Assessing Canada’s Hydrogen Ambition: Model Development and Policy Analysis with MESSAGEix-Canada

by

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We acknowledge and respect the Lək̓ʷəŋən (Songhees and Xʷsepsəm/ Esquimalt) Peoples on whose territory the university stands, and the Lək̓ʷəŋən and W̱SÁNEĆ Peoples whose historical relationships with the land continue to this day.

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Abstract

Canada's national hydrogen strategy has positioned low-carbon hydrogen as a key pillar in the transition to a net-zero energy future. Energy system modelling is essential for understanding the complex interactions and regional impacts of policy design on the Canadian energy system. This thesis presents both the development of a detailed hydrogen framework within the MESSAGEix-Canada energy system model and its application in national hydrogen policy assessment. Notably, this work provides the first evaluation of the Clean Hydrogen Investment Tax Credit, Canada’s dedicated policy for incentivizing clean hydrogen production. Scenarios explore current policy measures, the projected roll-out of major announced hydrogen projects, and net-zero pathways under optimistic and pessimistic cost projections. Findings showcase a gap between federal strategy ambitions and cost-optimal hydrogen deployment: investment tax credits alone are insufficient to scale hydrogen adoption to reach net-zero levels. Hydrogen production is shown to be regionally diverse, with more electrolysis in hydro-rich provinces such as Quebec and more natural gas reforming in fossil-rich regions like Alberta. Industrial applications have the largest uptake of hydrogen, while usage in transportation and synthetic fuels is limited. Lastly, in all scenarios, electrification prevails as the primary energy carrier relative to hydrogen. The results highlight the need for production-based, sector-specific, and regionally differentiated policy to unlock hydrogen’s full decarbonization potential. With MESSAGEix-Canada released as a fully open-source platform, policymakers, stakeholders, and researchers can assess and refine hydrogen strategies in line with evolving technological, economic, and policy conditions.

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List of Acronyms

GHG	Greenhouse Gas
CH-ITC	Clean Hydrogen Investment Tax Credit
MESSGAEix	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
CODERS	Canadian Open-Source Database for Energy Research and Systems Modelling
IDEA	Integrated Data Exploration and Analysis
SMR	Steam Methane Reforming
ATR	Auto Thermal Reforming
OBPS	Output-Based Pricing System
ITC	Investment Tax Credit
CER	Clean Electricity Regulations
CI	Carbon Intensity
GDP	Gross Domestic Product
IAM	Integrated Assessment Model
CCS	Carbon Capture and Storage
BAU	Business as Usual
CHS	Canada Hydrogen Strategy
NZ-Opt	Net Zero Hydrogen Optimistic
NZ-Pes	Net Zero Hydrogen Pessimistic
SSP	Shared Socioeconomic Pathway
LULUCF	Land Use, Land Use Change and Forestry

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Author Contributions

The purpose of this section is to define the scope of work conducted in this thesis and outline where this thesis leverages others' work. MESSAGEix-Canada was developed by the Sustainable Energy Systems Integration and Transitions group at the University of Victoria. Specifically, model development was led by Dr. Muhammad Awais, who focused on downscaling and calibrating the MESSAGEix global model to the Canadian context. The model calibration process ensured that the model aligned with historical energy balances, sectoral energy trends, and economic drivers in each Canadian province and territory. Further details on the calibration work conducted by M. Awais are outlined in Appendix A2.

From this point, B. Danaher focused specifically on parameterization of the hydrogen commodity within the model. The MESSAGEix global model included some basic provisions for hydrogen, but it was not yet calibrated for the Canadian context. These provisions included parameterization of electrolysis, steam methane reforming, gasification processes, and the generalized sectoral end uses of hydrogen outlined in this work. This was used as a starting point by B. Danaher, who calibrated and verified the existing parameterization of these technologies for the Canadian context. From this point, the following new technologies were parameterized in the model: auto thermal reforming (with and without carbon capture and storage), methane pyrolysis, Fischer-Tropsch synthesis, hydrogen methanation, geological hydrogen storage, hydrogen and natural gas blending, and methanol production from hydrogen.

Policies were defined in the model by B. Danaher, M. Awais and Yalda Saedi. B. Danaher developed the methodology and implemented the scripts for the federal Output-Based Pricing System and the Clean Hydrogen Investment Tax Credit, which are the two primary policies focused on in Chapter 2 of this thesis. Complementary policies included in the model but not explicitly investigated are the Clean Electricity Regulations, developed by M. Awais and the Clean Technology Investment Tax Credit, Clean Technology Manufacturing Investment Tax Credit, and the Carbon Capture, Utilization and Storage Investment Tax Credit developed by Y. Saedi.

Validation and comparison work with other models was conducted by M. Awais and B. Danaher. This was to ensure key variables aligned with other modelling organizations' trends and results. This work was conducted utilizing the IDEA visualization platform, which was developed by Jonas Kraasch and Erica Attard. To be able to see results in the IDEA visualization platform and generate graphs internally for this thesis, the reporting script for MESSAGEix-Canada had to be updated. This work was conducted by Cristiano Fernandes, Omar Attia, and M. Awais. B. Danaher further added to this work to include new hydrogen technologies being reported.

Lastly, in an effort to clean up the model and add functionality, C. Fernandes and O. Attia worked on adding new functions to the model, solving software bugs, and provided general software support when needed.

Chapter 2 of this thesis has been submitted as a peer-reviewed manuscript. Below, the contributions of each author are clarified.

B. Danaher, A. Rowe, and M. McPherson, "Beyond Tax Credits: Identifying Policy Shortfalls in Scaling Clean Hydrogen for Canada's Net-Zero Future," Int. J. Hydrog. Energy (Manuscript Submitted)

B. Danaher developed the methodology, worked on model development and wrote the manuscript. M. McPherson supervised, contributed to manuscript editing, and provided insights on model development. A. Rowe provided insights and contributed to manuscript editing.

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Lastly, thank you to my family for whose support has made this journey possible despite the distance between us. Your unwavering encouragement and readiness to help with life's challenges have provided a foundation of strength and security throughout my studies

Chapter 1: Introduction

The Government of Canada has pledged to reduce Greenhouse Gas (GHG) emissions by 40% below 2005 levels by 2030 and achieve net-zero emissions by 2050 in an effort to combat climate change [1]. A serious examination of climate change cannot be considered without investigating its ties to energy. Anthropogenic climate contributions depend on how energy is produced and used more than any other factor [2]. The role of energy systems innovation in reducing GHG emissions has been identified as a significant aspect of the transition to a cleaner energy system in Canada. To achieve this goal, a wide variety of energy sources and technologies must be utilized to diversify and transform the energy system as we know it [3].

Among Canada's options for decarbonization, hydrogen has surfaced as a promising energy carrier. Hydrogen has the potential to enable emission reductions in hard-to-abate sectors, including hard-to-electrify industrial applications, transport and synthetic fuel production, while providing valuable system flexibility and supporting a broader integration of renewables [4]. The Hydrogen Strategy for Canada envisions hydrogen as a key pillar in the national clean energy transition, with over 80 low-carbon hydrogen projects announced and more than $100 billion in committed or proposed investment as of mid-2024. These projects span multiple provinces and target both clean hydrogen production and end uses, including an increasing network of hydrogen hubs and corridor initiatives [4],[5].

Despite these developments, uncertainty remains about hydrogen's realistic role in Canada's energy future. Policymakers and stakeholders grapple with critical questions: Which regions are best suited for hydrogen production? What applications deliver the greatest decarbonization impact? Which policy instruments can bridge the cost gap between clean hydrogen and conventional fuels? Academic and policy literature has outlined central barriers in answering these questions. Firstly, there is a need for open-source energy system models that can evaluate hydrogen pathways in Canada [6]. Secondly, there is a lack of assessments of key legislated policies that incentivize hydrogen, such as the Clean Hydrogen Investment Tax Credit (CH-ITC) [5]. Lastly, government strategies may promote hydrogen in applications that are not consistently supported by techno-economic analysis and may risk misallocation of investment and delay climate action [7].

This research addresses these gaps by combining open-source modelling, comprehensive policy assessment, and scenario analysis. The overarching objective of this work is to develop an open-source tool that can extensively investigate hydrogen pathways in relation to the rest of the Canadian energy system. This is accomplished within the Model for Energy Supply Strategy Alternatives and their General Environmental Impact for Canada (MESSAGEix-Canada) integrated assessment model, a linear programming framework that represents Canada's energy system across all 13 provinces and territories. As part of the work conducted, explicit hydrogen production technologies, transport and storage, sectoral end-uses, and policy instruments are defined. Details on model parameterization can be found in Appendix A1, and the CH-ITC and Output-Based Pricing System (OBPS) policy formulations can be found in Appendix A3 and A4, respectively.

MESSAGEix is a systems optimization framework developed by the International Institute of Applied Systems Analysis. The modelling framework has been utilized for medium to long-term energy system planning, energy policy analysis, and scenario development in major international assessments. Such assessments include the Intergovernmental Panel of Climate Change, the World Energy Council, and the Global Energy Assessment. This thesis builds on the work conducted by Awais et al.[8] who derived and calibrated MESSAGEix-Canada based on the MESSAGEix global model. This involved aligning historical energy balances, sectoral energy trends, and economic drivers in each Canadian province and territory. Final energy consumption by end-use technology and fuel was compiled from national sources, and demand was forecast using population and GDP projections. Further details of the demand projection workflow by Awais et al.[8] can be found in Appendix A2.

MESSAGEix-Canada is a part of the M3 modelling platform under development by the Sustainable Energy Systems Integration and Transitions group. The M3 platform is a holistic, integrated platform for performing a plethora of energy system decarbonization analyses for a range of spatial scales and sectors. The platform includes the Canadian Open-Source Database for Energy Research and Systems Modelling (CODERS), a suite of 9 models that span different methodologies, spatial and temporal scales, and the Integrated Data Exploration and Analysis (IDEA) visualization platform. MESSAGEix-Canada sits as one of the broadest models in the platform, covering all energy sectors, and is designed to investigate long-term energy pathways and comprehensively assess energy policy packages.

As a part of developing the model, MESSAGEix-Canada underwent model comparison and validation exercises to ensure result legitimacy. This included being a member of the Energy Modelling Hub Multi Model Comparison Forums in 2024. Results were also compared with the Canada Energy Regulator Exploring Canada’s Energy Future Dashboard tool, Navius Research Canada Energy Dashboard tool, and Institut de l'énergie Trottier Pathways Explorer tool. Lastly, results were cross-referenced with private modelling exercises published in federal documents, such as the modelling work conducted in the Hydrogen Strategy for Canada Progress Report.

By developing and releasing open-source modelling resources and transparent scenario definitions, this research responds directly to recommendations in Canada’s Senate report *HYDROGEN: A Viable Option for a Net-Zero Canada in 2050?* and supports the emergence of more accountable, evidence-based policy and public engagement. MESSAGEix-Canada provides stakeholders, researchers, and decision-makers with a powerful platform for continual refinement and assessment of hydrogen policy under evolving technological and economic conditions.

For the manuscript presented in Chapter 2, MESSAGEix-Canada is applied to answer the following questions: (1) Does the current policy mix, including the CH-ITC, scale hydrogen to levels required for net-zero? (2) How does regional resource availability, policy design, and technology cost evolution interact to shape hydrogen's uptake across Canada? (3) What policy innovations are needed to close the gap between government ambition and techno-economic attractiveness? Scenario design spans current measures, a scenario where all proposed hydrogen projects in the Hydrogen Strategy for Canada move forward, and transformative net-zero pathways with optimistic and pessimistic hydrogen cost trajectories.

The remainder of this thesis is organized as follows. Chapter 2 presents the full manuscript submitted to the International Journal of Hydrogen Energy, "Beyond Tax Credits: Identifying Policy Shortfalls in Scaling Clean Hydrogen for Canada's Net-Zero Future," including methods, scenarios, results, and policy implications. Chapter 3 concludes the thesis by outlining key findings and future model development.

