require substantial investments in the electricity sector

Steering Ontario's economy onto a pathway to achieve net-zero in 2050 will require additional cumulative investments of CAD2022 $173B (in the NZ50 IP) beyond costs projected in the REF IP (Figure 6-1) from 2019 to 2050. Incremental investment will be primarily concentrated in the electricity sector, due to the high need for emissions-free electricity supply and transmission and distribution. The buildings sector will also require incremental investments to drive further electrification. Incremental investment in the transportation sector is relatively small, as current policies and cost trends already drive significant decarbonization of transportation in REF.

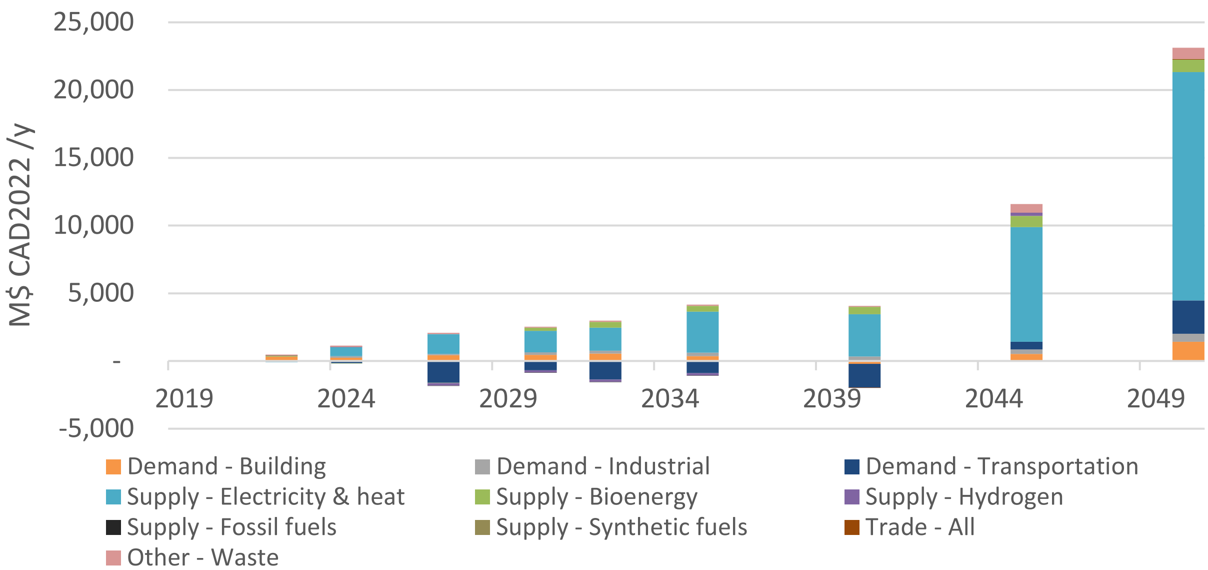


Figure 6-1. Annual incremental investment cost (M$ CAD2022/y) of the NZ50 integrated pathway compared to the REF IP in 2019 to 2050

This section summarizes key highlights and findings from Deliverable 3: Cost-Effective Pathways (Main Analysis) and Deliverable 4: Abatement Cost Curves. For further details, readers can refer to Deliverables 3 and 4.

Significant Reductions Can be Achieved at Lower Abatement Costs

The findings indicate that substantial GHG emissions reductions can be achieved at costs significantly lower than the end-point abatement costs. For example, in 2050, over 80% of the emission reductions achieved at the NZ50 IP endpoint can be achieved for 50% or less of the final abatement cost (CAD2022 $528/t CO2eq vs. $1,029/t CO2eq). The average marginal abatement cost required to reach the NZ50 end point is CAD2022 $355/t CO2eq. [49]

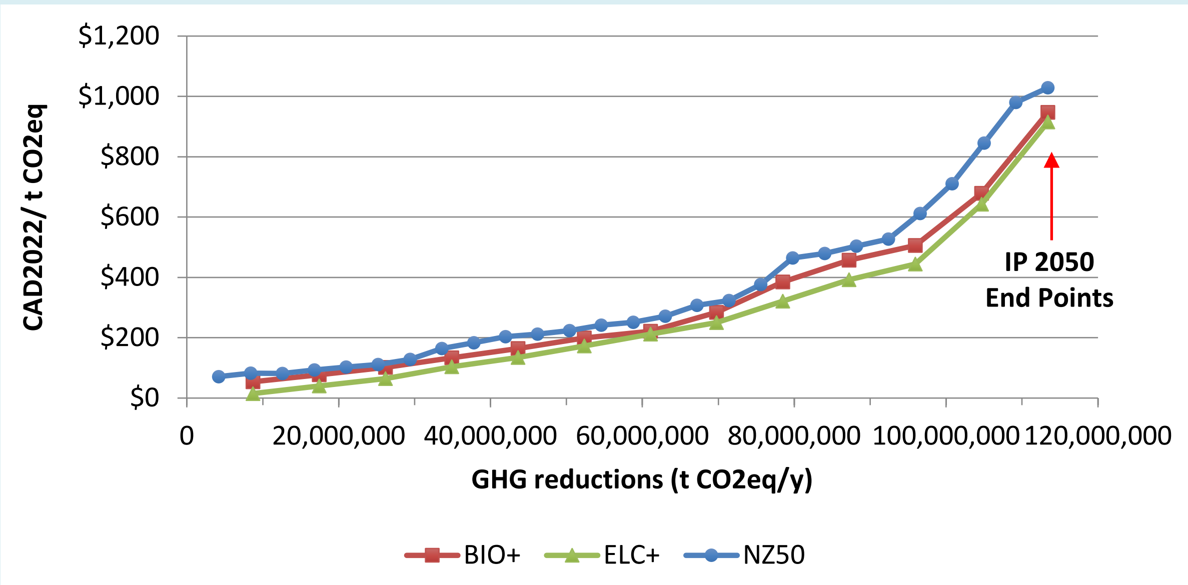


Figure 62. 2050 Abatement cost (CAD2022/t CO2eq) for different GHG emissions reductions (t CO2eq/y) relative to the REF IP (excluding points past net-zero-)

Energy and climate policies represent a minor impact on GDP

Incremental impacts of Ontario's energy transition on GDP will be 0.02-0.08 percentage points per year[50] lower in NZ IPs compared to REF, or between CAD2022 $0.4 and $1.2 billion per year in 2050 in absolute terms (Figure 6-3). Although fuels and energy technologies are used in all sectors, the share of GDP that is associated exclusively with energy services and goods is small. For example, the Ontario Energy sector (aggregate T016 that combines the North American Industry Classification System (NAICS) codes 211, 2121, 21229, 213111, 213118, 2211, 2212, 32411, 486) represents around 3% of the total Ontario GDP, while the energy labour force is about 5% in 2019.

[49] The actual (i.e., not marginal) average abatement cost is lower than the average marginal or total marginal abatement cost.

[50] Difference in average real annual growth (%/y) (2019-2050) between REF and NZ IPs

Therefore, the overall impact on provincial GDP and other global indicators (such as labour demand) from energy and climate policies is minor, although impact in individual sectors can be relatively larger.

