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Deputy Minister | Sous-ministre
Ottawa, Canada
K1A 0E4

Cédric Taquet
Clerk of the Committee
Standing Committee on Public Accounts
Sixth Floor, 131 Queen Street
House of Commons
Ottawa ON K1A 0A6
Canada

Jerry V. DeMarco
Commissioner of the Environment and Sustainable Development
Office of the Auditor General of Canada
240 Sparks Street
Ottawa ON K1A 0G6

Dear Clerk Taquet and Commissioner DeMarco:

I am writing to provide you with updated modelling of the hydrogen opportunity in Canada and its potential role in Canada's net-zero pathway. In conjunction, I would also like to update you on the current progress of the Biennial Report on *A Hydrogen Strategy for Canada* (Hydrogen Strategy). This fulfills a commitment I made to you following the April 2022 Commissioner of the Environment and Sustainable Development (CESD) Report, "Report 3—Hydrogen's Potential to Reduce Greenhouse Gas Emissions", and the December 2, 2022 meeting of the Standing Committee on Public Accounts.

In 2021, the CESD initiated a performance audit on the role of hydrogen in Canada's energy system. The audit was released in April 2022, and noted that Natural Resources Canada (NRCan) and Environment and Climate Change Canada (ECCC) had different perspectives on the role that hydrogen should play to reduce greenhouse gas emissions, and questioned the assumptions in the modelling of hydrogen's potential.

Further, at the Standing Committee on Public Accounts on December 2, 2022, I offered to follow up with additional information on the Biennial Report for the Hydrogen Strategy for Canada.

The CESD provided the following two recommendations for NRCan in the 2022 Audit:

3.34 Natural Resources Canada should perform a comprehensive bottom-up modelling for the use of hydrogen. This modelling should account for the following:

- a. emission reduction efficiencies by sector (cost of emission reductions per megatonne of carbon dioxide equivalent)
- b. substitutional fuels (for example, biofuel, electrification, credit systems)
- c. feasible deployment of technologies and supporting infrastructure

3.35 Based on the updated modelling, Natural Resources Canada, in partnership with interested stakeholders, should publish a hydrogen market development roadmap to track progress and outcomes of the deployment of the hydrogen in Canada.

Recommendation 3.34 has been undertaken by the Department over the past year and is attached, entitled "Modelling Hydrogen's Potential Across Multiple Sectors of the Canadian Economy". The report was conducted by ESMIA, an energy system modelling consultant, and provides updated modelling that will be included and released publicly as part of the Biennial Report for the Hydrogen Strategy.

The original modelling undertaken in 2020 looked at the potential overall opportunity for hydrogen to deliver greenhouse gas (GHG) reductions. The updated modelling uses the North American Times Energy Model (NATEM), a comprehensive energy system model. It is based on similar modelling submitted by Canada as part of its Long-Term Strategy Submission to the United Nations Framework Convention on Climate Change. The model is fuel and technology neutral – energy production and consumption over the time period is assessed through estimated cost-competition across all potential technologies. The model results reflect a simulation of the economy evolving over time, with hydrogen being one energy type that competes directly with all others, including electrification and other substitution fuels.

The updated modelling outlines three primary scenarios, including:

1. ***Technology Neutral*** – a base case with parameters reflecting a neutral approach to the range of values in the literature. Relative to the original modelling done for the Hydrogen Strategy for Canada, this scenario could be considered closest to the 'incremental' scenario.

2. ***Hydrogen Supportive*** – a scenario showing results if more supportive conditions for hydrogen were to exist, such as lowered costs, greater policy support, or technological innovations. Relative to the original modelling done for the Hydrogen Strategy for Canada, this scenario could be considered closest to the 'transformational' scenario.

3. ***Hydrogen Challenging*** – a scenario showing results if more challenging conditions for hydrogen were to exist, such as lesser cost reductions over time, or other policy or technological limitations. There was no equivalent to such a scenario in the Hydrogen Strategy for Canada.