Chapter 2: Beyond Tax Credits: Identifying Policy Shortfalls in Scaling Clean Hydrogen for Canada's Net-Zero Future

2.1 Abstract

Canada has positioned hydrogen as a cornerstone of its net-zero strategy, introducing federal policies and investment incentives to accelerate deployment. This work provides the first fully open-source, provincial-scale assessment of the Canadian hydrogen policy landscape using the MESSAGEix-Canada modelling framework. The impact of the CH-ITC and related federal policies on hydrogen deployment is investigated and compared with scenarios aligned with Canada's net-zero emissions targets. Results indicate a gap between federal hydrogen ambitions and cost-optimal deployment: tax credits alone are insufficient to scale hydrogen adoption to levels consistent with net-zero targets. Hydrogen production varies regionally depending on the natural resources available in each province and territory. Industrial applications are the largest adopters of hydrogen, while transportation and synthetic fuel production account for a smaller share. The findings suggest the need for production-based, sector-specific, and regionally differentiated policies to achieve hydrogen's full net-zero potential.

2.2 Introduction

Climate change has been widely regarded as humanity's most pressing and daunting challenge. Anthropogenic climate contributions depend on how energy is produced and used more than any other factor [2]. The role of energy system innovation in reducing GHG emissions has been identified as a significant lever in the transition to a cleaner energy system in Canada. To achieve this goal, a wide variety of energy sources and technologies must be utilized to diversify and transform the energy system as we know it [3]. Hydrogen has been recognized for its potential to decarbonize many sectors of Canada's economy, including resource extraction, freight, transportation, power generation, manufacturing, and the production of steel and cement [4]. Natural Resources Canada published the *Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen* in December 2020, which lays out an ambitious framework to cement hydrogen in the energy system to achieve net-zero emissions by 2050 and position the nation as a leader in clean renewable fuels [4].

2.2.1 Hydrogen as a Global Energy Carrier

The global hydrogen economy has the opportunity to decrease fossil fuel utilization, and in doing so, reduce GHG emissions, making it a fundamental component of the global energy system transition [9]. Hydrogen can play a key role in the integration of multiple energy sectors to optimize renewable use and allow for a more efficient and flexible energy system. Gawlick et al. [10] found that the coupling of electricity and hydrogen sectors in the European energy system can decrease electrical storage needs by 35% and substitute 40% of electrical transmission capacity while also improving renewables integration and reducing curtailment by two-thirds.

Nations are recognizing the role of hydrogen in the energy system transition. As of 2023, the International Energy Agency reported that 41 governments have published hydrogen strategies, while some are in the process of further updating strategies to raise ambitions [11]. These strategies typically include scaling up clean hydrogen production, such as setting electrolyzer capacity targets, incentives for green hydrogen, and funding for research and development projects, as well as promoting infrastructure for storage, distribution, and end-uses in hard-to-abate sectors [11] . Many also feature mechanisms like subsidies, contracts-for-difference, and both investment and production tax credits to bridge cost gaps with fossil fuels and create early demand [12].

Despite growing policy activity, recent research finds that there remains little agreement on the most effective policy portfolios for hydrogen deployment. Nations often rely heavily on ITCs and targeted sectoral policies, yet this alone has not led to transformative hydrogen scale-up [13]. Research finds that policies tend to be fragmented or focused on early-stage project support and suggests that merely adopting ITCs is not sufficient without complementary measures that address production scale, long-term market certainty, and infrastructure [7],[8],[9],[10].

2.2.2 The Case for Canada

Canada is well-suited to leverage hydrogen in its transition to a sustainable energy system, given the nation’s abundant natural resources, government support and research capabilities [16]. Hydrogen can be leveraged in the Canadian context through a multitude of applications, including industrial processes, feedstock production, transport, electricity storage and building heat [5]. As of May 2024, approximately 80 low-carbon hydrogen production projects have been announced in Canada, representing over $100 billion in potential investments dedicated to hydrogen-related infrastructure and opportunities [5]. However, there remains skepticism as to how hydrogen should be leveraged in the Canadian energy system. Recent work by Aguilar et al. [7] highlights that government hydrogen plans may focus on inappropriate uses of hydrogen and fail to prioritize applications where hydrogen provides real decarbonization potential. Their review finds that the government promotes the use of hydrogen applications for decarbonization that is not supported by consistent scientific evidence, and this risks delaying effective climate action. The authors call for consistent, detailed, and transparent assessments to guide policy on when hydrogen should be deployed versus electrification.

Currently, hydrogen is primarily produced through SMR, ATR, and electrolysis in Canada [16]. On the demand side, major projects are targeting hydrogen’s role in hard-to-abate industrial sectors, blending projects, and transportation applications [5]. There are also several “hydrogen hubs” under development or in the proposal stages nationwide, including in Edmonton, Vancouver, Prince George, Sarnia-Lambton, Quebec’s Vallée de la transition énergétique, Calgary, Selkik, and Grey-Bruce, Ontario [5]. These hubs are areas where hydrogen production, consumption, connective infrastructure and expertise are located in one area.

The Canadian federal government has implemented dedicated policies to support hydrogen buildup, such as the CH-ITC. An ITC is a policy instrument designed to encourage capital investment in a specific technology by allowing businesses to claim a tax reduction on qualifying expenditures. This approach lowers the upfront cost of deploying new technologies and supports the scale-up of capital-intensive clean energy solutions [17]. The CH-ITC operates based on the assessed carbon intensity (CI) of the hydrogen that is produced. The CH-ITC rates can be seen in Table 1 and apply to investments in projects that produce all, or substantially all, hydrogen through their production process [18]. There are also other policies in place that indirectly support hydrogen implementation, such as Canada's federal industrial carbon pricing system [19], clean electricity regulations [20], and clean fuel regulations [21].

Table 1: CH-ITC Credit Rate Definition [18]

Carbon Intensity (kg CO_2e/kg H_2)	**CH-ITC Credit Rate**
<0.75	40%
$0.75 \leq CI < 2$	25%
$2 \leq CI < 4$	15%

2.2.3 Previous Investigations of Hydrogen in Integrated Assessment Models

Hydrogen's rise as an energy carrier for decarbonization has spurred a variety of modelling approaches, each addressing different aspects of the hydrogen value chain and its integration into energy systems. Techno-economic & process models investigate plant feasibility and process design, sector-specific optimization models can explore specific dynamics of hydrogen within sectors, and macroeconomic/general equilibrium models can study economy-wide effects of hydrogen deployment, such as job creation, Gross Domestic Product (GDP) impacts and trade balances.

Integrated assessment models (IAMs) are excellent tools for investigating hydrogen in future energy scenarios regarding multi-sector and multi-region policy, linking economic, social, and environmental data to evaluate pathways. A recent review by Ghaboulian Zare et al. [22] highlights that IAMs have evolved rapidly to better represent hydrogen technologies, including advances in linking hydrogen production, storage, and end-use across energy, industry, and transport sectors. The authors emphasize that this cross-sectoral integration is crucial for accurately assessing hydrogen's system-wide mitigation potential, given its flexibility as both a fuel and energy carrier. Xiang et al. [23] investigated the role of hydrogen in China's energy transition towards carbon neutrality using the IPAC-AIM IAM; when hydrogen technologies were implemented in the transportation and industrial sectors at a provincial level, the authors found that demand for hydrogen could reach upwards of 52.4 Mt by 2050 and be powered by renewables and nuclear energy. The authors also identified that there are several regions in China with abundant renewable energy where a hydrogen-based industry can be competitive after 2035. McPherson et al. [24] investigated the implications of future storage and hydrogen technology costs for low-carbon energy transitions at the global scale; techno-economic representations of electricity storage and hydrogen technologies implemented into the MESSAGEix IAM found that research and development investments are required to lower the cost of storage and hydrogen technologies to increase variable renewable energy deployment and mitigate coal generation. The authors also identified that electrolysis is an important technology for mitigating climate change as it can be deployed for both seasonal and short-term curtailment even under pessimistic costs. Lastly, Hanley et al. [25] conducted a review of results from multiple IAM studies in analyzing the role of hydrogen in energy systems and found that hydrogen can deliver emission reduction in various sectors and is important in integrated complex energy systems for deep decarbonization policy scenarios. However, it is important to recognize that assessment of hydrogen cannot be considered in an isolated manner, and its synergies with other fuel and energy carriers will be key to its development and success. Ghaboulian Zare et al. [22] also note persistent challenges in hydrogen modelling within IAMs, such as limited granularity on spatial and process details, the treatment of emerging hydrogen applications, and uncertainty in key cost and policy assumptions. They conclude that future research should focus on enhancing these dimensions to accurately guide technology and policy development for hydrogen transitions.

2.2.4 Paper Outline and Contribution

There are two main contributions to this piece of work. First, this study provides the first assessment of the CH-ITC effectiveness in relation to the Canadian energy system, delivering insights to inform future policy development. Second, this work provides a fully open-source, sub-national energy system model accessible to researchers and stakeholders to investigate hydrogen deployment and related policies in Canada.

There is a lack of existing work investigating the CH-ITC effectiveness on hydrogen implementation within Canada. This gap is significant because the CH-ITC represents a major federal investment and policy lever, and its real impact on hydrogen uptake, cost-optimal energy pathways, and Canada's ability to meet net-zero targets remains untested in scholarly literature. To further signal this papers importance, the various modelling initiatives conducted in the Hydrogen Strategy for Canada Progress Report didn't include this key policy at the time [5]. Without rigorous, transparent assessment, policymakers and stakeholders risk overestimating the strategy's capacity or missing critical barriers to deployment.

This work addresses this research gap by presenting the first fully open-source, scenario-based analysis of the CH-ITC's effects, leveraging a comprehensive modelling framework that can be examined and applied by researchers and stakeholders across Canada. This approach directly responds to the second recommendation in the Canada Senate report *HYDROGEN: A Viable Option for a Net-Zero Canada in 2050?*, which calls for transparent, accessible, and peer-reviewed energy modelling to improve accountability and public trust [6]. By openly sharing both methods and results, this work fills a crucial gap and offers a resource for future policy refinement, modelling, and governance in Canada's hydrogen transition. MESSAGEix-Canada can be accessed through the link found in the data availability segment of this work. In Section 2, we describe the modelling methodology used in this study. Section 3 presents the key results and findings, followed by a discussion in Section 4 focusing on policy implications and recommendations.

2.3 Methodology

2.3.1 Model Architecture

The MESSAGEix-Canada model is based on the MESSAGEix integrated assessment model architecture [8], [26]. MESSAGEix is a linear programming framework designed for strategic energy planning and the integrated assessment of energy-engineering-economy-environment systems. The model optimizes the reference energy system throughout the entire time horizon, utilizing historical data, future projections and constraints to determine the most cost-effective energy pathways. The model utilizes a 5-year time step and comprises 13 subregions, representing Canada's provinces and territories. Each subregion has distinct techno-economic limitations, mirroring the energy profiles, resource availability, and policy landscape of each province. This representation is effective for understanding regional disparities in energy systems and facilitating a robust evaluation of policy effects. For this piece of work, all relevant hydrogen production methods, transport and distribution methods, and end-uses of hydrogen were calibrated to assess pathways where hydrogen can be leveraged in the Canadian context. Figure 1 depicts the hydrogen framework within MESSAGEix-Canada developed and utilized for this study, which segregates hydrogen production, transmission and distribution, and its interties within final energy. The arrows in the figure represent commodity flow between technologies within the model.