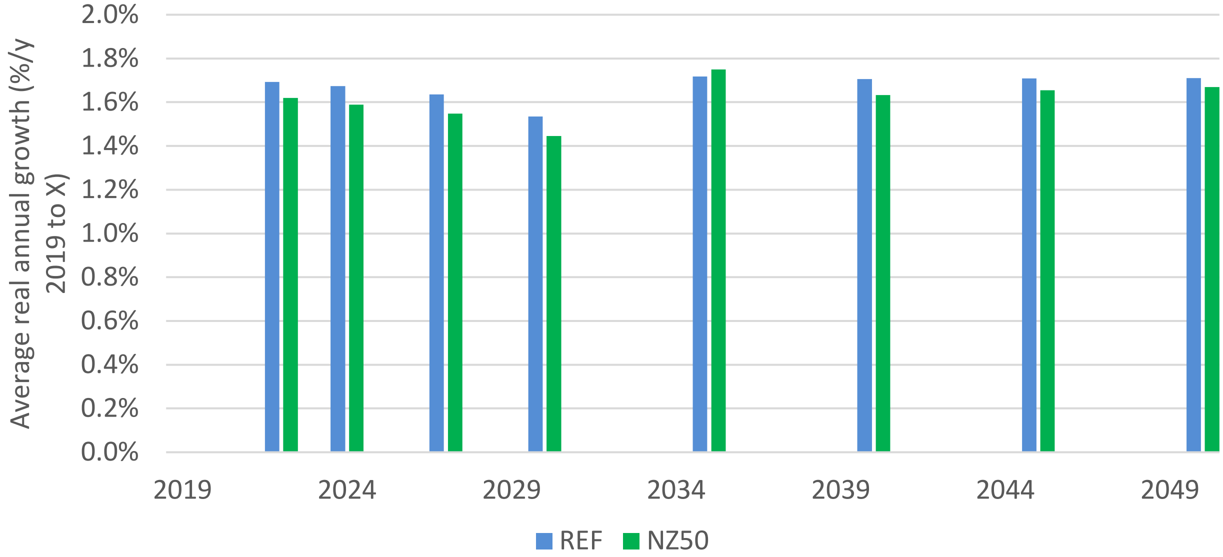


Figure 6-3. Average real annual GDP growth (%/y 2019 to X) in REF and NZ50

6.2 Household Impacts

Household energy bills are expected to decline

At a more granular level, **household energy bills are generally expected to decrease by 40-56% (or CAD 2022 214-304/month)** [51]between 2022 and 2050 across the REF IP and NZ IPs (as seen in Figure 6-4, which represents the "average" or total normalized monthly household energy cost in NZ50).[52] While the transition of Ontario's energy system towards net-zero may put upward pressure on electricity tariffs (due to the need for building out electricity supply capacity, for example), ultimately **households will still decrease the total amount they are spending on energy thanks to an overall reduction in energy consumption, driven by fuel switching and other energy savings.**

[51] Without OER, with legislated carbon price.

[52] The "average" or total normalized energy bill refers to the total cost of residential electricity and fuels (such as natural gas, gasoline, heating oil) divided by the number of households in the province.

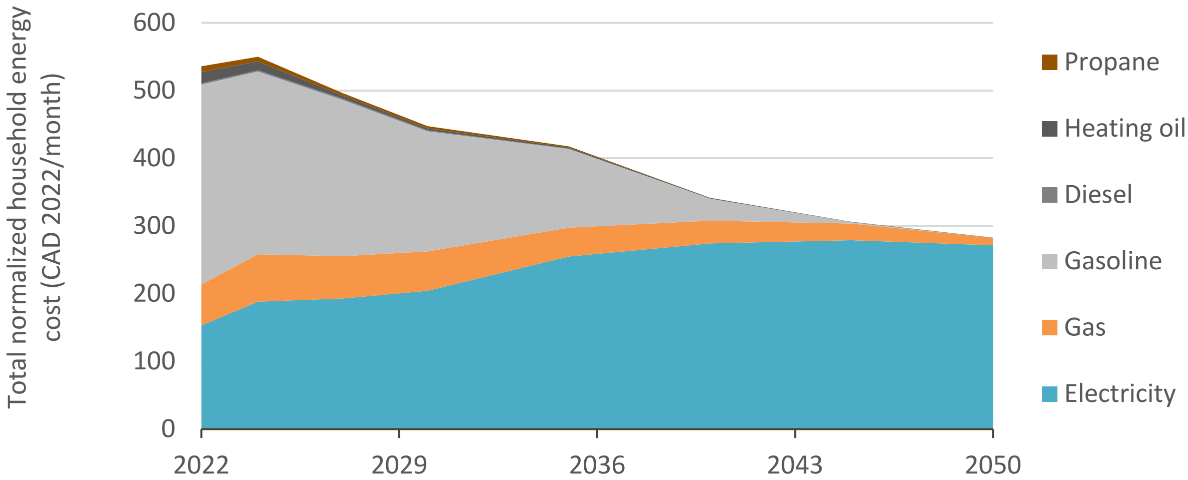


Figure 6-4. Evolution of normalized residential energy cost 2022 to 2050 for NZ50 IP without OER with legislative carbon price (HST, federal excise tax, provincial fuel tax, and the federal fuel charge are included)

The same decreasing trend is seen for "typical" household energy bills, defined for a household which uses the plurality (most common) technologies for space heating, water heating, vehicles and cooking. Typical household energy bills are expected to decrease by 15-31% (or CAD 2022 78-159/month) (Figure 6-5). Note that the modelled "typical" households may be different than specific households.

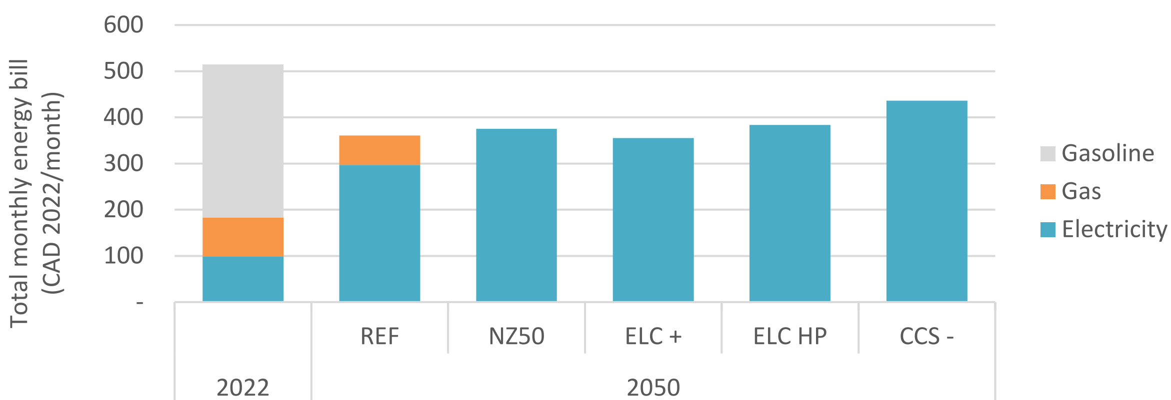


Figure 6-5. Comparison of typical energy bills for a household using the plurality technologies for different integrated pathways for 2050 without OER with legislated carbon price (HST, federal excise tax and provincial fuel tax are included).

However, customers remaining on the natural gas network may experience increasing bills in NZ IPs, as there is a risk that (fixed and volumetric) rates increase significantly as the number of customers on the network decreases as a result of the energy transition. As a consequence, there is risk of stranded assets and the need to abandon gas infrastructure in NZ IPs.

Natural Gas System: Key Considerations

These results broadly lead to the conclusion that under all IPs (REF and NZ IPs), electricity is the most efficient and cheapest energy source - driving households to stay on electricity or switch to it from 2024 to 2050. Gas could become more expensive as the number of consumers decline, negatively impacting energy affordability and potentially leading to a "death spiral" effect (not modelled) for natural gas by 2045-2050 in the NZ IPs. The death spiral refers to a decline in gas consumption and connected customers, leading to higher costs for those remaining and resulting in even higher and faster disconnections.

However, at the same time, as suggested by the least-cost pathway modelling results, it could be of interest for the province to maintain a small but strategic amount of RNG in dual heating systems, especially as Ontario shifts to winter peaking due to space heating electrification. From this perspective, the gas network and consumers who use gas with dual systems may be regarded as an asset for electricity utilities, and alternative compensation that adequately values their service to the electricity system could help to mitigate the death spiral effect.