The analysis also explores specific hypothetical scenarios based on market developments that have occurred since the publication of the Hydrogen Strategy. This includes exploring the impacts of significant levels of hydrogen export, greater hydrogen use for space heating in buildings, and greater conversion of natural gas infrastructure to hydrogen.

In conducting the modelling, all assumptions on key data points, including associated emissions, technology performance, technology uptake and cost inputs, were supported by publicly available studies and data sets, and adapted to Canadian technological, temporal and geographical considerations.

Over 90 subject matter experts from across the private sector, provinces and territories, academia, and non-government organizations were consulted on the inputs and preliminary modelling results through three formal engagement sessions and workshops. Experts at ECCC and the Canada Energy Regulator were directly engaged.

Overall, the results indicate that hydrogen can continue to play an important role in decarbonizing hard-to-abate sectors, but that (based on the Export scenario) sector growth and economic benefits may be more likely to be driven by exports. Hydrogen would be projected to remain in competition with other technologies and to best penetrate sectors where the use of other forms of energy, especially electricity, would not be economically or technically feasible.

The results are more conservative than the 2020 Hydrogen Strategy, but consistent with projections by other net-zero studies, including ECCC's Long-Term Strategy and Trottier Canada Energy Outlook. For instance, in this model's supportive scenario, hydrogen consumption would reach 9.3 million tonnes (Mt/H_2) in 2050, compared to 20 Mt in 2050 estimated by the 'transformative' scenario in the Hydrogen Strategy for Canada.

Similar to the Canada Energy Outlook, the model projects substantial production from hydrogen produced from biomass gasification with carbon capture and storage by 2050, likely due to the model's assumption of this pathway providing negative emissions (sequestration credits during plant growth). The Export scenario projects the greatest increase in production from electrolysis.

Regarding GHG emissions, the updated modelling estimates 69 MT of carbon dioxide equivalent avoided and attributed to clean hydrogen consumption in 2050 in the supportive scenario, compared to 190 MT of 'hydrogen decarbonization potential' by 2050 estimated by the Hydrogen Strategy's transformative scenario.

NRCan recognizes that the evolution of Canada's hydrogen sector engages a complex interplay of policy, economic and social considerations across the country. Ongoing work to continually refine our understanding of the trajectory of the industry as it changes over time, relative to the modelling projections, will provide a clearer picture for policymakers of the ultimate role of hydrogen vis-à-vis other decarbonization pathways in Canada's economy. It is noteworthy that this modelling only includes existing policy measures that were in place as of March 15, 2023, and new measures that were announced in budget 2023 were not considered.

In that spirit, while the modelling report represents an important step forward to understanding the role of hydrogen in a decarbonized and net-zero energy system between now and 2050, additional work is ongoing. NRCan will continue to engage stakeholders on the modelling results, and monitor key developments in the hydrogen sector.

The modelling results will also be incorporated into the forthcoming Biennial Report for the Hydrogen Strategy for Canada to be published this year, which will provide a public update on progress and the modelling results, as per NRCan's previously provided plan for addressing CESD recommendation 3.35.