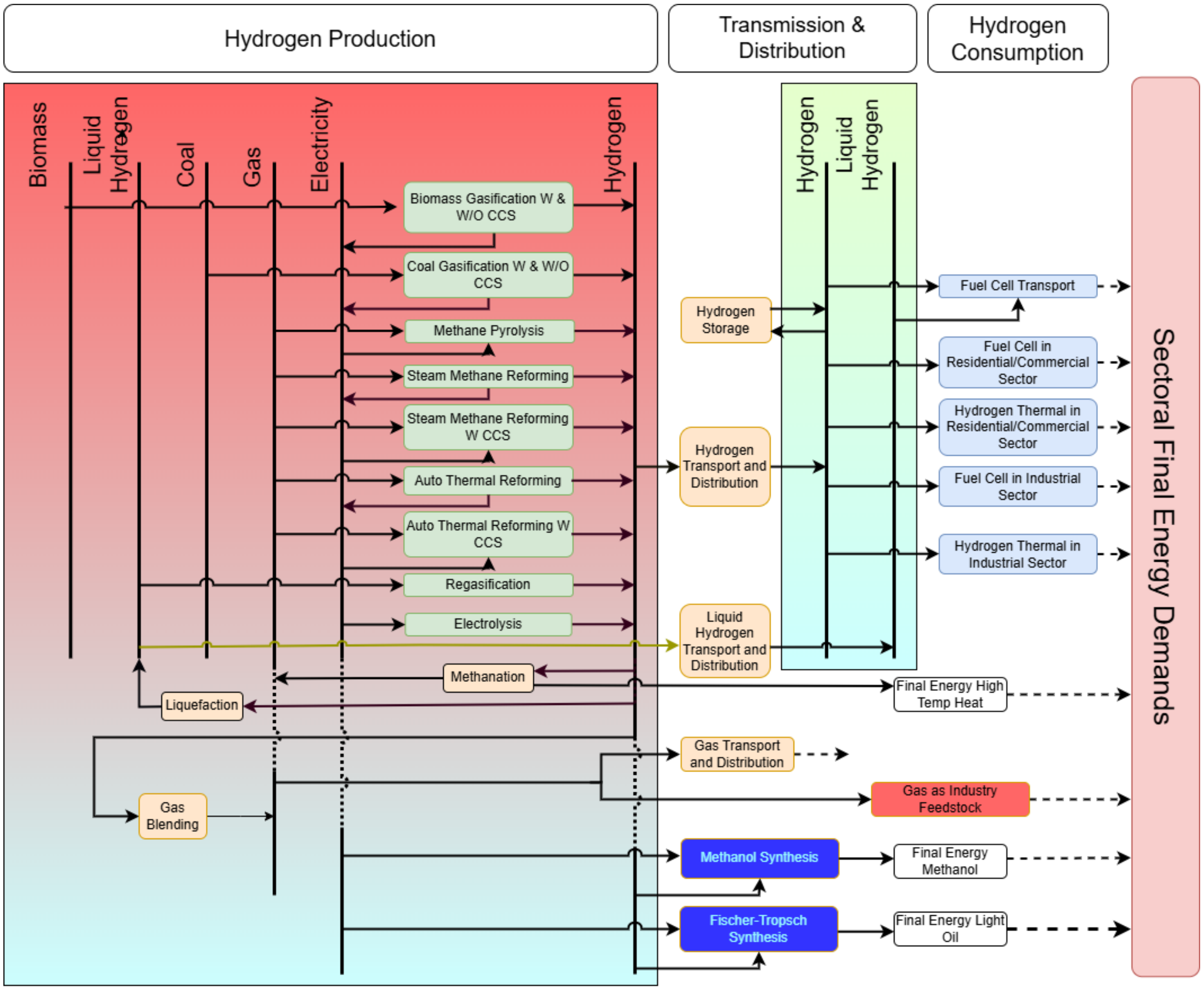

Figure 1: Hydrogen Flowchart in MESSAGEix-Canada

Primary energy sources related to hydrogen in MESSAGEix-Canada include biomass, methane (natural gas) and coal. Six hydrogen production methods exist in MESSAGEix-Canada: SMR, ATR, biomass gasification, coal gasification, methane pyrolysis and electrolysis. For MESSAGEix-Canada, proton exchange membrane electrolyzers have been utilized for parameterization over other electrolyzer technologies due to a higher hydrogen production rate, better energy efficiency, and prevalence in the current hydrogen generation sector [27]. SMR, ATR, biomass gasification, and coal gasification have two configurations in the model, both with and without the utilization of carbon capture and storage (CCS), each with its own CCS rate.

Hydrogen transport and distribution is modelled as two linking technologies for the commodity. One technology is parameterized for the transport of gaseous hydrogen, while the other models the transport of liquid hydrogen. These linking technologies represent the associated costs for building and maintaining hydrogen transport networks, as well as transmission and distribution losses for the associated technologies when transitioning from a secondary to final energy level.

The model allows for the representation of blending in the natural gas system. Blend ratios are controlled through a relation in the model that specifies the maximum amount of hydrogen that can be incorporated into the gas transmission and distribution network. The model framework doesn’t incorporate a specific blended gas commodity; instead, each technology that utilizes the natural gas commodity can utilize hydrogen up to a specified maximum blend ratio, if deemed cost optimal under a variety of emission and operational constraints.

Underground hydrogen storage was selected for parameterization as a storage medium in the model. This includes salt caverns, saline aquifers, depleted oil and gas deposits, and lined or unlined rock caverns. The reason for this decision is due to the ability of underground hydrogen storage to be able to store large amounts of hydrogen for extended periods of time at a low cost and environmental impact [28]. This technology is also mature in the Canadian context, with uses in the natural gas system.

There are two means of liquid production from hydrogen in the model. Methanol production and light oil production. Methanol production from hydrogen is parameterized in the model based on the CO2 hydrogenation process, and light oil production from hydrogen is parameterized in the model based on the Fischer-Tropsch Synthesis process.

Lastly, energy service demands are provided to the model exogenously in five categories.

1. Heat applications in the industrial sector
2. Heat applications in the residential/commercial sectors
3. Specific applications for industrial applications
4. Specific applications and residential/commercial applications
5. Transport

Demands were defined from the MESSAGEix Global model, where data is used for North America, and service demands were downscaled and adjusted for historical provincial energy consumption, population and GDP projections provided by Statistics Canada. Further details on demand calibration can be found in Appendix A1. Hydrogen final energy technologies compete with other technologies in the model based on cost and efficiencies to meet these demands.

2.3.2 Policies

To assess the interaction of policy and hydrogen uptake in Canada, this work represents multiple cornerstone federal policies, including carbon pricing and targeted investment support within the energy system modelling framework. Since the modelling in this work is heavily focused on the supply side, other policies such as the zero-emission vehicle mandates have not been included in this work. Due to the model's limited end-use granularity, the Clean Fuel Regulations have also been omitted from this study. Below are descriptions of each policy included, with a focus on the policy purpose, key design features, and relevance to hydrogen production and use.

2.3.2.1 Industrial Carbon Pricing

The federal OBPS is a form of carbon pricing applied to large industrial emitters. Rather than a straight carbon tax, the OBPS sets facility or product-level emission benchmarks. Emitters must pay the carbon price on emissions that exceed these benchmarks, but receive credits for emissions below the threshold [19]. The intended effect is to maintain an incentive to decarbonize while limiting competitiveness impacts for emission-intensive, trade-exposed industries. OBPS thus reduces cost pressure on hydrogen-intensive heavy industry while still providing further incentive for lower-carbon production.

In MESSAGEix-Canada, the OBPS policy is represented by applying dynamic, regional, and technology-specific emission benchmarks and tightening rates to sectors. The model calculates a payable emission intensity for technologies based on their emission factor relative to these evolving standards and applies corresponding carbon costs. This approach allows for scenario analysis of how industrial carbon pricing influences costs, emissions, and investment decisions across provinces and technologies.

2.3.2.2 Clean Electricity Regulations

The CER comprise federal rules that drive the decarbonization of Canada's electricity grid. These regulations phase out unabated coal generation by 2030, promote emissions limits for natural gas power generation, and set increasingly stringent limits for grid emissions in alignment with Canada's 2035 net-zero electricity target [20]. By shaping the electricity mix, the CER influence the carbon intensity of grid-supplied hydrogen via electrolysis, as well as the overall economics of clean hydrogen routes.

In MESSAGEix-Canada, the CER policy is implemented as a set of technology and region-specific emission intensity constraints applied to electricity generation technologies. The model imposes emission intensity limits and restricts the use of offset credits per facility, ensuring federal targets for grid decarbonization are met.

2.3.2.3 Investment Tax Credits

Canada has introduced several ITCs in recent years to reduce the capital cost of deploying clean energy technologies, each with specific aims relevant to hydrogen.

1. Clean Hydrogen Investment Tax Credit

The CH-ITC provides a tax credit for capital expenses in eligible hydrogen production projects. The credit rate is tied to the carbon intensity of hydrogen production, with higher credit rates for lower-emission hydrogen (See Table 1). This design incentivizes investment in clean hydrogen pathways, including electrolysis using clean electricity, and natural gas with CCS, by lowering capital costs [18].

2. Clean Technology Investment Tax Credit

The Clean Technology Investment Tax Credit offers incentives for a wide range of clean technologies, covering investments in renewables, energy storage, and select low-carbon heating and electricity generation technologies [29]. For hydrogen, it reduces the cost of integrating renewables that can be used as an electricity input and other related infrastructure.

3. Clean Technology Manufacturing Investment Tax Credit

The Clean Technology Manufacturing Investment Tax Credit aims to grow the domestic supply chain for clean energy solutions by supporting investments in new manufacturing capacity for clean technology components, including hydrogen production and storage equipment, fuel cells, and carbon capture [30].

4. Carbon Capture, Utilization, and Storage Investment Tax Credit

The Carbon Capture, Utilization, and Storage Investment Tax Credit is designed to accelerate the deployment of carbon capture projects in power generation and industrial sectors. The credit rates vary: direct air capture projects receive up to 60%, other carbon capture projects up to 50%, and transportation/storage investments up to 37.5% of eligible capital expenses [31]. By decreasing costs for CCS, this policy supports lower-carbon hydrogen routes in regions with existing fossil-based infrastructure.

In MESSAGEix-Canada, ITCs are modelled as technology-specific reductions applied to investment costs. The model reads ITC policy parameters for different technology categories and dynamically adjusts the investment cost parameters. This approach allows for a detailed representation of the varying ITC rates tied to technology types, enabling scenario analysis of how tax incentives influence the economic attractiveness and deployment of targeted technologies.

2.3.3 Scenarios

Table 2 outlines an overview of the four scenarios investigated through this research. IAMs offer a broad overview of the energy system, employing coarse spatial and temporal granularity, and rely on inputs that are typically inherently uncertain. Therefore, these models are best suited for exploring long-term transition pathways and scenario analysis, rather than for detailed studies of specific energy system dynamics or operational decisions [32]. With this in mind, scenarios were developed that outline where the hydrogen strategies' goals fall under a current legislated measures scenario and different future net-zero projections.

Table 2: Scenarios Explored

Scenario	Description
Current Measures (BAU)	Hydrogen production before 2025 is parameterized in the model. All policies are implemented as legislated.
Canadian Hydrogen Strategy (CHS)	Proposed projects identified in the Hydrogen Strategy for Canada are assumed to proceed through planning and construction and begin production by 2030. All policies are implemented as legislated.
Net Zero Hydrogen Supportive (NZ-Opt)	High learning rates are specified for hydrogen technologies as defined by shared socioeconomic pathway (SSP1) cost projections [24] [25]. Hydrogen can be blended into the natural gas system up to 20% by volume. The CH-ITC is assumed to continue past 2035 until 2060, which is the maximum model lifetime. All other policies continue as legislated.
Net Zero Hydrogen Pessimistic (NZ-Pes)	Cost reductions due to research and learning-by-doing are limited to a more pessimistic scenario as defined by shared socioeconomic pathway (SSP4) cost projections [24] [25]. Hydrogen blending in the natural gas system is limited to 5% by volume. All policies are implemented as legislated.