Alternatively, if death spiral effects make dual systems and continued maintenance of the natural gas system infeasible or too expensive, other solutions, such as on-site thermal storage, could also provide peak shaving services.

6.3 Co-Benefits

Beyond the direct implications of the transition highlighted above, climate change mitigation and the reduction of Ontario's GHG emissions will bring many associated environmental, social and economic co-benefits – including, but not limited to, agricultural productivity, improved human health, economic activity, and reduced risk of disruption of energy systems and conflict.

Based on the social cost of greenhouse gases (SC-GHG), which is a commonly used measure of the societal benefits/damages associated with GHG emissions reductions over a given period of time, achieving GHG emission reductions in-line with the NZ IPs would result in CAD2022 $245B to $874B of cumulative climate change impact mitigation benefits (incremental to the REF IP) from 2019 to 2050, (Figure 6-6). [53]

While investments in the energy sector can also bring co-benefits, such as increasing GDP, creating jobs, and improving Ontario's trade balance, it is also interesting to note that co-benefits

[53] To estimate the benefits associated with the emission reductions modeled in IPs and SAs, Canada's SC-GHG guidelines were used, which include estimates for the social cost of carbon (SCC), the social cost of methane (SCM), and the social cost of nitrous oxide (SCN) discounted through 2080. The federal government provides values for the SC-GHG based on a 2% near-term Ramsey discount rate. Two additional sensitivity scenarios are also provided at 1.5% and 2.5% which are used to calculate the range of cumulative benefits.
Government of Canada, Social Cost of Greenhouse Gas Estimates – Interim Updated Guidance for the Government of Canada. Available online: https://www.canada.ca/en/environment-climate-change/services/climate-change/science-research-data/social-cost-ghg.html

due to climate change mitigation are expected to significantly outweigh any incremental investment required to reach net-zero in 2050.

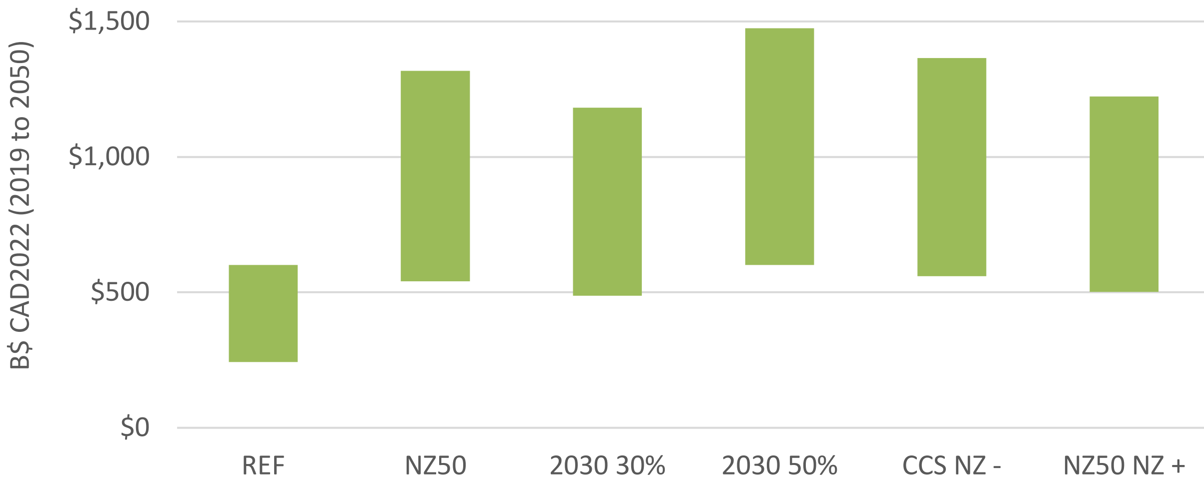


Figure 6-6. Estimated Range of Cumulative Benefits (2019-2050) from Avoided Climate Change Impacts for Key IPs and SAs, compared to a baseline of 2019 annual GHG emissions

While the SC-GHG captures many of the impacts associated with GHGs and climate change, there are some limitations and additional co-benefits should be considered. For example, while some key health impacts are quantified, including heat and cold related mortality and mortality due to extreme weather events and sea level rise, the **SC-GHG does not currently include the health benefits associated with the reduction of other pollutants, such as particulates (e.g., PM2.5).** Quantification of these benefits is challenging due to the uncertain range in potential emission factors, which are technology dependent, as well as the highly localized nature of these impacts, meaning that a proper understanding of the impacts would require regional geographic analysis, which was outside the scope of this study. However, reduction of air pollutants such as PM2.5 and the resulting reduction in human life lost due to poor air quality is another key co-benefit of NZ IPs and SAs.

Further, while the SC-GHG captures many of the impacts related to GHG emissions, it typically does not include other damages associated with increasing concentration of GHGs such as extreme weather events, impacts associated with electricity supply reliability due to extreme weather events, uncertainty around impacts to ecosystem services such as water filtration and wildfire mitigation, national security, and social dynamics including poverty due to high uncertainty in modelling and quantifying these costs. Collectively, these impacts present an unprecedented risk that would have significant impact on our energy needs, economy and prosperity. **Therefore, the full range of estimates of climate change costs / climate change mitigation benefits using SC-GHG should be interpreted as a conservative estimate of the impacts associated with climate change.** Moreover, as the impacts of climate change are difficult to quantify and predict, this study's modelling framework does not consider future climate adaptation requirements for Ontario's energy system.

SECTION 7

7. The Barriers

7.1 Key Barriers to Ontario's Cost-Effective Energy Pathways

This section summarizes key barriers to scaling specific fuels and technologies in Ontario, which may impact the cost-effective pathways' practical implementation. These barriers highlight the complexity of the energy transition in Ontario and the need for targeted action to enable the scaling of fuels and technologies necessary for achieving a net-zero economy.

> This section summarizes key highlights and findings from Deliverable 5: Barrier Identification. For further details, readers can refer to Deliverables 5.

Awareness

There is a general lack of awareness or knowledge among the public and key stakeholders about emerging fuels and technologies still in the early stages of development. These technologies, which have not yet reached commercial operation, do not have the same visibility as more established counterparts. For example, renewable diesel's use cases are largely misunderstood compared to petroleum diesel and biodiesel. This lack of awareness is common across most emerging technologies, including ASHPs, BEVs, electricity storage, and SMRs. Increasing education and awareness is crucial to promote the adoption of these critical technologies.

Public Acceptance

Public hesitation and pushback towards new infrastructure initiatives and the adoption of these fuels and technologies present significant barriers. Concerns about safety and land impacts often lead to resistance against siting SMRs and wind turbines, which are essential for the electricity supply. Similarly, pumped hydro storage projects and the expansion of T&D infrastructure face public opposition. Significant early efforts to engage and communicate with the public are necessary to mitigate these concerns and ensure adequate infrastructure capacity for the short-, mid- and long-term integration of these technologies.

Labour and Supply Chain

There is a significant deficit in skilled workers and supply chain challenges across almost all key fuels and technologies assessed, and addressing this deficit is critical to support their deployment and continued use in the economy. This issue is particularly important for technologies critical to a successful transition, such as ASHPs and BEVs. Expanding T&D infrastructure to support widespread electrification also requires a substantial increase in specialized workforce capacity. Addressing these gaps through targeted training programs and supply chain enhancements is vital for the successful deployment of new technologies.