Yours sincerely,

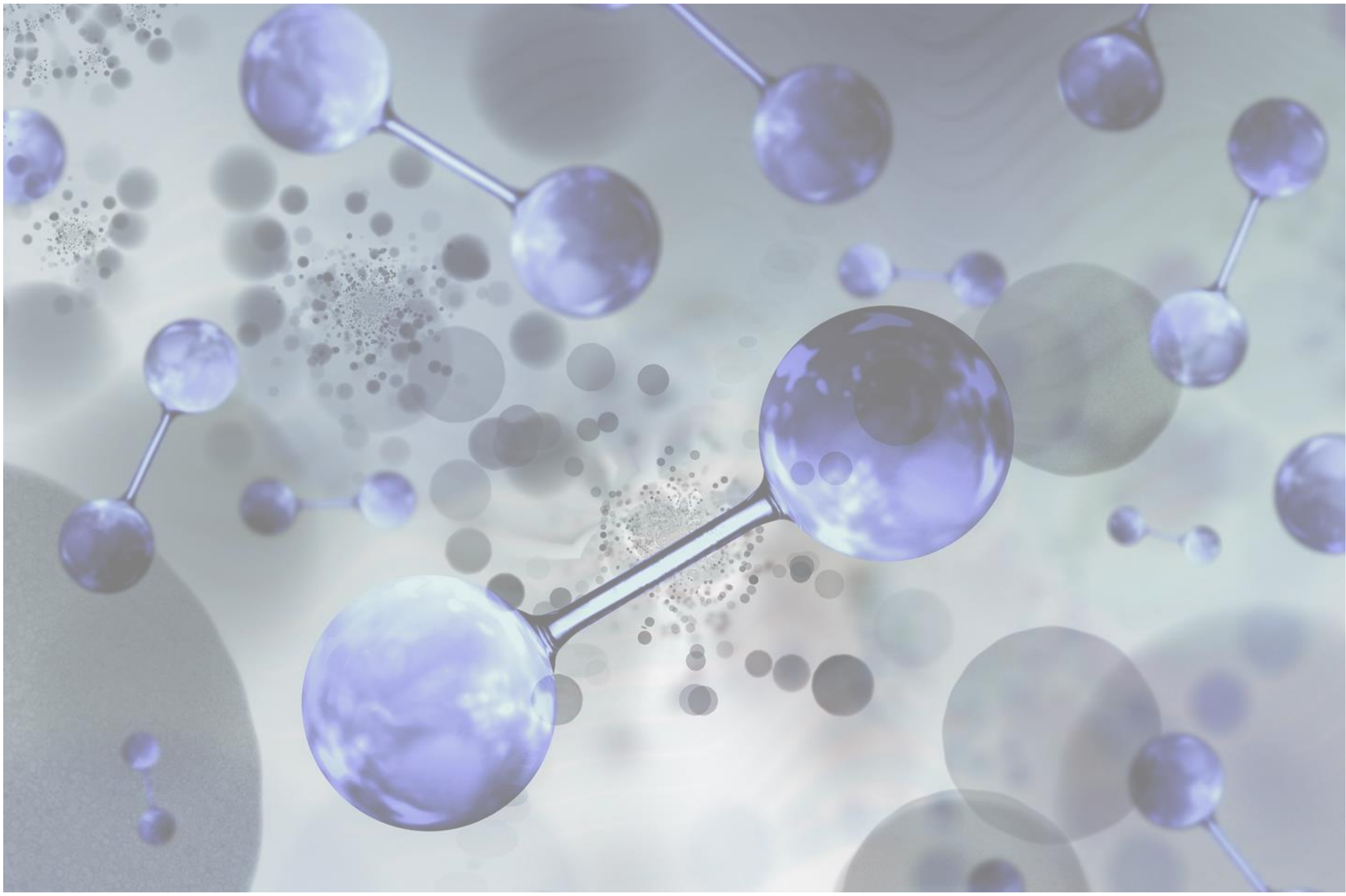
John Hannaford
(he/him/il)
Deputy Minister
Natural Resources Canada

March 20, 2023

Modelling hydrogen's potential across multiple sectors of the Canadian economy

FINAL REPORT

For Natural Resources Canada, Contract No: 3000752048



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ESMIA
Energy Super Modelers
and International Analysts

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.

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All conclusions, recommendations, and opinions are solely the authors’ and are endorsed neither by the financial sponsor of this work nor by the many people who offered comments and suggestions.

It is noteworthy that this modelling only includes existing policy measures that were in place as of March 15, 2023, and new measures that were announced in budget 2023 were not considered.

ACKNOWLEDGEMENTS

The authors are grateful to Natural Resources Canada (NRCan) for the financial support to carry out this project.

The authors would like to thank the people in the energy, engineering and modeling community who provided input and feedback during the term of the project.

All the conclusions, recommendations and opinions are solely the authors, and have not been endorsed by any other party.