The purpose of the BAU scenario is to provide context of current measures. This scenario is simply parameterized using existing hydrogen projects identified in the Hydrogen Strategy for Canada. In essence, under current legislated policies, and with no emission bounds, this is how much and where the model predicts hydrogen to be leveraged until 2050 in a cost-optimal scenario.

The CHS scenario takes the BAU scenario a step further and identifies the impacts of developing the proposed provincial hydrogen hubs and strategic corridors. Due to MESSAGEix-Canada's spatial and temporal granularity, proposed projects are defined on a per-province scale for the year 2030 in an effort to kickstart development if all proposed projects were to move forward. Future production types were defined based on projects in various planning phases from around the country, discussed in the national strategy. Specific assumptions can be found in Appendix A6.

Lastly, the two net-zero scenarios provide context for hydrogen in relation to cost-optimal net-zero pathways. In these scenarios, emissions are constrained to a net-zero trajectory, while exogenously assuming a 100 Mt reduction from land use, land use change, and forestry (LULUCF).

2.4 Results

The Hydrogen Strategy for Canada outlines ambitious targets for hydrogen development and highlights policy levers to decrease costs and incentivize development [4]. However, it remains to be seen if these targets are realistic under the current policy mix. This section presents four central findings through the scenario-based modelling approach in MESSAGEix-Canada. First, the CH-ITC is insufficient in driving hydrogen deployment at a scale required for achieving net-zero targets. Second, hydrogen production varies significantly across provinces and territories, shaped by resource availability and historical energy mix. Third, model results indicate that hydrogen is primarily utilized in industrial applications and as a feedstock for various purposes. Finally, electrification will remain as the dominant energy carrier nationally, and hydrogen will play a complementary role in hard-to-abate sectors, with its uptake dependent on local conditions and cost competitiveness.

2.4.1 The Clean Hydrogen Investment Tax Credit Fails to Incentivize Hydrogen to Meet Net Zero Levels

National hydrogen production by scenario is highlighted in Figure 2, which provides a clear indication that hydrogen production falls well short of net zero levels under the current policy mix. If hydrogen production were to be competitive from a cost standpoint, the BAU and CHS scenarios would see hydrogen production reaching net-zero levels. However, the model is minimally investing in hydrogen production, indicating investment in other energy carriers to meet demands in the model. Therefore, even if proposed hydrogen projects in the Hydrogen Strategy for Canada were to be completed in 2030, hydrogen simply cannot compete in a least-cost energy system as other cheaper and higher-emitting energy carriers are leveraged.

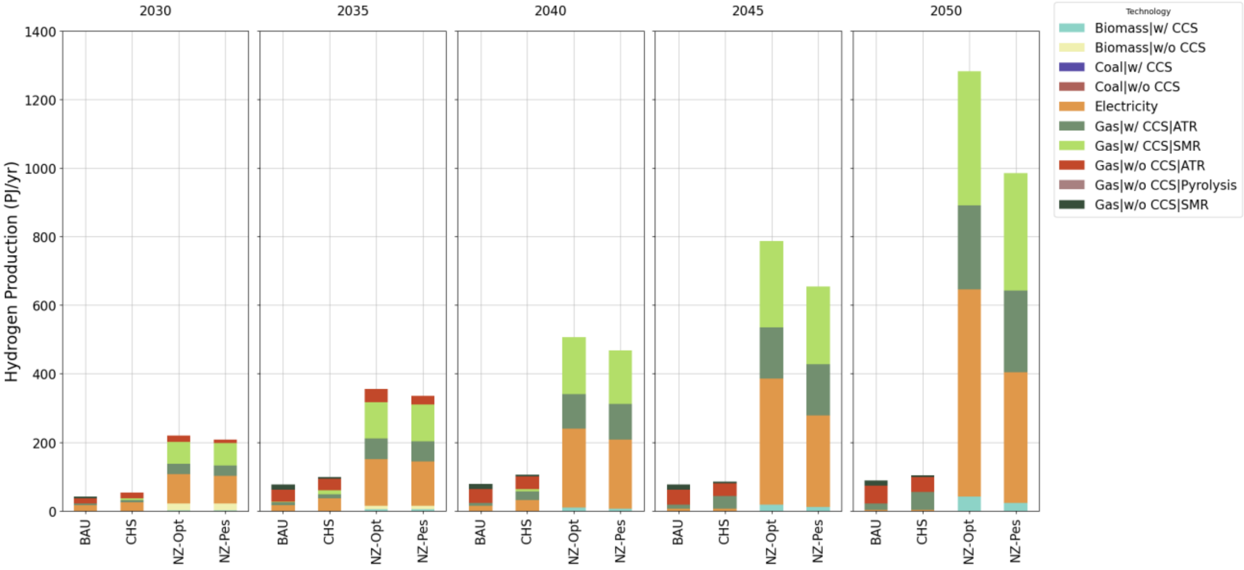

Figure 2: National Hydrogen Production by Scenario

In 2030, natural gas reforming is the primary form of hydrogen production (28 PJ of production), followed by electrolysis (24 PJ of production) in the CHS scenario. Of this 28 PJ, a shift is beginning where ATR and SMR with CCS are being incentivized over existing natural gas reforming infrastructure. This trend continues to 2050; however, electrolysis contributes significantly less of a share of the hydrogen production mix than in 2030. It can be seen that the model also begins to reinvest in non-CCS infrastructure after the CH-ITC ceases in 2034, and OBPS alone is not able to incentivize CCS investment. In 2050, the net-zero scenarios showcase a cleaner production mix with significant electrolysis, natural gas with CCS, and some biomass utilization.

Average annual investments can indicate the scale and pace of deployment of new infrastructure or technologies within the energy sector. The average annual investment in supply-side hydrogen infrastructure can be seen Figure 3.

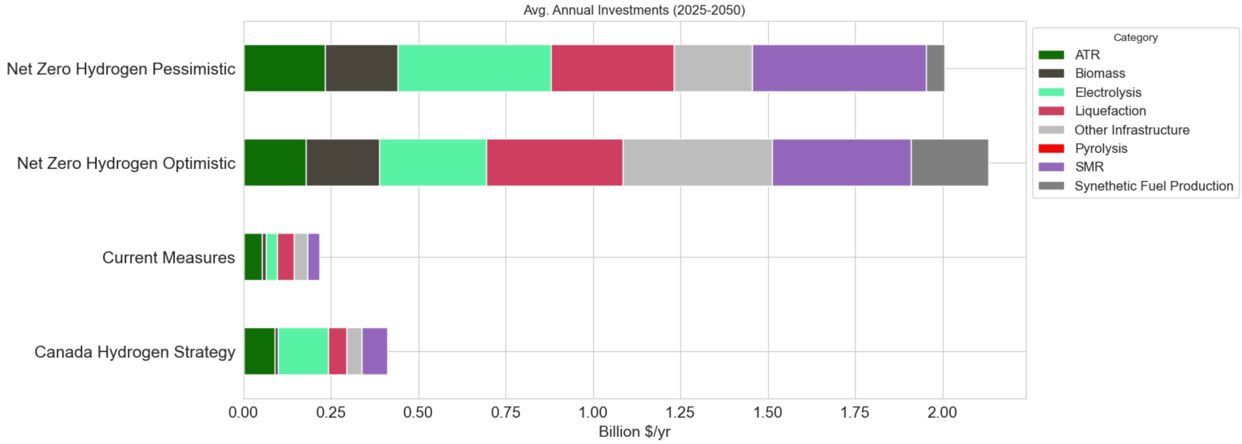

Figure 3: Average Annual Investments in Hydrogen Infrastructure

It can again be seen from the results that CH-ITC fails to incentivize the hydrogen production investments required for net-zero levels. This is because the level of investment in hydrogen-related infrastructure is significantly below that required for net-zero levels. The net-zero optimistic scenario results in the largest annual investment in hydrogen at over $2 billion/year. Electrolysis is a major component of these costs, highlighting hydrogen's dependence on clean electricity in a transition to net zero. There is also a large portion of annual investment in liquefaction to produce liquid hydrogen for transportation purposes.

2.4.2 Hydrogen Production Varies Across Provinces and Territories

Hydrogen production varies significantly nationwide as a direct function of a province's/territory's resources and historical energy mix. Figure 4 highlights hydrogen production per province under each scenario, showing that Alberta and Ontario cement themselves as the nation's largest hydrogen-producing province in all scenarios.

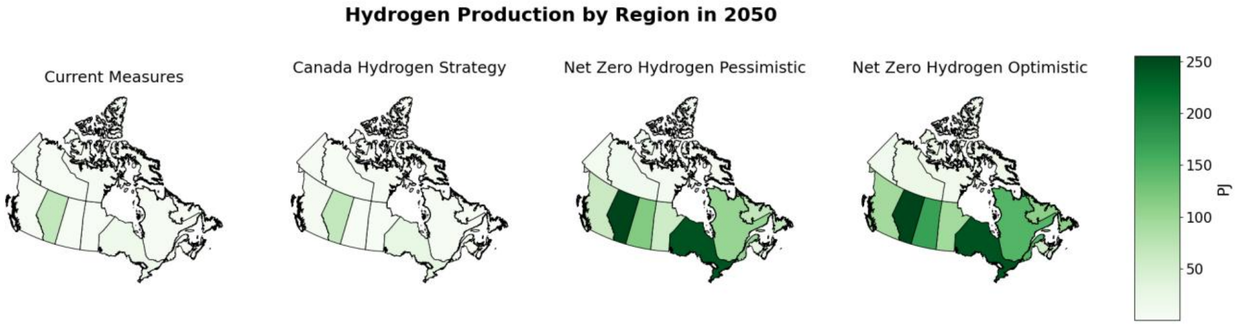

Figure 4: Hydrogen Production by Scenario and Region

The specific hydrogen production volumes and types can be analyzed further in Figure 5. Alberta produces most hydrogen from natural gas resources in the BAU and CHS scenarios and contributes the majority of hydrogen production nationwide post 2040. This is because most provinces that produce hydrogen through electrolysis tend to phase out production after this period, notably after the CH-ITC ceases. Quebec is an example, producing hydrogen via electrolysis utilizing its large hydro and clean electricity potential, but it phases out production after 2040, signaling demand for the electricity commodity in other, more cost-competitive uses.