Investment Uncertainty in New Markets

There is a "chicken and egg" dynamic between the need for robust supply chains and infrastructure to support the introduction of new fuels and technologies and the lack of an existing market to justify investments and their build-out. Key fuels and technologies with high uptake in the long-term, such as hydrogen networks and heavy-duty vehicle (HDV) electrification, may have initial uptake in modelled least-cost pathways in the short- or medium-term and require significant planning, decisions and investments beforehand to generate demand. However, the absence of an established market often deters these investments. For example, the lack of hydrogen storage and transportation infrastructure limits the adoption of hydrogen fuel cell vehicles. Coordinated early and mid-term investments are necessary to stimulate market development and demand.

High Upfront Costs for Long-term Benefits

Many key fuels and technologies for Ontario's cost-effective energy pathways – including ASHPs and GSHPs, BEVs, and building envelope retrofits – face financial challenges related to high upfront costs for consumers, which create a barrier to adoption even if that fuel or technology may be cost-effective from a societal perspective (and with regards to total cost of ownership) and part of the least-cost pathway to meeting GHG constraints. Policies and programs that offer subsidies for these technologies can help to reduce upfront costs for consumers but remain limited. Additional and longer-term support, particularly for low- and middle-income consumers and small businesses for whom upfront cost represents a significant barrier, will be necessary to encourage adoption and set Ontario on a least-cost pathway to net-zero.

Policy and Regulatory Drivers

A lack of policy and regulatory drivers leaves the uptake of some mature fuels and technologies to voluntary action, stagnating market development. For instance, the absence of regulations enforcing the phase-out of new fossil fuel connections, or the introduction of EV-ready buildings limits the adoption of mature heat pump technologies and retrofit measures. Similarly, the lack of RNG content mandates or carbon intensity requirements for natural gas contributes to slow uptake of RNG and/or hydrogen blending, acting as a barrier to achieving economies of scale for these fuels and the least-cost pathway to net-zero within the province. Implementing clear policies and regulations can improve consumer and investor confidence in decarbonization fuels and technologies and drive the adoption of these fuels and technologies to support Ontario's energy transition.

The Need for Updated Regulations

New and advanced fuels and technologies require updated regulations that promote their use while setting clear guidelines for their integration into the market. For example, storage technologies, crucial for meeting peak demand and capacity constraints, need a regulatory framework that fully recognizes their benefits. Further, CCS and NET technologies are essential for hard-to-abate sectors but lack a supportive regulatory regime in Ontario. The Ontario Mining Act currently prohibits the permanent storage or disposal of any substance, including CO2, on Crown land, significantly limiting sequestration opportunities. Developing clear regulatory guidelines for these technologies is essential to support their market introduction and integration.

Other Considerations and Cross-Jurisdictional Barriers

While the analysis focused on key market, technical, financial, regulatory, social/cultural, and environmental barriers specific to Ontario, there are other barriers that are cross-jurisdictional and influenced by broader factors. These include technology risks, global economic conditions, trade risks, and other considerations that Ontario cannot directly control but which significantly impact the province's energy transition.

Emerging technologies such as hydrogen and SMRs carry inherent risks related to their development and deployment. The uncertainty surrounding the technological readiness, scalability, and cost trajectory of these innovations presents challenges. Early adoption and investment are needed, often before a technology may be profitable, to secure long-term cost declines driving further adoption. Additionally, global supply chain disruptions can affect the availability and cost of critical components, further complicating the integration of new technologies into Ontario's energy system.

International fuel price fluctuations and global market dynamics also contribute to significant uncertainties. For instance, fluctuations in international fuel prices can influence the cost-effectiveness of different energy sources, affecting investment decisions.

7.2 Implications for Key Technologies and Fuels

The barriers described in the preceding section will have broad implications for scaling the fuels and technologies necessary for Ontario's clean energy future; however, there are a few key technologies for which these barriers may have an outsized impact on their implementation. This section outlines the implications of the barriers described in the preceding section for select fuels and technologies, including SMRs, biomass, ASHPs, and T&D.

Small Modular Reactors

Since SMRs are still in earlier stages of development, there remains uncertainty surrounding their deployment. Beyond the technical barriers described in Section 4.1, nuclear technologies have faced a longstanding historical opposition and contention, due to societal perception of risks (e.g., related to reactor safety, nuclear waste disposal, proliferation, and security).[54] Therefore, attaining environmental approvals, permitting requirements, and municipal support required for development of these projects will likely be time consuming. Thus, planning, siting, community engagement, and procurement must begin as soon as possible to have projects operational by 2030. Ontario has already begun this process with the Powering Ontario's Growth plan, which announced the deployment of 1,200 MW of SMR capacity at Darlington. The first of these is expected to enter commercial operation in 2029 (assumed to be 2028 in the model).

These considerations also apply to the use of SMR waste heat in DES, which faces similar barriers due to societal perception and public concern regarding nuclear technologies.

Additionally, all the SMR designs under consideration require different forms of fuel that are not currently manufactured in Canada. For example, they may require low-enriched uranium, fuel salts or reprocessing of used fuel from CANDU or other reactors. In some cases, fuels can be procured from an existing global supply. Some forms of fuel have limited global supply, whereas other forms of fuel are still under development.

Wind

Wind energy is a key technology for decarbonizing Ontario's electricity supply and plays a particularly significant role in meeting short-term (2030) needs. Attaining environmental approvals, permitting requirements, and municipal support required for development of these projects is often time consuming thus, planning, siting, community engagement and procurement must begin as soon as possible to have projects operational before 2030.

Additionally, the availability of skilled labor and essential installation equipment, such as hoists and cranes, is limited, potentially slowing down project timelines. For the projected growth in wind capacity to be achievable, there will be a need to increase the supply of skilled workers.

Public resistance to new wind projects, driven by concerns over noise impacts, biodiversity, and the legacy of the Green Energy Act make siting of new projects challenging. Early and transparent communication with communities will be necessary to build support for projects.

Wind is a variable resource, and projects must be sited in areas with adequate wind resources, which may be far from population centers and transmission lines, increasing project costs. Efforts should be made to identify and streamline permitting at suitable locations.

[54] Shobeiri E, Genco F, Hoornweg D, Tokuhiro A. Small Modular Reactor Deployment and Obstacles to Be Overcome. Energies. 2023; 16(8):3468.

Biomass

Bioenergy plays a key role for the decarbonization of sectors and end-uses where electrification is challenging or costly and for use as a negative emission technology. However, there is a limit to the amount of biomass feedstock which can be used sustainably to meet demands. Currently, Ontario is not utilizing biomass feedstocks to its full potential but will need to do so, and optimally, by 2050.

Biomass feedstocks suffer from weak supply chains, including unstable feedstock supply (including cultivation, harvesting, and collection; pre-treatment; and upgrading)[55], lack of qualified workers, and sustainability risks, leading to a perceived high risk and difficulties securing financing for bioenergy projects, programs, and investments at reasonable rates. Given the critical role that biomass plays in achieving net-zero, emphasis should be placed on strengthening and developing supply chains to secure supply. This includes stabilizing feedstock supply, supporting workforce growth, and demonstrating market security to enable better financing options for bioenergy projects.

Biochar

Many of the CCS and NET pathways that become a key factor in achieving net-zero, involve the use of biomass feedstocks. Of these, biochar accounts for the plurality of negative emissions in 2050 in most NZ IPs. In addition to the barriers affecting supply of biomass feedstocks, biochar faces an additional set of barriers that must be addressed to ensure its long-term viability. Biochar used as a soil amendment is a negative emission technology. However, there is a general lack of awareness, among agricultural producers, of the agronomic and environmental benefits of biochar application to cropland.[56] Efforts should be made to educate agricultural producers of these benefits to generate firm market demand.