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List of abbreviations

CO_2	Carbon dioxide
GDP	Gross domestic product
GHG	Greenhouse gas
IESO	Independent Electricity System Operator
IPCC	Intergovernmental Panel on Climate Change
N_2O	Nitrous oxide
PFCs	Perfluorocarbons
LULUCF	Land use, land use change, and forestry
NIR	National Inventory Report

List of units

GW	Gigawatts (10^9 watts)
Mt CO_2 eq	Million tonnes of CO_2 equivalent
t CO_2 eq/MWh	Tonnes of CO_2 equivalent per megawatt hour
PJ	Petajoules (10^{15} joules)
TWh	Terawatt-hour (10^{12} watt-hour)

SUMMARY

Executive Summary

Context

The purpose of this project is to update the modelling, which was previously undertaken for the Hydrogen Strategy for Canada, to help inform the development of the first biennial Hydrogen Strategy Implementation Progress Report, and broader Government of Canada actions related to hydrogen. The scenario results are intended to be directional in nature since technology development, costs and policy implementation will evolve over time from today's available information. Due to this time-sensitivity, caution is advised for future use of these results.

Natural Resources Canada (NRCan) retained ESMIA Consultants (ESMIA) to provide energy system modelling to explore the potential for hydrogen to support pathways for Canada to achieve its goal of net zero emissions by 2050.

ESMIA's approach for this exploration involved using a detailed energy system model that finds the least-cost path to meeting Canada's economic needs while staying at or below the GHG emissions trajectory to meet net-zero emissions. The model, NATEM, is fuel and technology neutral – each opportunity for energy production and consumption over the time period is assessed through cost-competition across potential technologies represented in the model. NATEM includes over 290 representative technologies for equipment that produces, transports, processes and consumes hydrogen or ammonia, as part of a database of thousands of representative technologies for the full energy system.

The goal of Net Zero GHG emissions by 2050 strongly frames the analysis. Modelling by the Government of Canada, as well as in the United States and elsewhere, have shown the extensive changes across the entire economy and including the use of negative emissions technologies[1] needed by developed countries to meet Net Zero GHG goals (for example, Lawson et al 2021, IEA 2021). This project also projects major energy system changes, independent of the role of hydrogen.

Core Scenarios

ESMIA used contrasting scenarios to test alternate conditions that could support or detract from hydrogen's role in meeting net zero emissions and, importantly, quantify the magnitude of the impacts. The scenarios are designed to test alternate conditions that impact potential hydrogen in Canada and these tests must not be interpreted as representing any Government of Canada future energy policy vision or goals. Elements of the scenarios relate to input assumption uncertainties or gaps due to the still evolving research on hydrogen technology costs and performance over time.

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[1] Negative emissions technologies contribute to carbon-dioxide removals from the atmosphere and consequently generate negative emissions, for example direct-air capture (DAC) and bioenergy with carbon capture and storage (BECCS). Natural climate solutions, such as reforestation, are also negative emissions options.

ESMIA developed multiple scenarios based on feedback from our preliminary modelling that was shared with over 80 participants from federal and provincial governments, industry, and academia. We grouped the scenarios into a set of three core scenarios that meet the objective of the project, plus additional scenarios for added robustness. The core scenarios are:

- *Technology neutral* - This scenario determines the energy system in Canada that reaches the Net Zero GHG emission goals at the lowest social cost. Fuels and technologies compete to meet the needs of the economy and the GHG trajectory. The technology parameters reflect a neutral approach to the range of values in the literature. This scenario assumes no new hydrogen-specific policies, so Canada's proposed Investment tax credit for hydrogen production is excluded.
- *Hydrogen supportive* – For this scenario, more hydrogen-optimistic costs and efficiencies from external literature are used for technology assumptions. We also assume additional actions occur that further reduce capital costs – such actions could be on-going support from federal or provincial governments or greater impacts of research and learning-by-doing than currently anticipated. A subsidy on hydrogen production is applied and the allowable blend for hydrogen with natural gas that is permitted for transport in the current gas pipeline system and for use in gas appliances and equipment is higher than in the Technology Neutral.
- *Hydrogen Challenging* – For this scenario we assume that capital cost reductions due to research and learning-by-doing are limited beyond what is currently forecast for costs in 2025. We also assume lower allowed levels for hydrogen blending with natural gas.