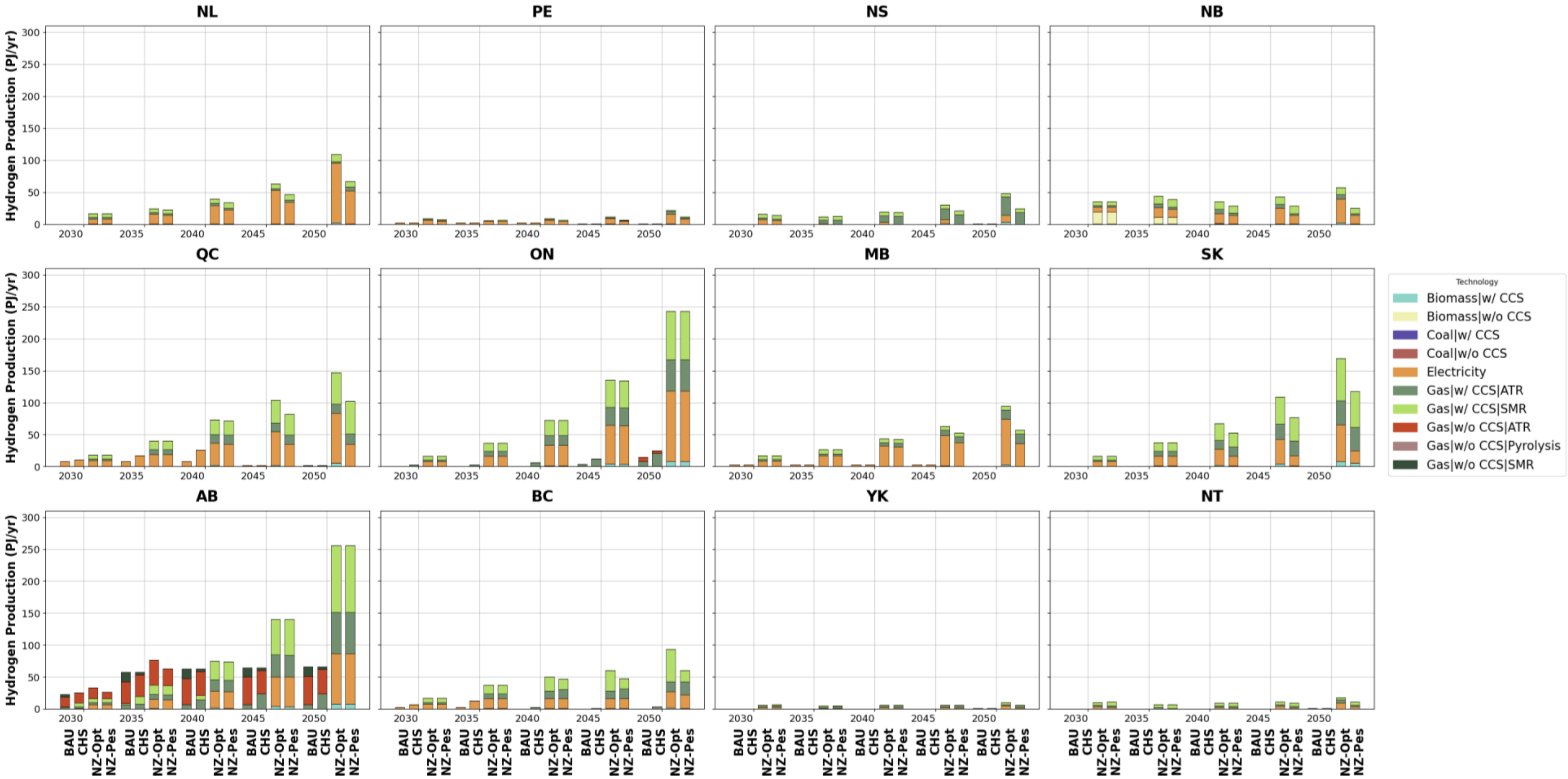

Figure 5: Hydrogen Production Over Time by Region (excluding Nunavut for figure simplicity)

The net-zero scenarios highlight that hydrogen is utilized in all provinces/territories at varying levels. All production mixes highlight electrolysis and natural gas with CCS as production methods. Again, the amount of electrolysis compared to natural gas varies between regions, with provinces like Alberta and Saskatchewan seeing more hydrogen from natural gas and provinces like Quebec and Newfoundland and Labrador seeing more production from electrolysis.

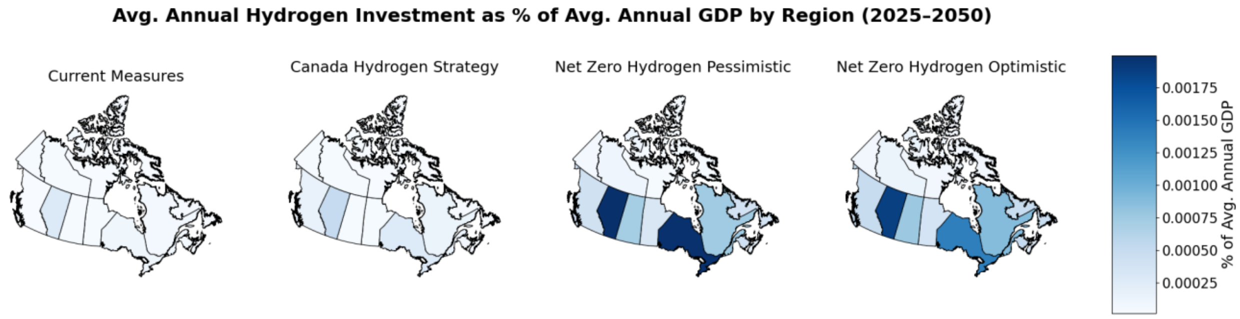

Figure 6: Average Annual Investments in Hydrogen as a Function of GDP

Hydrogen investment costs as a share of GDP can be seen in Figure 6. To put this into context, energy investment typically falls within a range of 2% of GDP [35]. Therefore, even under a pessimistic scenario, hydrogen investments contribute to about 0.0175% of Ontario's GDP, or roughly 0.875% of Ontario’s average annual investment in the energy system. These results cement that while hydrogen is being leveraged in all net-zero scenarios, it is still not the major commodity being invested in. The highest investment intensities are observed in Alberta, Ontario, and Quebec, reflecting their resource advantage. The results underscore the importance of regionally differentiated policy and infrastructure strategies to realize hydrogen’s potential.

2.4.3 Hydrogen is Primarily Utilized in Industrial Applications and Feedstock Production

Hydrogen utilization in the model is outlined in Figure 7 and Figure 8. In the CHS scenario, 80 PJ of hydrogen is used directly in industrial applications in 2050. Of this 80 PJ, Alberta and Ontario utilize the majority, with 56 PJ and 15.5 PJ, respectively. In the net-zero scenarios, Hydrogen is used in industrial applications both through blending applications with natural gas and direct consumption. In 2050, this leads to a peak net zero contribution of roughly 10% of Canada’s industrial energy demand. This result aligns with the hydrogen strategies' claims that hydrogen has the potential to provide 10-20% of Canada’s industrial energy demand by 2050 [4]. The net-zero scenarios also highlight the use of hydrogen in light oil production and methanol production as a feedstock for other sectors within the model.

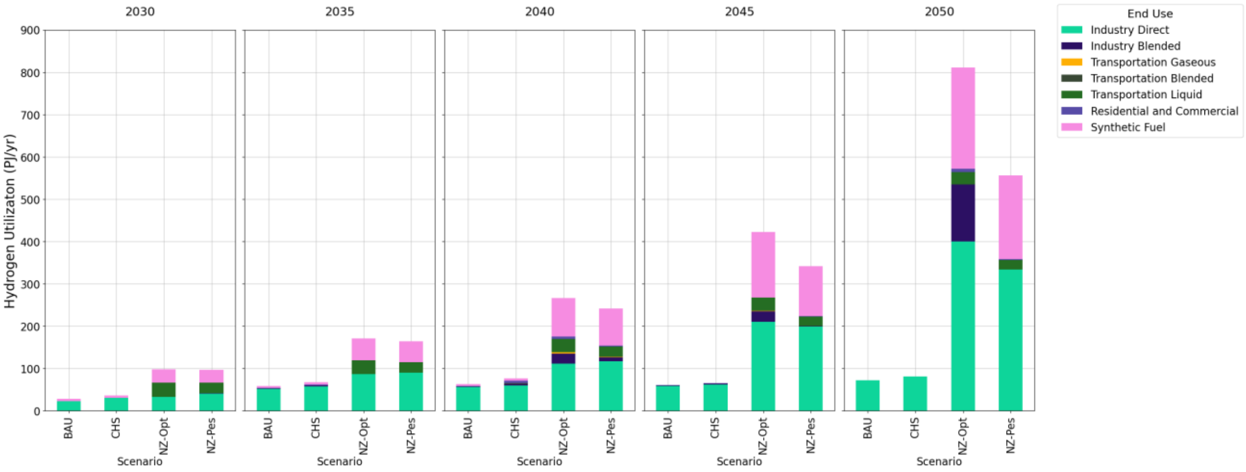

Figure 7: Hydrogen End Use by Sector and Scenario

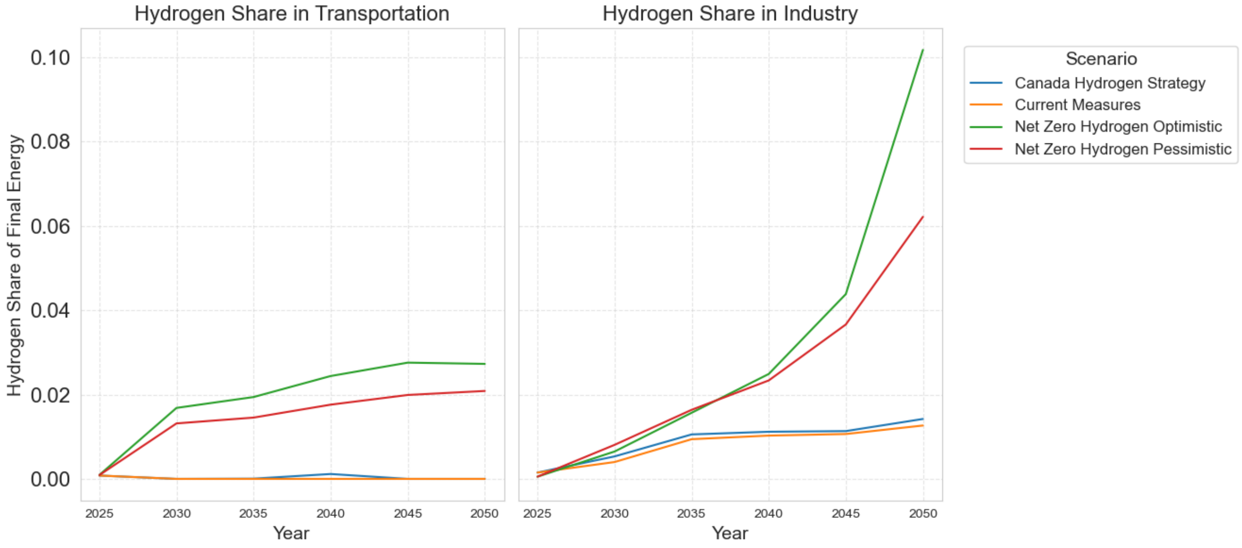

Figure 8: Share of Hydrogen in End Use Sectors Over Time by Scenario

The lack of hydrogen seen within the transportation sector in the CHS scenario is a clear indication that the model is choosing to prioritize hydrogen in industrial applications first. However, in the net-zero scenarios, hydrogen is seen to jump to a ~1.8% share of transportation's final energy in 2030 to meet emission bounds within the model. Growth in this sector continues until 2045, where the optimistic scenario contributes a share of ~3% in 2050. This is due to electricity and ethanol being leveraged as a cleaner option for net zero by 2050.

This differs from modelling organizations' findings in the Hydrogen Strategy for Canada progress report, which, on average, sees a 12 - 35% share in the transport sector for achieving net-zero emissions by 2050 [5]. However, there is a lack of synergy amongst the progress report results regarding where hydrogen is best leveraged. When investigating the results further, hydrogen and ethanol/methanol are competing for a similar role in the transportation sector, as can be seen in Figure 9. With this, there is likely sensitivity in the model to assumptions on the costs of these options. It should also be noted that a production pathway for methanol within the model is from hydrogen, meaning that hydrogen may still act as a feedstock for this commodity within the transportation sector.