Additionally, since the transportation of raw biomass is expensive, pyrolysis projects (the dominant pathway for biochar production) are forced to consider feedstocks that are proximate to their site to make production economical. Only recently has there been the development of early mobile pyrolysers which can decentralize pyrolysis and improve the cost-effectiveness of biochar production. To capture economies of scale, the strategic siting of pyrolysis projects to minimize biomass transportation costs should be explored and established early.[57]

Biochar yield, physical properties and carbon content vary depending on pyrolysis conditions, such as temperature, as well as feedstock type, leading to variability in the rate of carbon

[55] IRENA. 2022. Bioenergy for the energy transition: Ensuring sustainability and overcoming barriers.
[56] Shrestha, R. K. et al. Biochar as a negative emission technology: A synthesis of field research on greenhouse gas emissions. Journal of Environmental Quality, 52, 769–798 (2023).
[57] D. Zilberman, D. Laird, C. Rainey, J. Song, G. Kahn. Biochar supply-chain and challenges to commercialization. GCB Bioenergy. 2023;15:7–23.

sequestration.[58] Biochar production pathways should be consistently monitored to ensure they are adequately capturing the benefits and the long-term persistence of the sequestered carbon.

Air Source Heat Pumps

ASHPs become the dominant space heating technology across all IPs in 2050. ASHPs are an established, mature technology; however, a few key barriers exist that stand to limit its adoption. The primary constraint is the lack of a trained workforce for installation and servicing, particularly in the residential sector, including minimal support for training the existing gas equipment technicians and contractors on heat pumps.[59] The pathway for tradespeople looking to specialize in HVAC and heat pumps specifically is complex, sometimes requiring multi-trade trainings, which can be a barrier to attracting new workforce. For the projected uptake of ASHPs to be achievable, there will need to be robust support (e.g., programming, policy, funding) to increase the supply of qualified workers.

While technical and financial barriers are limited, there are some barriers, such as the need for electrical panel upgrades or high upfront costs associated with equipment purchase and installation, which can often be prohibitive. Coupled with the current increased cost of living, building and homeowners see the investment costs of ASHPs as too prohibitive. Addressing these barriers, along with increasing customer awareness, is essential for cost-effective adoption of ASHP installations over fossil fuel systems.

Transmission and Distribution (T&D)

In the NZ IPs, Ontario's economy becomes predominantly electrified and electricity demand also increases significantly in the REF IP. The provincial T&D system is a critical component in supporting new electricity generation projects and enabling the electricity supply to meet system demand at any given time. However, the development of transmission and distribution projects can be a lengthy process. Transmission projects typically take 5-7 years, or longer (7-10 years) for long transmission lines. Distribution projects, while typically faster for small system upgrades (1-3 years), can also take longer for larger projects (e.g., 3-5 years for a new distribution feeder or increase in substation capacity; 7 years or more for a new substation).[60]

The associated challenges and costs can vary significantly based on location (e.g., increased costs due to lack of infrastructure (roads) or the need to build assets that are resilient to changing weather patterns) and future planning. Transmission projects face unique challenges, such as the

[58] Gupta, D.K. *et al.* (2020). Role of Biochar in Carbon Sequestration and Greenhouse Gas Mitigation. In: Singh, J., Singh, C. (eds) Biochar Applications in Agriculture and Environment Management. Springer, Cham. https://doi.org/10.1007/978-3-030-40997-5_7

[59] Posterity Group. 2018. Study of Low Carbon Heating Options for Ontario: Detailed Analysis of Short List Technologies and Fuels.

[60] PG&E, SCE, and SDG&E. (2023). *Joint Presentation on Distribution Planning Process*. Docket Number: 23-IEPR-05, TN#: 250051.

need for Ontario Energy Board leave to construct approval, more extensive and involved environmental approvals, consultation with potentially affected communities, and acquisition of rights of way from landowners. These factors can increase the timeline and cost required to build transmission infrastructure necessary to support the transition. To minimize these barriers, planning and consultation with potentially affected communities should begin immediately.

Beyond the costs of the physical infrastructure, there is a potential significant shortage of skilled labour. In addition, there's a shortage of experienced professionals in key support sectors/fields that are needed to manage all aspects of a transmission line build (e.g., management, environmental professionals, Indigenous engagement). Addressing the need for expanded supply chains and the development of a sufficient, qualified workforce capacity will be paramount to minimizing unnecessary delays due to workforce and supply chain shortages.

According to the modelling done in this study,[61] the relative increase of labour demand in 2050 compared to 2019 in NZ50 is highest for the utilities sector, whose labour force increases 90% from 2019 to 2050.

[61] Modelling of macroeconomic impacts using the North American General Equilibrium Model (NAGEM). See Deliverable 3: Cost-Effective Pathways for more details.

SECTION 8

8. The Solutions

8.1 No-Regret

This section outlines key no-regret solutions to achieving net-zero in Ontario, based on analysis of modelled cost-effective IPs. No-regret solutions are those that are characterized by significant uptake in 8 or 9 NZ IPs (excluding the H2+ IP) and low variability of uptake. **No-regret solutions will be critical to unlocking Ontario's transition to a net-zero economy at least-cost.**

This section summarizes key highlights and findings from Deliverable 6: No- and Least-Regret Solutions. For further details, readers can refer to Deliverables 6.

There are 9 key solutions for 2030 that should be supported immediately

There are nine solutions for 2030 that appear in almost all of the NZ IPs and exhibit little to no variability in the magnitude of uptake (i.e., no-regret solutions), described in Table 8-1. Early success across these nine solutions will be critical to long-term decarbonization.

No-regret solutions for 2030 are concentrated in the buildings, transportation, and energy supply sectors, indicating that these sectors are critical areas for early action. In contrast, solutions for sectors including agriculture, industry, and carbon capture and negative emissions technologies are less certain in the short-term.

Table 8-1. No-Regret Solutions for 2030

#	Solution
	Buildings
1	Pursue full economic potential for demand reduction in the building sector through energy efficiency and building control measures.
2	Pursue rapid electrification of residential and commercial space heating with ASHPs.
	Transportation
7	Pursue the rapid electrification of light- and medium-duty vehicles via batteries as well as the majority of buses.
	Energy Supply – Electricity
27	Continue to deploy electricity storage technologies to meet near-term (before 2030) capacity requirements and peak demand.
28	Deploy onshore wind as a solution to meeting near-term 2030 system needs and monitor the need for additional growth by 2050.
29	Build out electricity T&D infrastructure within Ontario.

#	Solution
30	Deploy rooftop PV and other distributed energy resources (DERs) to meet system needs.
32	Continue exploration and **development of SMRs** to reduce first-of-kind deployment risks and work with federal government to ensure that its regulatory processes facilitate timely and safe deployment, to achieve economies of scale and enable significant growth in SMR capacity by 2050, per the Powering Ontario's Growth initiative.
	Energy Supply – Clean Fuels
34	Ramp up the sustainable utilization of forests to fulfill the growing demand for biomass.

The electricity sector offers several immediate, no-regret solutions. There are five short-term, no-regret solutions for electricity, indicating that the sector is a key action area for early progress toward net-zero. These near-term solutions comprise electricity storage, onshore wind, T&D, solar PV and DERs, and SMRs.

For **transportation,** electrifying light- and medium-duty on-road vehicles using batteries is a no-regret solution for 2030, as BEV technologies are already nearing cost-parity on a total cost of ownership basis with their fossil fuel counterparts on a total cost of ownership basis. Across all NZ IPs, the entire light-duty vehicle segment and medium-duty freight trucks are electrified. In the longer-term, partial electrification is expected to play a role in reducing GHG emissions from off-road transportation.

In **buildings**, the path to decarbonization is clear: five out of six solutions identified in the building sector are no-regret. Solutions for 2030 and 2050 in the buildings sector have high certainty, so much so that there is similar uptake of technologies across NZ IPs and the reference case for most technologies. GHG emissions reductions are driven by the electrification of space and water heating in both residential and commercial sectors, and these technologies are mature and receive policy support, facing limited uncertainty. ASHPs become the dominant space heating technology across all IPs (including the REF IP), supplying 59-60% and 32-54% of annual useful heating demand in residential and commercial sectors respectively in 2050.