To develop comparable results, all scenarios are subject to the following modelling constraints:

1. Canada's GHG emissions meet Net Zero emissions in Canada in 2050 and follow the same trajectory for annual emissions from now until 2050.
2. Technology choice is determined by the model using its least social cost algorithm.
3. The demands for all goods and services must be met; each scenarios uses the same exogenous input for these demands, but the model will adjust the values based on price elasticities for a limited set of goods and services.

Hydrogen Production

Figure 1 shows both hydrogen and ammonia production by technology type for the three core scenarios.

In 2018, over 3 million tonnes (Mt) of hydrogen were produced in Canada, primarily (97%) from Steam Methane Reforming (SMR) using natural gas and process gas (Okunlola, A, et al., 2021). In 2030, the Hydrogen Challenging and Technology Neutral scenarios show production from SMR without CCS declines slightly but production from Autothermal Reforming (ATR) with CCS and electrolysis using

Polymer Electrolyte Membrane (PEM) technology is added. The Hydrogen Supportive scenario has more hydrogen production from PEM and ATR with CCS, than the other two scenarios.

By 2050, when Canada meets its net zero goals, SMR production without CCS will not be feasible, under the modelled constraints. The three scenarios differ in terms of both total production and the mix of production technologies. Total production is determined by demand as described in the next sections. Equipment using ATR with CCS that was installed by 2030 is still producing at almost the same capacity in 2050 and additional hydrogen needs are met by new PEM electrolysis combined with biomass gasification with CCS. Producing hydrogen using biomass gasification with CCS is assumed to provide negative emissions due to accounting for sequestration credits during plant growth plus storing the CO_2 emissions released from biomass combustion.[2]

Caveat: Current modelling projections show that achieving net-zero targets will require net negative emission options to compensate for the hard-to-abate sectors such as some industrial process and agriculture process emissions (based on the actual knowledge around existing and emerging technologies and based on the options included in NATEM). Important limitations related to net negative emissions from biomass gasification options should be noted. There are reasons for the projected increasing use of bioenergy; primarily it is viewed as being CO_2 neutral; CO_2 emitted during combustion is considered equal to CO_2 absorbed during tree growth. However, there is a lag in the temporal aspects of bioenergy production from the forest sector, as CO_2 releases are immediate when burning wood-based biomass, while corresponding absorption from the atmosphere occurs progressively over future decades of tree growth. This accounting method is the one used by most governments today in preparation of their submissions to the United National Framework Convention on Climate Change (UNFCCC). Also, there are important technology risks because the hydrogen pathway using biomass gasification with CCS is currently not available (to ESMIA’s knowledge) at the commercial scale or even at the project scale in Canada.