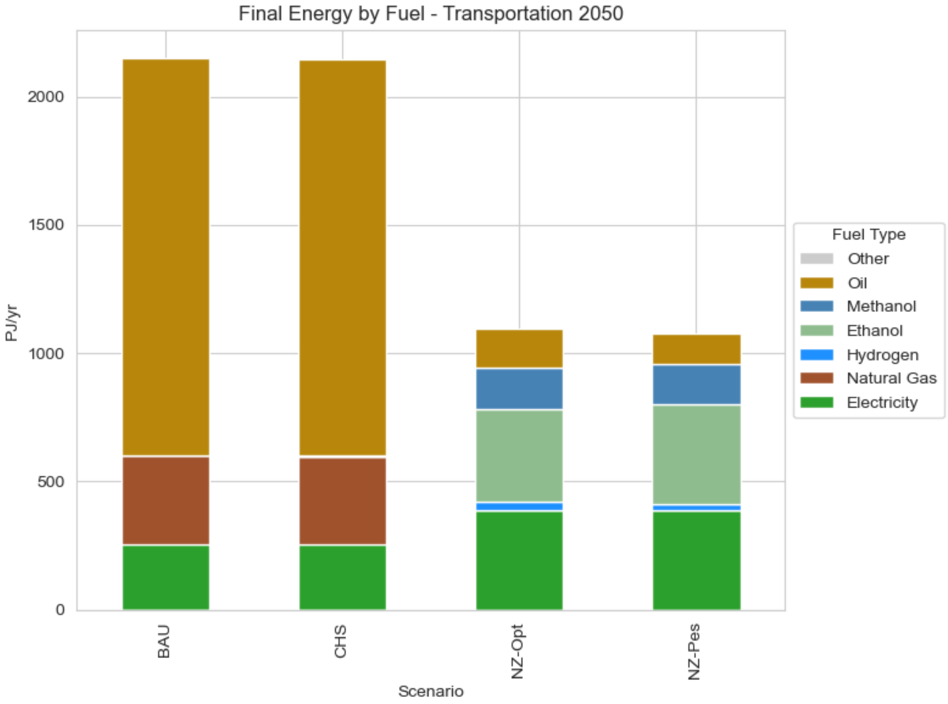

Figure 9: Transportation Final Energy by Fuel Type

2.4.4 Electrification Remains as the Dominant Energy Carrier in a Net Zero Transition

With the model choosing to leverage hydrogen in industrial and transportation applications, the share of hydrogen relative to electrification can be investigated to understand how different provinces utilize the energy carriers in a shift to a cleaner energy system.

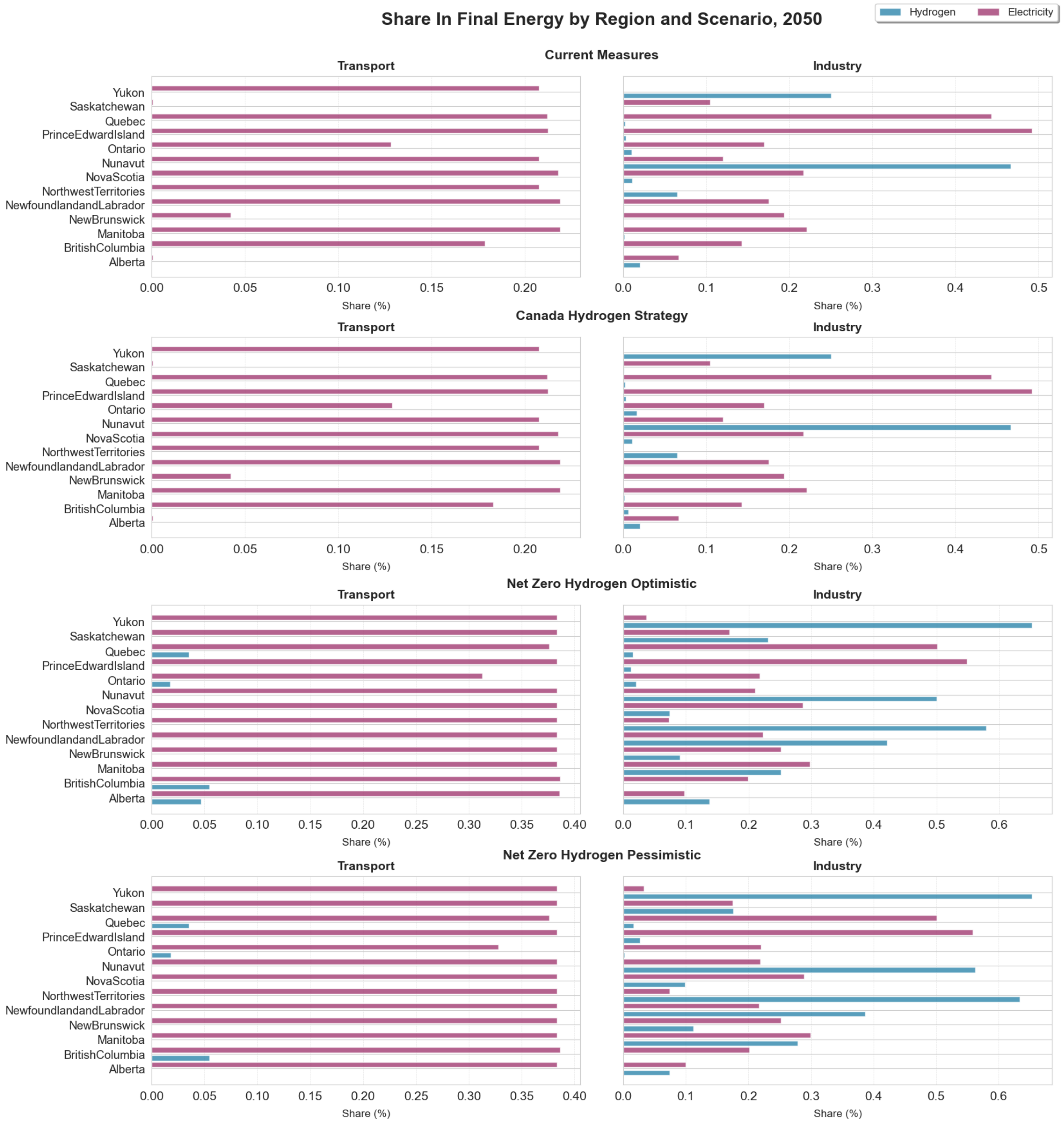

Figure 10: Share of Electricity and Hydrogen in Transport and Industrial Demand by Province and Scenario

Electricity is the dominant energy carrier compared to hydrogen nationwide in all scenarios; however, some regions and scenario combinations do see a shift to more hydrogen utilization than electricity. Newfoundland and Labrador is a notable example, with almost twice the share of hydrogen as electricity in both net-zero scenarios for industrial applications. This hydrogen is being utilized to meet the province's high-temperature heat demand for industry, while electrification is occurring in other sectors. There are also instances where the larger share between the two commodities varies depending on the net-zero scenario. In Alberta, the net-zero hydrogen optimistic scenario sees a greater share of hydrogen in industry, but not in the net-zero hydrogen pessimistic scenario. This makes sense when considering that Alberta's electricity system has historically been dominated by emitting generation [36], and a shift to hydrogen would allow for cleaner energy under net-zero constraints, but cost reductions and higher blending limits are needed to leverage the commodity. Greater-populated provinces such as Ontario and British Columbia, which have higher electricity production, keep a negligible share of hydrogen and leverage electricity where possible instead. Lastly, an interesting insight under the business-as-usual case sees Nunavut and Yukon having a higher share of hydrogen in industrial demand; however, due to these territories having such small industrial activity, this result is marginal.

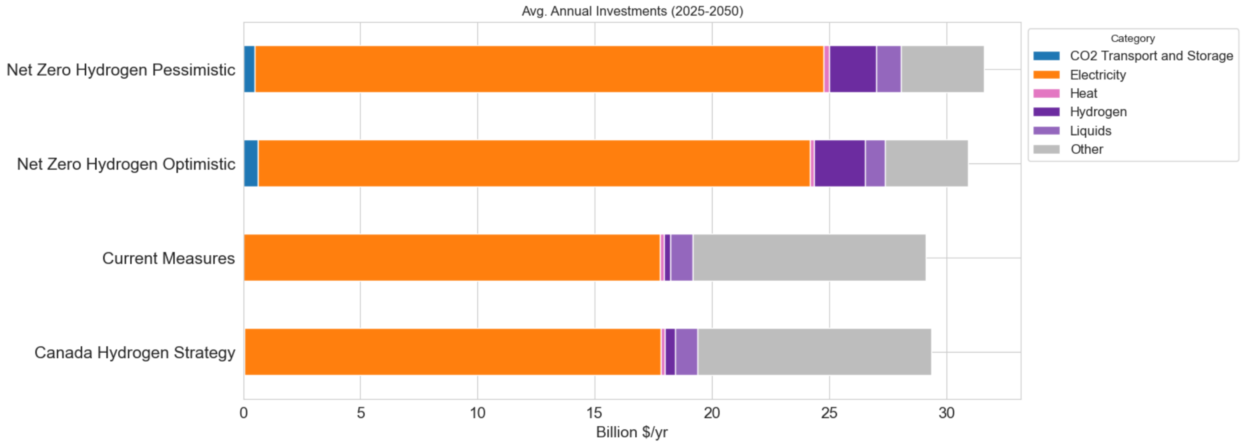

Figure 11: Average Annual Investments in Energy Supply

When comparing the average annual investment in hydrogen to the rest of the energy system, electrification is the dominant investment in all scenarios. The BAU scenario highlights that under the current policy mix, there is little incentive for future fossil fuel-based plants, but it still invests in infrastructure such as transmission and distribution associated with these plants that have a shorter life span.

2.5 Discussion

Model results provide a clear indication that, regardless of cost projections, hydrogen will be an important energy carrier in a net-zero pathway. Hydrogen will be produced by a variety of sources, but will primarily be from natural gas reforming with carbon capture and storage and electrolysis in a net-zero world. Domestically, results suggest that the commodity will be leveraged primarily in industrial applications and liquid feedstock production with a smaller share in transport applications.

When comparing MESSAGEix-Canada results to other modelling work done in the hydrogen strategy for Canada's progress report, the results are within a similar range to other proprietary models' net-zero scenarios, although all scenario assumptions differ between models and are not open source. What sets MESSAGEix-Canada apart in this analysis is the incorporation of the CH-ITC. The CH-ITC is referenced in the Hydrogen Strategy for Canada progress report as a significant policy lever to promote hydrogen investment in achieving the hydrogen strategy's transformative goals of 4 Mt and 20 Mt of hydrogen demand in 2030 and 2050, respectively [4]. However, when incorporating this policy in a non-net-zero case, along with the federal OBPS system, other ITCs and CER policies, there remains a notable hydrogen implementation gap. This is a clear indication that hydrogen lacks incentive for development, and the current policy mix is not adequate in meeting the strategy's goals.

One option for strengthening the incentive for hydrogen production is to extend the CH-ITC, which currently ceases in 2034.

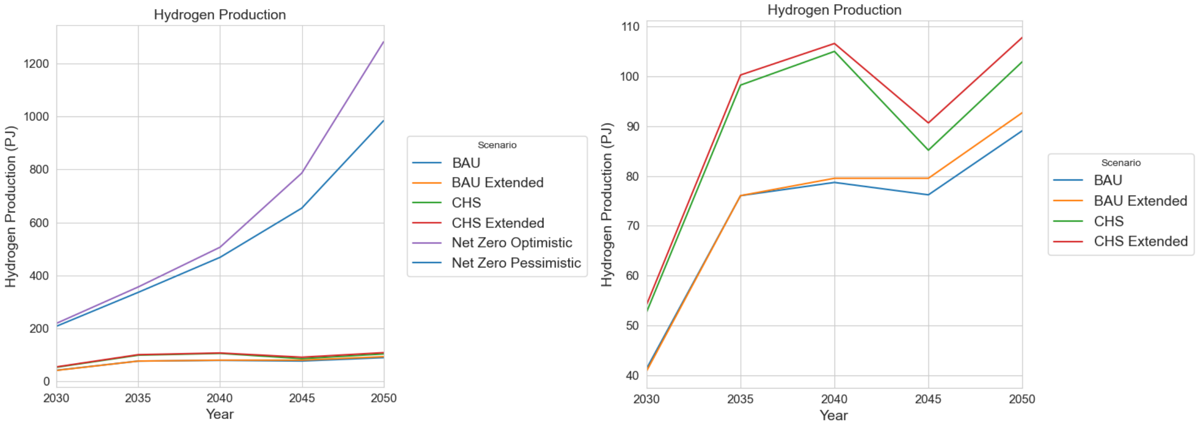

Figure 12: National Hydrogen Production by Scenario

As can be seen in Figure 12, continuing the CH-ITC until 2050 still lacks the incentive required to achieve net-zero targets in both the CHS and BAU scenarios. This is a clear indication that while the CH-ITC does provide incentives to invest in clean hydrogen production, a policy gap exists in meeting net-zero requirements. The current tax credit and an extended form of the tax credit fail to bridge the cost gap with cheaper alternatives, such as fossil fuels and other energy carriers that are also incentivized within the policy mix, such as electrification.