Progress on building envelope retrofits and control measures by 2030 is foundational for success in the sector, as many of the 2050 solutions build on their implementation. The no-regret solutions for 2030 can be pursued with a high degree of confidence as early as possible (before 2030) by providing continued policy support and addressing any remaining market or financial barriers.

No-regret **clean fuels** solutions focus on maximizing the sustainable use of biomass resources to meet growing energy demands. For 2030, this involves ramping up the utilization of forest residues, ensuring that this abundant and renewable resource is effectively harnessed. By 2050, the strategy expands to include the maximum sustainable utilization of various biomass feedstocks such as agricultural residues, source-separated organics, and dedicated fast-growing trees and crops, diversifying the biomass supply.

By 2050, there are several additional no-regret solutions, in industry and agriculture, and negative emissions technologies

Both solutions identified for the **agriculture** sector are classified as no-regret for 2050. Decarbonization in this sector is dependent on two key fuels: electricity and RNG. There is some uncertainty to the extent and pace with which early electrification occurs. Regardless, sufficient T&D capacity to meet the increased load in more rural areas where agricultural producers are typically located (not modelled) will be necessary. RNG plays an important role in the long-term, representing approximately 19% of agricultural final energy consumption in 2050.

In **industry**, strategic use of RNG is expected to be a key solution for select hard-to-electrify end-uses, especially those requiring high-grade heat. Alongside this, pursuing all cost-effective electrification opportunities within the industrial sector, particularly in manufacturing, will play a crucial role in reducing GHG emissions and enhancing energy efficiency. Across all NZ IPs, electricity accounts for a minimum of 42% of annual energy demand in 2050, 63% of which is consumed within the manufacturing industry.

For **carbon capture and negative emissions technologies**, no-regret solutions include biochar production and leveraging carbon capture technologies to capture CO2 from industrial processes and energy production. These solutions provide the necessary tools to offset GHG emissions from hard-to-abate sectors.

A full list of no-regret solutions for 2050 (excluding no-regret solutions for 2030) across sectors is presented in Table 8-2.

Table 8-2. No-Regret Solutions for 2050 (excluding no-regret solutions for 2030)

	Solution
	Buildings
3	Pursue the decarbonization of residential and commercial space heating with DES.
4	Pursue the use of GSHPs to meet space heating demand in commercial buildings.
5	Leverage waste heat to meet space heating demand in residential and commercial buildings.
	Transportation
10	Pursue the partial electrification of off-road transportation, mainly agricultural machinery.

	Solution
	Industry
15	Pursue the strategic use of RNG in select hard-to-electrify end-uses, mainly processes requiring high-grade heat.
16	Pursue significant electrification of the industrial sector, particularly within the manufacturing industry
	Agriculture
18	Pursue widespread electrification of the agricultural sector.
19	Pursue the strategic use of RNG to decarbonize the remaining hard to electrify end-uses.
	Carbon Capture and Negative Emissions Technologies
20	Pursue biochar production as the primary pathway for negative emissions.
21	Leverage carbon capture technologies to capture CO2 from industry and energy production.
	Energy Supply – Electricity
31	Deploy 7 GW of advanced (GEN III+) and conventional nuclear reactors. Note: This solution is driven by the Powering Ontario's Growth initiative and is already underway.
	Energy Supply – Clean Fuels
35	Pursue the maximum sustainable utilization of most available biomass feedstocks (beyond forest residues and roundwood) in particular, agricultural residues, source separated organics, and dedicated fast-growing trees and crops.

8.2 Least-Regret

Least-regret solutions are solutions that have significant uptake in 8 or 9 NZ IPs (excluding the H2+ IP) but have high variability in the magnitude of their contribution. **Least-regret solutions will also be critical to unlocking Ontario's transition to a net-zero economy at least-cost**, although the magnitude of their contribution is uncertain. Immediate support for least-regret solutions may also be required if Ontario wishes to pursue modelled least-cost net zero pathways.

Least-regret solutions for 2050 (excluding those that are no-regret solutions for 2030) are summarized in Table 8-3.

Table 8-3. Least-regret solutions for 2050 (excluding no-regret solutions for 2030)

	Solution
	Buildings

	Solution
6	Actively explore, invest in, and pilot the use of commercial dual-fuel heating systems, in addition to all-electric ASHPs.
	Transportation
8	Pursue the electrification of rail transportation.[62]
11	Actively explore, invest in and pilot industrial off-road decarbonization that can be achieved with bioenergy.
14	Actively explore, invest in and pilot the use of catenary vehicles (CAT) to decarbonize the heavy-duty vehicle segment.
	Industry
17	Actively explore, invest in, and pilot hydrogen as a replacement for natural gas.
	Carbon Capture and Negative Emissions Technologies
24	Actively explore, invest in, and pilot opportunities to use Bioenergy with Carbon Capture and Storage (BECCS) as supplemental negative emissions technologies to biochar.
25	Introduce DAC as a negative emissions technology to sequester any remaining emissions in 2050.
	Energy Supply – Clean Fuels
36	Determine the degree to which hydrogen produced from BECCS can contribute to overall energy consumption.
38	Develop a robust hydrogen pipeline network to facilitate transportation of centralized hydrogen production.

8.3 Wild cards

Wild card solutions are those with significant uptake in 1 to 7 NZ IPs (excluding the H2+ IP). The lower consistency across NZ IPs could point to higher uncertainty regarding their cost-effectiveness relative to other solutions. Immediate support for wild card solutions may also be required if Ontario wishes to pursue modelled least-cost net zero pathways. Wild card solutions are observed in the transportation sector, carbon capture and negative emissions technologies, electricity, and clean fuels, with key uncertainties relating to hydrogen and carbon sequestration. Notably, there are no wild card solutions in the buildings sector, as solutions for the buildings sector are more certain.

[62] Note that the rail transportation sector in the model excludes light-rapid transit and subways, which are categorized under road transport.

These wild card solutions are less certain but could offer transformative solutions depending on technological advancements and market conditions. Their successful implementation hinges on careful observation, timely decision-making, and strategic investments to overcome existing uncertainties.

Regarding **carbon sequestration,** there is a high degree of certainty that Ontario will need to capture a significant amount of CO2 (whether with DAC, BECCS, or other CCS). However, there is less certainty as to where the captured CO2 will be allocated (exports, domestic sequestration, or utilization). Accordingly, CCS solutions related to domestic sequestration and exports are classified as wild cards.

The biggest uncertainty in the **transportation** sector is the least-cost pathway for decarbonization of HDVs. While catenary vehicles are a least-regret solution for 2050, even by 2050, HDV solutions of FCEVs and BEVs are wild cards and will depend heavily on the evolution of the future hydrogen and electricity landscape. However, specialized infrastructure is required for all zero-emission HDV technologies, and therefore success for HDV transition is dependent on careful observation of electricity and hydrogen conditions and timely decision making/investments. Wild card solutions for 2050 are summarized in Table 8-4.

Table 8-4. Wild card solutions for 2050

	Solution
	Transportation
9	Actively explore, invest in, and pilot using hydrogen and biofuels to complement electricity in decarbonizing rail transportation.[63]
12	Determine the role of FCEV in decarbonizing the heavy-duty vehicle segment; and initiate pilots.
13	Actively explore, invest in, and pilot the use of battery-electric vehicles (BEV) to decarbonize the heavy-duty vehicle segment.
	Carbon Capture and Negative Emissions Technologies
22	Identify and develop sites and infrastructure needed to geologically sequester captured carbon within Ontario.
23	Actively explore, invest in, and pilot exporting captured CO2 to the United States (US) for sequestration or utilization.
26	Actively explore opportunities for capturing and utilizing CO2 emissions from industry and energy production.
	Energy Supply – Electricity

[63] Note that the rail transportation sector in the model excludes light-rapid transit and subways, which are categorized under road transport.