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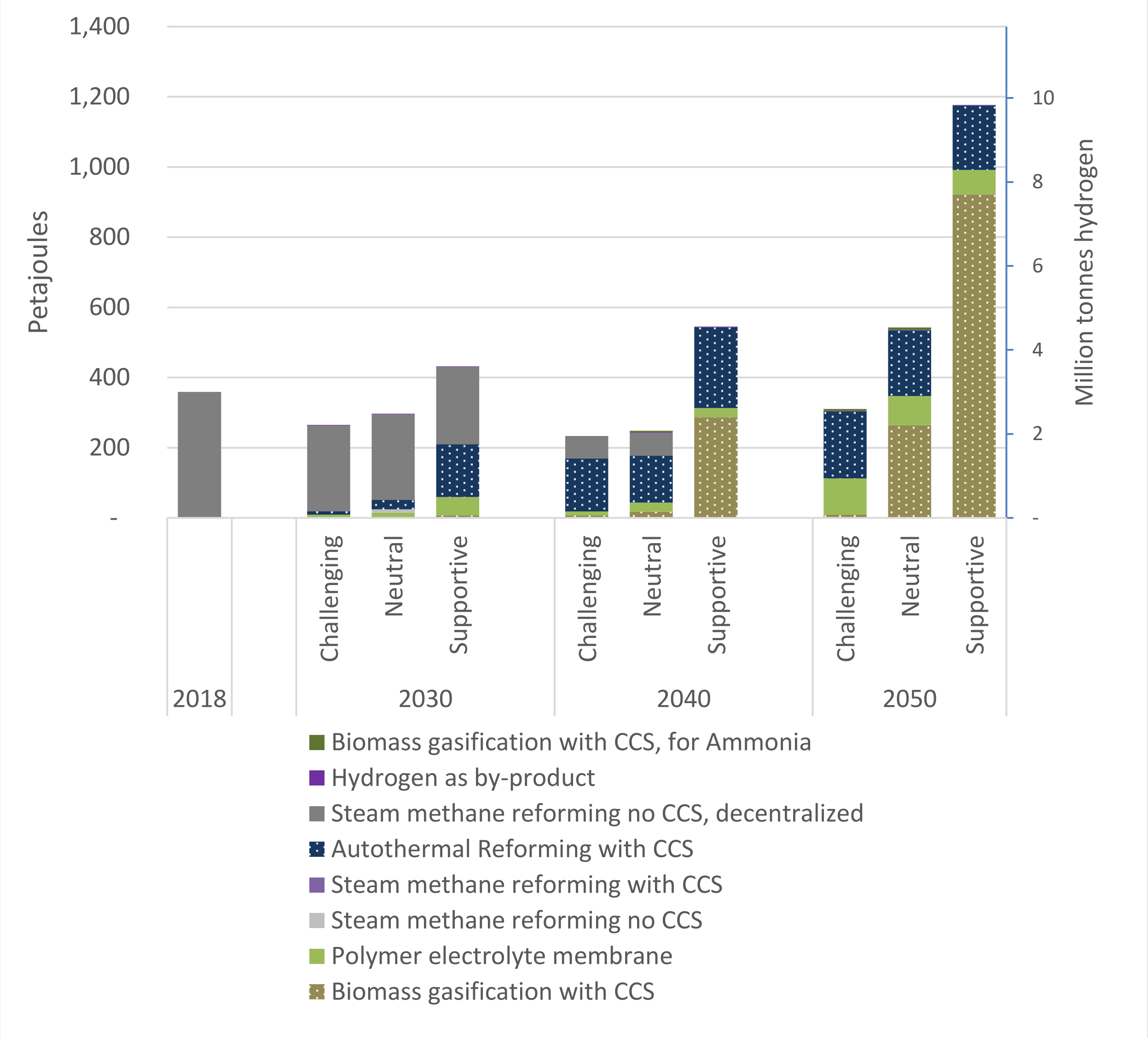
[2] Biomass availability is restricted in NATEM to reflect sustainable sources, using ESMIA’s best reflection of available information. The definition of sustainable biomass is an area of evolving knowledge and only limited review was within the scope of this project.



Notes: Technologies are centralized production of hydrogen unless otherwise noted.
Hydrogen energy is converted from petajoules to million tonnes using the factor 120.1 PJ/Mt.

Figure 1 Hydrogen and Ammonia Production by technology type, 2030, 2040 and 2050 (PJ), existing and new production

Aggregated Hydrogen Consumption

Hydrogen consumed by sector is shown in Figure 2. In the Technology Neutral scenario, hydrogen consumption is projected to reach 3.3 Mt in 2050.[3] While only about 10% higher than in 2018, consumption declines from oil production while increasing for transportation and other industries. The Supportive scenario shows strong growth in hydrogen consumption, where it reaches about 9 Mt.