To identify the incentives required to close this gap, multiple scenarios were run with varying cost reductions to explore when hydrogen production reaches net-zero levels. This resulted in a total cost reduction of 55% being required. However, it must be noted that this is a 55% reduction in total hydrogen system costs and not just investment costs for hydrogen production facilities. Both investment costs and operating costs across the hydrogen value chain would need to decrease by 55%, including production, transport infrastructure, and end-use applications. This suggests that policies focused solely on investment costs, such as the CH-ITC, might not address the cost dynamics that limit hydrogen deployment. A broader incentive mechanism, such as a clean hydrogen production tax credit that applies to levelized hydrogen costs, could better address operating expenses and delivery costs across the hydrogen value chain. Similar approaches are being explored internationally, such as the United States Clean Hydrogen Production Tax Credit [37].

While a 55% total cost reduction incentive may be unrealistic, the effects of adjusting other compounding policies to be more stringent can also be investigated. The federal carbon price was not varied for this study; however, an interesting investigation would be to increase the carbon price post-2030 while still providing a smaller full scope hydrogen incentive to see what effect that has on hydrogen production. When exploring this relationship, it was seen that even under a carbon price \$300/tonne CO_2e, hydrogen costs would still need to be reduced by approximately 42% to reach a hydrogen production level in line with the model's net-zero projections.

Hydrogen’s modelled role remains important, especially in hard-to-abate sectors, but results indicate heavy reliance on technologies such as CCS in meeting net-zero targets. Throughout the scenarios, a pattern emerges following the expiration of the legislated CH-ITC, investments in natural gas reforming without CCS increase. This may imply risks of lock-in to higher-emitting assets without sufficient incentives linked to emissions standards. Therefore, continued scrutiny of emission reductions and life-cycle accounting will be crucial to ensure climate benefits.

The modelling results also highlight variations in regional hydrogen production profiles, driven by resources and existing infrastructure. Province’s rich in natural gas, like Alberta, show a greater dependence on natural gas-based hydrogen production, whereas hydro-rich provinces such as Quebec demonstrate higher shares of green hydrogen via electrolysis. This suggests that policy measures aligned with provincial strengths could influence where and what types of hydrogen are most competitive.

Overall, the MESSAGEix-Canada results indicate that while current policies, including the CH-ITC, contribute to hydrogen deployment, additional or adjusted policy mechanisms will be necessary to realize hydrogen’s potential in achieving net-zero targets in a cost-optimal energy system. The results suggest the value of multi-tiered incentive structures that target sector priorities, regional characteristics, and lifecycle emission considerations. Similarly, increasing carbon pricing levels beyond current projections appears to complement hydrogen cost reductions.

2.5.1 Limitations and Future Work

A significant challenge with Canadian energy system modelling is the limited transparency and availability of high-quality data, particularly for hydrogen production, infrastructure, and end-use sectors. This includes costs, capacity factors, technical lifetimes, emission factors and exogenous growth constraints utilized to mimic real-world capacity expansion limits within the model. With this, and with the inherent uncertainties in long-term multi-sector modelling, it means that sensitivity analysis of individual parameters offers limited insight. Instead, broad scenario analysis provides a more robust exploration of possible futures and policy outcomes. Therefore, a sensitivity analysis of parameters is out of scope for this research piece.

The current model formulation aggregates the transportation, industrial, and residential end-use sectors to single demands. This limits the model's ability to assess the specific roles of hydrogen and other fuels in sub-sectors such as heavy freight, aviation, steel, and chemicals. Future work will focus on incorporating the MESSAGEix-Materials and MESSAGEix-Transport modules from the International Institute of Applied Systems Analysis and downscale demand to meet the Canadian context. This will provide sectoral and technological disaggregation to better capture the diversity of decarbonization pathways and end-use demands.

MESSAGEix-Canada's five-year time step resolution simplifies modelling and reduces computational load but also poses limitations in capturing short-term details. Such details include costs and system outputs aggregated and averaged over five years. Therefore, results are best interpreted as mid-term trends, not as precise annual or finer-resolution projections. This approach is suitable for long-term pathways but is limited for modelling operational flexibility and high-resolution dynamics. Linkages with capacity expansion and dispatch models can be explored in the future to investigate model outputs at a more granular level.

Ammonia is touted as an increasingly important vector for hydrogen transport and storage [5]. Currently, the model lacks this commodity, which may understate hydrogen's domestic market potential, particularly for heavy transport and industrial uses. Incorporating ammonia as a commodity is a priority for future model development.

Lastly, hydrogen export is not included in this study. This limits the ability to capture the full economic and strategic implications of Canada's potential as a hydrogen exporter. Future work will focus on endogenously linking export decisions through the incorporation of the MESSAGE-Trade module and linkages with other models to integrate feedback signals from global hydrogen markets.

2.6 Conclusion

This study provides the first fully open-source, provincial-scale assessment of hydrogen's role in Canada's energy transition using an integrated assessment modelling framework. The results reveal a policy gap between the Hydrogen Strategy for Canada's ambitions and cost-optimal energy system pathways, even under enhanced CH-ITC scenarios. While the CH-ITC and related incentives are important in promoting early clean hydrogen investment, the model results show that investment tax credits alone are insufficient to drive hydrogen adoption at the scale required for net-zero targets.

Model results show that hydrogen is mainly produced through electrolysis in hydro-rich provinces like Quebec and via natural gas reforming with CCS in resource-rich regions such as Alberta. Sectorally, industrial applications are the primary adopters of the commodity, with hydrogen accounting for up to 10% of industrial energy demand in a net-zero optimistic scenario, aligning with national strategy targets. Additionally, hydrogen is used in the production of synthetic fuels and, to a lesser extent, in transportation. This highlights the importance of policy measures that consider regional resources and each sector’s readiness to strategically adopt hydrogen. Policies that include production-based tax credits, tiered sectoral incentives, and differentiation based on geographic resource availability will be key to unlocking hydrogen’s potential in the Canadian energy system.

Beyond policy implications, this work contributes an open-access modelling platform that can support ongoing evaluation and refinement of hydrogen policy under evolving technological and economic conditions. Future research will aim to enhance model technological and sectoral granularity, incorporate emerging hydrogen energy carriers such as ammonia, and capture the dynamics of international hydrogen trade to better understand hydrogen’s potential role in Canada’s clean energy transition.

Chapter 3: Conclusion

Canada will need to strategically utilize an array of energy carriers to enable deep decarbonization in its future energy system. However, uncertainty remains about hydrogen's role in Canada's energy future. The purpose of this thesis was to assist in answering such questions by developing an open-source tool that provides policy assessment and scenario analysis of hydrogen in the Canadian energy system. Specifically, this thesis developed and applied MESSAGEix-Canada, an open-source, provincial-scale integrated assessment model, to evaluate the role of hydrogen under current federal policies, with a particular focus on the CH-ITC. By advancing the MESSAGEix-Canada platform and transparently assessing potential pathways, this work responds to a critical gap in literature and meets the openness demanded by federal recommendations.

The results indicate that under current policy measures, federal tax credits are insufficient to deliver on the hydrogen ambitions laid out in the Hydrogen Strategy for Canada. Industrial applications emerge as the primary application for hydrogen uptake, while hydrogen production varies significantly between provinces/territories as a direct function of regional resource endowments. Despite this hydrogen utilization, electrification remains the primary energy carrier nationally, underscoring hydrogen's complementary role. The findings highlight the need for more nuanced, production-based incentives combined with regionally tailored strategies to unlock hydrogen's full decarbonization potential.

Model limitations remain within MESSAGEix-Canada. The current model aggregates end-use sectors, omits ammonia and hydrogen exports, and relies on techno-economic assumptions that may shift as markets develop and mature. This outlines clear next steps for future model development. Work will be conducted that focuses on sectoral disaggregation by end use in industry, transportation, and residential/commercial applications. This work will begin by targeting the industrial sector, and disaggregating demands and technologies for the concrete, iron and steel, chemicals, and aluminum sectors. Ammonia should be added as a new commodity to the model, and mapping will occur for all technologies that can generate and use this new commodity. A trade module should be added or linked with a separate model to integrate feedback signals from global hydrogen markets that may drive increased hydrogen production. Lastly, where possible, data scraping exercises should occur to ensure the most relevant and up-to-date techno-economic data is being utilized.

Linkages with other models under the M3 platform will also be explored in the next steps for MESSAGEix-Canada. The purpose of this is to develop a suite of models capable of answering climate policy questions at a range of scales. Such linkages include energy demand growth through the CIMS energy-economy model, economic indicators through the MacroABM economy model, and power system dispatch through the SILVER electricity dispatch model. Also, as part of the M3 Platform, work will be conducted to align MESSAGEix-Canada data to be pulled from the CODERS database, where possible. To this point, the CODERS database will be enhanced to include energy system data relevant to MESSAGEix-Canada and the other energy system models within the M3 platform.

Overall, the development and refinement of hydrogen in MESSAGEix-Canada provides a platform that policymakers, researchers, and stakeholders can utilize to assess and refine hydrogen strategies in response to evolving technological and economic landscapes. By empowering policymakers and stakeholders with transparent tools and scenarios, this thesis advances reproducible evidence-based decision-making in support of Canada's net-zero energy transition. The MESSAGEix-Canada platform provides a robust foundation for continued assessment, policy refinement, and academic collaboration in a rapidly changing hydrogen landscape.

Data Availability Statement

The input data and model code used in this study are publicly available at https://gitlab.com/sesit/message-ix-canada. Comprehensive documentation, including model structure, scenario definitions, and implementation guidelines, can be accessed at https://sesit.gitlab.io/message-ix-canada/model/.

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Appendix

A1: Hydrogen Technology Specification

A1.1 Hydrogen Production Processes:

Steam Methane Reforming (SMR): The model incorporates hydrogen production from SMR, both with and without carbon capture and storage (CCS). SMR plants operate by utilizing methane as an input commodity. An endothermic reaction with steam occurs at roughly 700-1000°C and 15-50 bar to produce carbon monoxide and hydrogen. An exothermic reaction then occurs with the carbon monoxide and steam to produce carbon dioxide and hydrogen [38]. These reactions can be summarized in A1.1 and A1.2.

$$CH4(g) + H2O(g) \rightarrow CO(g) + 3H2(g) \qquad \text{(A1.1)}$$
$$CO(g) + H2O(g) \rightarrow CO2(g) + H2(g) \qquad \text{(A1.2)}$$

Typical CCS for SMR is an add-on absorption technology that occurs post-reaction with roughly an 80% carbon capture rate and an increased overall electricity consumption for the system [39].

Autothermal reforming (ATR): The ATR process is a combination of the steam reforming process and partial oxidation process, making it more thermodynamically efficient than steam methane reforming. The partial oxidation reaction releases heat in an exothermic reaction, which is then used to promote the steam reforming reaction [40]. The chemical reaction can be seen in equations A1.3-A1.5.

$$CH4(g) + \frac{1}{2}O2(g) \rightarrow CO(g) + 2H2(g) \qquad \text{(A1.3)}$$
$$CH4(g) + H2O(g) \rightarrow CO(g) + 3H2(g) \qquad \text{(A1.4)}$$
$$CO(g) + H2O(g) \rightarrow CO2(g) + H2(g) \qquad \text{(A1.5)}$$

CCS for ATR occurs in the same manner as SMR but can capture slightly more carbon at roughly a capture rate of 90% due to nearly all CO2 emissions being present in the process gas stream [41].