	Solution
33	Examine the role of hydrogen turbines in meeting peak electricity demand
	Energy Supply – Clean Fuels
37	Actively monitor technological advancements and market conditions for other clean hydrogen production pathways: blue and electrolytic hydrogen; and invest in, and initiate pilots.

SECTION 9

9. Conclusion

9.1 Key Takeaways

This study explores several pathways to decarbonizing Ontario's energy system in 2050 in a least-cost manner. The results highlight several critical key takeaways that provide insights into Ontario's energy transition and the pathway to a net-zero economy.

èTakeaway 1: The transition's positive outcomes on energy affordability and societal co-benefits will offset energy investment costs and GDP impacts

The net-zero transition will have numerous implications. **At a macro-economic scale, there will be minor aggregate impacts to GDP and labour demand.** GDP growth is expected to be negligibly lower in the NZ IPs compared to REF, but economic growth continues, and the impact is minor (0.04 percentage points per year[64] lower in NZ50); the energy sector represents only a small piece of Ontario's overall economy.

At a more granular level, consumer energy bills will also be impacted by the transition. **Average ("normalized") household energy bills are expected to decline substantially in both the REF and NZ IPs, e.g. 47% from 2022 to 2050 in NZ50,** [65] as fuel switching, and other energy savings lead to lower overall energy consumption. However, there is risk of increasing energy bills for households remaining on natural gas as consumer numbers drop in net-zero pathways.

Besides this, the net-zero transition is expected to have **numerous co-benefits, such as improved human health, avoided impacts on agricultural productivity and economic activity, and reduced risk of disruption to energy systems.** While quantifying these benefits is challenging, the social cost of greenhouse gases (SC-GHG) can be an effective metric for assessing potential benefits/avoided damages. Based on Canada's federal SC-GHG values, cumulative benefits resulting from **avoided damages associated with CO2, CH4 and N20 emissions reductions are estimated to range from 245 to 874 B$ CAD2022 cumulatively (2019-2050) across the NZ IPs (incremental to the REF IP).** While investments in the energy sector can also bring co-benefits, such as GDP growth, job creation, and decreasing Ontario's trade deficit, it is also interesting to note that **co-benefits due to climate change mitigation are expected to significantly outweigh any incremental investment required to reach the net-zero in 2050.**

[64] Difference in average real annual growth (%/y) (2019-2050) between REF and NZ50.
[65] Without OER and with the legislated carbon price

è Takeaway 2: Significant action and investments are required to reach net-zero

Achieving net-zero in 2050 will require significant action and financial investment. In the least-cost REF pathway, Ontario would reach its 2030 GHG emissions target if all assumed policies and actions materialize. However, business-as-usual policies, including committed policies, fall short of net-zero in 2050.

Putting Ontario's economy on a pathway to achieve net-zero in 2050 will require additional investments on the order of 173 B$ CAD2022 in the NZ50 IP (cumulative from 2019 to 2050) beyond what would occur in the REF IP. A majority of this incremental investment goes towards electricity generation capacity and T&D infrastructure to expand the electricity system to meet the expected doubling or tripling of demand from 2019 to 2050 in the NZ IPs. The necessary developments across many sectors will require coordinated commitments from federal, provincial, and municipal governments, Indigenous communities, along with other stakeholders, to support the energy transition.

èTakeaway 3: A major energy system transition is required to reach net-zero

In all NZ IPs, significant changes in Ontario's energy supply, demand, and infrastructure are needed to meet net-zero in 2050. Despite the nuances across the results from the NZ IPs and SAs modeled in the study, four key pillars are required to enable a least-cost pathway for Ontario to achieve net-zero in 2050.

1. **REDUCING** total final energy consumption relative to current forecasts through a significant acceleration of the pace and magnitude of energy efficiency efforts (with uptake of all cost-effective energy efficiency potential), and leveraging the efficiency gains associated with fuel-switching in key end-uses and applications across the economy;
2. **SWITCHING** greater than 80% of fossil fuel use, including the vast majority of heating, mobility and industrial needs, to predominantly emission-free electricity, with targeted use of clean fuels such as biofuels, clean hydrogen and RNG to support decarbonization in harder-to-electrify subsectors from 2019 to 2050;
3. **GROWING** electricity generation capacity, e.g. to over 2x in NZ50, primarily through new additions of wind, nuclear (mainly SMRs), energy storage (batteries and pumped hydro), and solar, and growing the associated transmission and distribution capacity from 2019 to 2050;
4. **SEQUESTERING** remaining GHG emissions (~20% of 2019) using CCS and negative emissions technologies, e.g., biochar, DAC, and BECCS.

èTakeaway 4: Several uncertainties and nuances will determine the exact trajectories

Despite the directional alignment of these four pillars across the modeled integrated pathways, the results also highlight specific nuanced considerations and uncertainties around:

- **The role of clean fuels**. Biofuels, RNG, clean hydrogen and synthetic fuels play a key strategic role in decarbonizing specific segments and end-uses where electrification is challenging and/or costly. However, their role may vary, depending on their market conditions and how favourable conditions are for electrification.
- **The magnitude of electricity growth.** The NZ IPs and SAs clearly indicate that significant growth of electricity generating capacity is key to achieving net-zero. However, the range of this growth varies – capacity grows to 2.0 to 3.2x between 2019-2050.
- **The trade-offs between wind and nuclear.** Both wind and nuclear (SMRs) are key to the future generation mix as complementary technologies. However, the relative contributions of wind vs. SMRs to the overall mix is sensitive to assumptions regarding the evolution of technology costs for SMRs in particular. In earlier years, the results consistently show wind capacity additions, but post-2040, there is less certainty.
- **The potential of CCS and negative emissions.** All NZ IPs and SAs use the maximum amount of geologic sequestration and a significant amount of biochar in 2050. However, there is some uncertainty regarding the capacity for long-term geologic sequestration of CO2, and annual budget for CO2 geologic storage, assuming Ontario may require these solutions to maintain net-zero or achieve negative emissions post-2050.
- **Future government policies, innovations, and climate impacts are key uncertainties.** These uncertainties (beyond emerging technologies and projected climate impacts on temperature) are not modelled because they are out of scope, or their development is largely unknown. However, it is expected that these factors and technology improvements beyond what is modeled will be major determinants of a transition to net-zero. New policies will be required to achieve the GHG emissions reductions imposed in the modelling work, represented by the evolving long-term marginal cost of carbon.

èTakeaway 5: There are 9 key solutions for 2030 that should be supported immediately

There are nine solutions for 2030 that appear in almost all of the NZ IPs and exhibit little to no variability in the magnitude of uptake (i.e., no-regret solutions). Early success across these nine solutions will be critical to long-term decarbonization. The nine solutions are:

- Pursue full economic potential for demand reduction in the building sector through **energy efficiency and building control measures**,
- Pursue the rapid **electrification of residential and commercial space heating** with ASHPs,
- Pursue the rapid **electrification via batteries of light-and medium duty vehicles as well as buses**,
- Continue to deploy **electricity storage technologies** to meet near-term (before 2030) capacity requirements and peak demand,
- Deploy **onshore wind** as a solution to meeting near-term 2030 system needs and monitor the need for additional growth by 2050,
- Build out **electricity T&D infrastructure** within Ontario,
- Deploy rooftop PV and other **distributed energy resources (DERs)** to meet system needs,
- Continue exploration and **development of SMRs** to reduce first-of-kind deployment risks and work with federal government to ensure that its regulatory processes facilitate timely and safe deployment, to achieve economies of scale and enable significant growth in SMR capacity by 2050,
- Ramp up the **sustainable utilization of forests** to fulfill the growing demand for biomass.