Currently and in 2030, domestic consumption of hydrogen is dominated by oil production and refining with some use of blended hydrogen in buildings and in transportation in the Hydrogen Supportive scenario, due to that scenario's lower costs for production and demand-side technologies. Demand is projected to decrease through 2040 as the oil production and refining sector has lower use and there is less use of blended hydrogen due to increased electrification leading to lower overall gas demand for buildings and industry. Demand for pure hydrogen occurs mostly after 2040 through industrial demand. This lag is reasonable due to long lived equipment in this sector. In the Hydrogen Supportive scenario, hydrogen demand for transportation is apparent by 2030 and accounts for similar demand as the industrial sector. The buildings sector also contributes to hydrogen demand in this scenario, which has costs set lower than other scenarios to account for the potential of either policies or technology evolution over time. Across these scenarios and years, hydrogen for export is close to zero by design by setting the price that Canadian producers could sell hydrogen at $2/kg (2022$ CAD).

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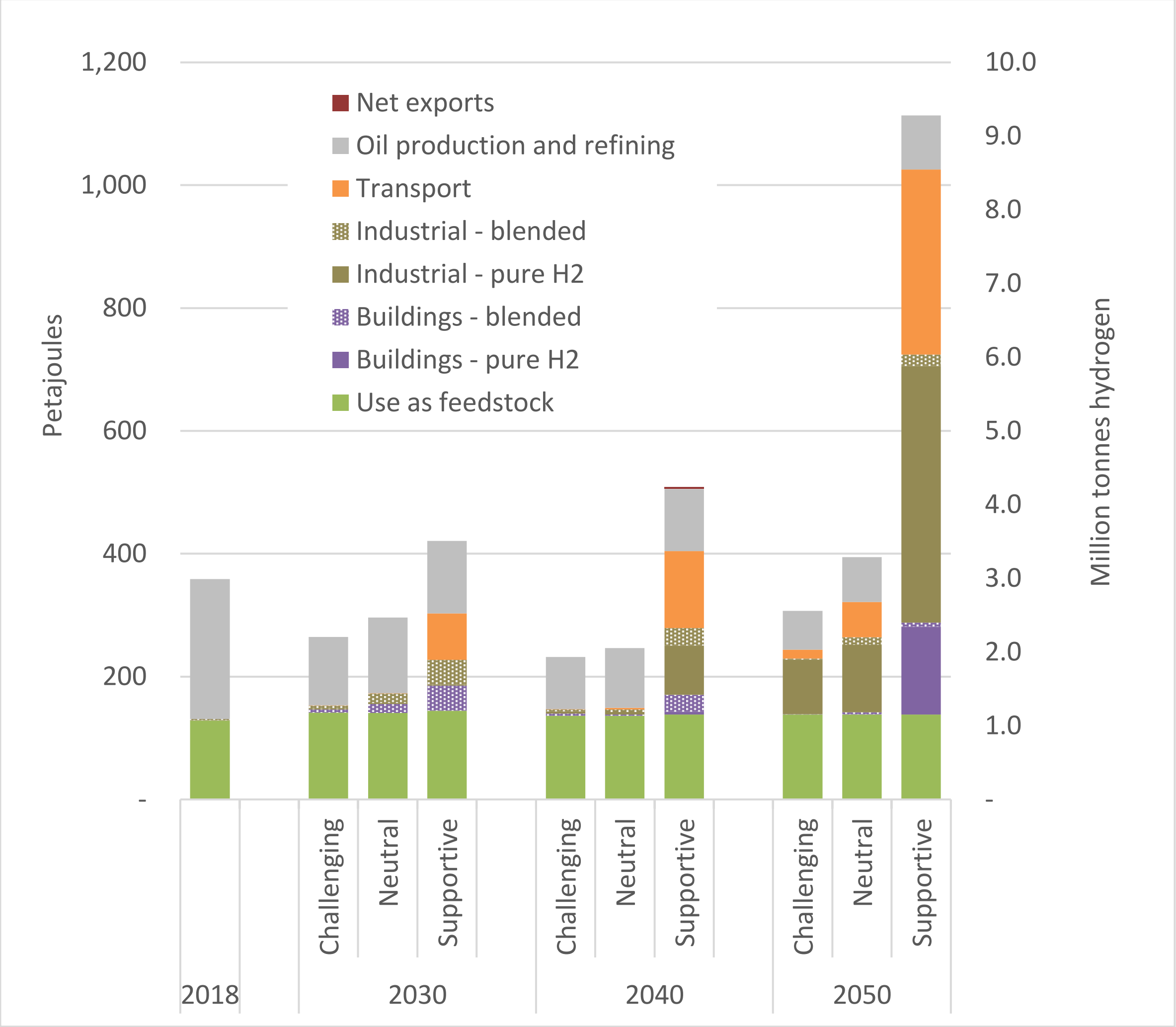
[3] Losses in transporting and storing hydrogen account for the difference between the projected total hydrogen and production values.