Biomass gasification: Gasification is the process of using controlled amounts of oxygen and/or steam to convert carbonaceous materials at temperatures greater than 700°C without combustion into carbon monoxide, hydrogen and carbon dioxide [42]. An example of the process equation can be seen in A1.6 [43].

$$C6H12O6 + O2 + H2O \rightarrow CO + CO2 + H2 + other\ species \qquad \text{(A1.6)}$$

Typical gasification plants also include a further water-gas shift reaction, which combines carbon monoxide and steam to produce carbon dioxide and more hydrogen in an exothermic reaction.

$$CO(g) + H2O(g) \rightarrow CO2(g) + H2(g) \qquad \text{(A1.7)}$$

CCS in a biomass gasification plant is modelled at 90% and utilizes a similar absorption process to that of SMR and ATR with CCS [44].

Coal Gasification: These plants operate in the same process as a biomass gasification plant and are included in the model both with and without CCS.

Methane Pyrolysis: is another technology gaining traction for hydrogen production and is included in the model. This process produces low carbon hydrogen without the presence of oxygen in an endothermic reaction that splits C-H bonds, resulting in Hydrogen and solid carbon [45]. While it is cleaner than traditional methods such as SMR, it does require higher activation temperatures of 800-1600°C. The chemical equation for methane pyrolysis can be seen in A1.8.

$$CH4(g) \rightarrow C(s) + 2H2(g) \qquad \text{(A1.8)}$$

Parameterization for this technology is directly from a gas heating methane pyrolysis design defined in the work conducted by Serrato-Arias and Rowe [46].

Electrolysis: A prominent means of producing clean hydrogen included in the model. Electricity is utilized as an input in this technology to split water into hydrogen and oxygen. For MESSAGEix-Canada, proton exchange membrane electrolysers were utilized for parameterization over other electrolyser technologies due to a higher hydrogen production rate, better energy efficiency, and prevalence in the current hydrogen generation sector [27].

A1.2 Transmission and Distribution of Hydrogen:

As discussed in Chapter 2, Hydrogen transport and distribution is modelled as two linking technologies for the commodity. One technology is parameterized for the transport of gaseous hydrogen, while the other models the transport of liquid hydrogen.

However, hydrogen can be blended with natural gas in the model for use by technologies that utilize the natural gas commodity. Blend ratios are defined by a linear relation in the model called "gas_mix_lim" which provides a limit on the amount of hydrogen that can be blended into the natural gas network from an energy density perspective, not a volumetric blend rate. The model chooses to invest in a technology called "h2_mix" if deemed cost-optimal to blend hydrogen into the natural gas network. The activity of "h2_mix" can be utilized to investigate how much hydrogen blending occurs within the model. The resulting blended gas is not utilized as a new commodity within the model, and instead, the natural gas commodity is still utilized for downstream technologies. However, for emission accounting purposes, the model can account for downstream emission reductions based on the activity of "h2_mix" and where the natural gas commodity is utilized in the linear relation "CO2_cc".

Trade of hydrogen in the model is parameterized for imports and exports between provinces using a high-level approach for model simplification. Provinces can export hydrogen to a new node called “trade_hub” and can import hydrogen from the same hub. Specific modelling of trade across borders was not performed for this work to simplify model development and solve time. There is currently no formulation for international trade in the MESSAGEix-Canada model.

A1.4 Hydrogen Based Fuel Production:

Methanol production from hydrogen is parameterized in the model based on the CO2 hydrogenation process.

$$CO2(g) + 3H2(g) \rightarrow CH3OH(l) + H2O(l) \qquad \text{(A1.9)}$$

Typical reaction conditions include Cu/ZnO-based catalysts utilized at generally 200–300 °C and 3–10 MPa. [47]

Light oil production from hydrogen is parameterized in the model based on the Fischer-Tropsch Synthesis process. This process combines hydrogen and carbon monoxide to produce different hydrocarbon products. While this process can produce a variety of specific products, for simplicity in the model, products from this process have been mapped to the light oil commodity. An example chemical equation for the production of Alkanes can be found in A1.10 [48].

$$nCO + (2n + 1)\, H2 \rightarrow H(CH2)nH + nH2O \qquad \text{(A1.10)}$$

A2: MESSAGEix-Canada Sectoral Demand Calibration

Demand was calibrated as part of the work conducted by Awais et al. [8]. The model calibration process ensured that the model aligned with historical energy balances, sectoral energy trends, and economic drivers in each Canadian province and territory. Population and GDP projections were sourced from Statistics Canada and extended using regression-based methods to provide long-term forecasts up to 2060 (see model documentation for more details). The demand projection workflow can be seen as follows:

Demand-Projection Workflow:

Historical Baseline

1. Compile provincial final-energy consumption (by end-use technology and fuel) from CER, NRCan, and Statistics Canada.

Socioeconomic Scaling & Consistency

2. Apply provincial-level population and GDP projections to scale historical consumption.

3. Solve a small linear program that minimizes the maximum absolute deviation across all projection years, between population-driven and GDP-driven growth rates, to produce a single, internally consistent demand forecast per province.

Useful-Final Energy Mapping

4. The forecasted service demands are mapped to MESSAGEix-Canada final-energy, with fixed efficiency factors for each technology to meet the service demands.

Further details on data sources, SSP-related assumptions, and demand-projection methodologies can be found in Awais et al. [8] and in the energy demand documentation from the International Institute of Applied Systems Analysis.

A3: Clean Hydrogen Investment Tax Credit Implementation

The CH-ITC is eligible to apply to electrolysis, natural gas reforming with CCS and pyrolysis within the model. The applicable technologies and associated reduction in investment cost based on carbon intensity can be seen in **Error! Reference source not found.**. The original horizon of the CH-ITC in the model is applicable until 2035, whereas the extended horizon is applicable until 2060.

Table A3. 1: Mapped CH-ITC Technologies and Percent Reduction in Investment Cost

Technology	Carbon Intensity Tier (kg CO_2e/kg H_2)	% Reduction in Investment Cost
h2_elec	<0.75	40%
h2_pyrolysis	$2 \leq CI < 4$	15%
h2_smr_ccs	$2 \leq CI < 4$	15%
h2_atr_ccs	$2 \leq CI < 4$	15%

A4: Output Based Pricing System Implementation

In MESSAGEix-Canada, the OBPS framework is incorporated by first developing a payable emission intensity. OBPS emission standards are defined by selecting a technology to map to a standard, then utilizing that technology's emission intensity and multiplying by a defined reduction as outlined in the OBPS policy.

Figure A4. 1: OBPS Standard Calculation

A list of a MESSAGEix-Canada technologies mapped to create standards can be found below:

Table A4. 1: OBPS Standard Mapping

Standard	Standard Technology	Description
Mining & Ore Processing, Coal, Sub-bituminous	coal_extr	Coal extraction
Electricity Generation, Solid Fuels	coal_ppl	Coal power plant
Oil & Gas, Natural Gas, Pipeline Quality	gas_extr_3	Natural Gas extraction Cat III
Final Energy, Industry, Feedstock	gas_fs	Natural Gas as an industry feedstock
Final Energy, Industry	gas_i	Natural Gas use in industrial applications
Electricity Generation, Gaseous Fuels, New	gas_ppl	Natural Gas power plant
Oil & Gas, Natural Gas, Transmission	gas_t_d	Gas transmission and distribution
Oil & Gas, Hydrogen	h2_smr	Hydrogen production through steam-methane reforming
Oil & Gas, Natural Gas, Liquids	LNG_regas	Gasification of liquid natural gas
Electricity Generation, Liquid Fuels	loil_ppl	Light oil power plant
Chemical, Petrochemicals, High Value	meth_ng	Methanol production from natural gas
Oil & Gas, Crude Oil, Heavy	oil_extr_3	Crude oil extraction

The difference between the OBPS emission standard and a technologies' emission intensity is the payable emission intensity. For years after 2023, the OBPS standard is decreased by a legislated and mapped tightening rate to further tax applicable technologies in the model, as the policy was designed. For model years past 2035, it is assumed that the policy remains active and tightening rates continue to grow following the same trends as before 2035. However, as with many other aspects of the model, users can vary the tightening rates to explore future scenarios. Where applicable, provinces that have specified their own standards and tightening rates have been mapped and applied. This includes Alberta, British Columbia, New Brunswick, Nova Scotia, Newfoundland and Labrador, Ontario, and Saskatchewan.

Figure A4. 2: Payable Emission Intensity Calculation

This payable emission intensity is then multiplied by the federal carbon price to create a carbon cost that is then applied to the mapped MESSAGEix-Canada technologies for each respective temporal period. Like the OBPS tightening rates, it is assumed that federal carbon price will continue to grow post 2035 at the same specified rate as before 2035, however this can be varied by users should one desire.

Carbon Cost (added to cost per unit of energy produced) = Payable Emission Intensity × Carbon Price

Figure A4. 3: Carbon Cost Calculation

As MESSAGEix-Canada is unable to depict revenue streams, credits must be depicted a different way. When OBPS mapped technologies have a lower emission intensity then the OBPS emission standards a negative "receivable emission intensity" can be defined. The amount of "payable" and "receivable" emission intensities can then be tracked. Through an iterative process, the credit price was varied until supply and demand of credits roughly matched in the model results.

A5: Scenario Learning Rates

Table A5. 1: High Cost Learning Rates (SSP4)

% Reduction in 2100 Cost	**Technology**
0%	h2_coal
25%	h2_smr
25%	h2_bio
25%	h2_coal_ccs
25%	h2_smr_ccs
25%	h2_bio_ccs
0%	h2_elec
25%	h2_atr
25%	h2_atr_ccs
5%	h2_stor_geo
5%	liq_h2
5%	meth_h2
25%	h2_fc_trp
25%	h2_gas_fc_trp
5%	gas_h2

Table A5. 2: Low Cost Learning Rates (SSP1)

% Reduction in 2100 Cost	Technology
40%	h2_coal
50%	h2_smr
50%	h2_bio
50%	h2_coal_ccs
50%	h2_smr_ccs
50%	h2_bio_ccs
20%	h2_elec
50%	h2_atr
50%	h2_atr_ccs
15%	h2_stor_geo
20%	liq_h2
20%	meth_h2
56%	h2_fc_trp
56%	h2_gas_fc_trp
20%	gas_h2

A6: Canada Hydrogen Strategy Announced Projects

Table A6. 1: Canada Hydrogen Strategy Announced Projects Defined In CHS Scenario

Province	Project Name / Location	Type	Assumed Capacity	Source
Alberta	Air Products Edmonton	Blue H_2 (ATR+CCS)	140,000 t/y H_2	[5]
	Suncor/ATCO Heartland	Blue H_2 (ATR+CCS)	300,000 t/y H_2	[49]
	Dow Fort Saskatchewan	Blue H_2 (SMR+CCS)	100,000 t/y H_2	[50]
Ontario	Enbridge Markham	Green H_2 (Electrolysis)	2.5 MW, expansion possible	[5]
	Atura Power (Niagara, Halton Hills)	Green H_2 (Electrolysis)	20 MW total	[5]

	Sarnia-Lambton H_2 Hub (early phase)	Blue H_2 (SMR+CCS)	150,000 t/y H_2	[51]
Quebec	Air Liquide Bécancour	Green H_2 (Electrolysis)	20 MW	[52]
	Varennes Carbon Recycling	Green H_2 (Electrolysis)	90 MW	[5]
	Evolugen and Gazifière Gatineau	Green H2 (Electrolysis)	20 MW	[5]
	TES Canada: Project Mauricie	Green H2 (Electrolysis)	70,000 t/y H2	[5]
Manitoba	Charbone: Selkirk	Green H2 (Electrolysis)	0.5 MW	[53]
British Columbia	HTEC North Vancouver	Green H_2 (Electrolysis)	5 MW	[54]
	FortisBC Prince George	Blue H_2 (SMR+CCS pilot)	10,000 t/y	[5]
Atlantic	EverWind (Nova Scotia)	Green H_2 (Electrolysis)	300 MW phase 1	[5]
	Bear Head (Nova Scotia, planned)	Green H_2 (Electrolysis)	60 MW	[55]