While least-regret and wild card solutions exhibit less consistency and/or more variability across the IPs, this does not indicate that no action is required. Immediate support from select stakeholders may be necessary if Ontario wishes to pursue modelled least-cost net-zero pathways.

èTakeaway 6: Advanced planning and decisions between now and 2030 will have important implications for the success and cost-effectiveness of solutions for 2050

Many solutions for 2050 require significant infrastructure development to support their implementation – for example, the construction of heavy-duty vehicle charging or hydrogen refuelling stations and expanded T&D to support industrial and agricultural electrification. Bioenergy plays a key role in decarbonization in sectors where electrification is challenging and costly – however, there is a limit to the amount of biomass feedstock which can be used sustainably to meet competing demands. Immediate efforts should be made to ramp-up supply of sustainable biomass feedstocks – and in tandem, a detailed roadmap for strategic and cost-effective allocation of this limited resource must be developed. Further, early exploration and developments in some technologies – such as the work being conducted for SMRs – will be key to ensuring that learnings can enable achievement of future cost reductions associated with Ontario-specific barriers. In the absence of timely decision-making, the cost of implementing solutions for 2050 may become higher, and the risk of not meeting net-zero in 2050 can increase.

For solutions for 2050, analysis beyond the scope of this deliverable is needed to determine the required timing of decisions, planning, construction, development of a supply chain, etc. Almost all solutions for 2050 have initial uptake in the modelled IPs before 2050 and require action before 2030, including developing regulatory frameworks, encouraging technology adoption and early investment, beginning infrastructure development, developing stable supply chains, and re-training of skilled workers. For example, in most NZ IPs, while CCS doesn't have "significant" uptake in 2030, some uptake starts as early as 2027. For other solutions for 2050, the evolution of market, policy, and technology conditions will need to be closely monitored in the meantime.

ANNEX A

Appendices

Appendix A: Model Descriptions

North American Times Energy Model (NATEM)

NATEM is the only economy-wide integrated energy system optimization model in Canada. NATEM-Canada describes the entire integrated energy system, as well as non-energy emitting sectors of the 13 Canadian jurisdictions, and provides a rigorous analytical basis for identifying least-cost solutions to achieve energy and climate objectives without compromising economic growth. NATEM includes thousands of technologies allowing modelled results to reach deep decarbonization levels (including net-zero targets by 2050).

NATEM follows a techno-economic modelling approach to describe the energy systems of North American jurisdictions through a large variety of specific energy technologies characterized with their technical and economic attributes as well as GHG emission factors. It offers a detailed representation of an energy sector, which includes extraction, transformation, distribution, end uses, and trade of various energy forms and materials.

NATEM distinguishes between generation technologies that convert primary energy into secondary energy (e.g., refineries, power plants, etc.) and end-use devices that transform final energy into energy services (e.g., cars that serve a demand for mobility, light bulbs that serve a demand for lighting). In particular, they include existing technologies, improved versions of the same technologies and emerging technologies, all characterized by their technical and economic attributes. Consequently, it allows for detailed accounting of all energy flows within the energy sector from primary energy extraction to final energy consumption. NATEM will select technologies based on what is optimal across all sectors of the energy system since they will be competing for the same resources. For instance, biomass feedstock is a limited resource, and the model will decide what are the best uses for this resource (e.g., biofuel production) and which end-use sectors will consume this fuel.

Sector service demand is an exogenous input to the model which is independent of fuel types or technologies. For example, demand for transportation will be in passenger-km per year and demand for heating or cooling will be in m2 of buildings. Furthermore, only prices for import/export external to the model system boundary (e.g., Canada) will be set exogenously, while all other commodity prices will be determined endogenously by the model. NATEM will determine the solution that both minimizes net discounted costs and maximizes economic surplus, e.g., NATEM integrates demand price elasticity and computes partial equilibrium. In all cases, the model solution must meet a set of constraints: supply must at least equal demand, emissions targets much be met, and other policies must be respected.

North American General Equilibrium Model (NAGEM)

NAGEM is a new generation dynamic macroeconomic model able to simulate deep transformation of the economy to achieve ambitious objectives of GHG reduction. This is the first model in Canada applied to identify economy transformation pathways for net-zero scenarios. It can be used as a standalone model or with NATEM, which is done in this study through a soft-linking between the two models.

NAGEM is composed of detailed economic models of the 13 Canadian jurisdictions, including inter-jurisdictional flows of trade and labour. The model starts from the baseline year reflecting the structure of the Canadian economy being in equilibrium. The model accounts for the inter-dependencies between different sectors, economic agents (industries, households, provincial and federal governments) and markets in the economy. Energy and climate policies are modelled and NAGEM derives the optimal economic solution by converging to a new set of prices, allocation of goods, capital, and labour to allow economic equilibrium.

RateVision

RateVision is used to evaluate the impact on tariffs[66] for distribution connected gas and electricity consumers in residential, commercial, and industrial categories. The model relies on the outputs from NATEM regarding future gas and electricity consumption, capacity expansion, and capital and operational costs, as well as current tariffs design specifics and regulation. The model outputs include annual revenues requirements for different cost categories for utilities, variable rates including commodity (gas or electricity) price, transportation/transmission, and distribution variable rates and fixed charges. For the natural gas distribution system, the RateVision estimates the level of abandonment under a decreasing number of connected consumers, reduction of revenues requirement, decommissioning and stranded assets cost for each time period until 2050 (typically 5-year steps). The model evaluates how stranded assets costs impact distribution volumetric rates and fixed charges. RateVision is not able to simulate the death spiral effect (natural gas consumers switching to electricity under increasing rates, pushing rates even higher), but it provides insights on the increase in fixed charges and variable rates that may initiate this effect.

RateVision estimates the normalized energy cost per provincial household and calculates energy bills for different household archetypes; their possible energy technology switch and changing energy demand under the effect of climate change.

For more information about NATEM, NAGEM, or RateVision, contact ESMIA at info@esmia.ca

[66] The term "tariffs" refers to both fixed charges and variable rates.

Appendix B. Sensitivity Analyses

Table B-1. Description of Sensitivity Analyses Conducted for Key Integrated Pathways.

IP	SA Label	Description
NZ50	**NZ50 SMR+**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. Lower cost of SMR (-45% in 2050).
NZ50	**NZ50 SMR-**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. Higher cost of SMR (+45% in 2050).
NZ50	**NZ50 NZ+**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. The exogenous GHG constraints are set assuming exogenous uptake of natural solutions, allowing for 3.57 and 10.59 Mt CO2eq/y more GHGs in 2030 and 2050 respectively. Natural solutions would otherwise be assumed to have no impact on the energy sector (e.g., they are assumed to have no cost, require no energy, and do not impact biomass supply).
NZ50	**NZ50 HURD**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. Hurdle rates increased by sector. The minimum hurdle rates by sector are as follows: Agriculture: 18%, Commercial: 12%, Residential: 8%, Transportation: 21%, Industrial: 18%.
NZ50	**NZ50 ELC**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. Electricity adequacy: lower wind and solar guaranteed contribution to peak. For wind, the values in the first level of the supply curve in Winter is 10%, Summer is 4%. Solar values are zero. Constraint on minimum storage required for renewables has been removed.
NZ50	**NZ50 LIM ELC**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. Lower growth in additional capacity.

IP	SA Label	Description
NZ50	**NZ50 LIM ALL**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. Build limit on several technologies: electricity (same as from the NZ50-LIM-ELC SA), hydrogen, biofuel production, transportation (medium & heavy duty, buses, rail), residential space heating, commercial space heating, and industrial boilers.
CCS-	**CCS NZ-**	GHG reduction of 40% in 2030 from 2005 levels and net-zero in 2050, in addition to "business-as-usual" including committed policies. Unfavourable CCS and NET conditions. GHG total includes international marine and aviation.