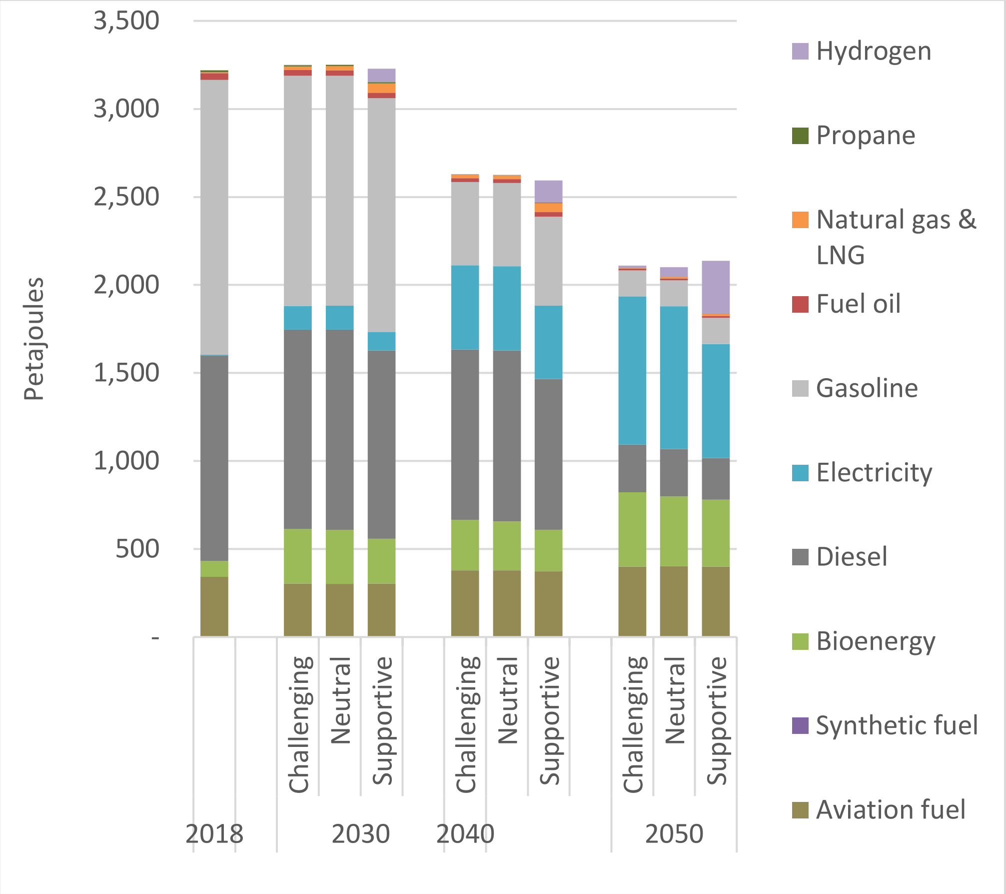
Note: Hydrogen energy is converted from petajoules to million tonnes using the factor 120.1 PJ/Mt.

Figure 2 Hydrogen Consumption by Sector

Transportation Sector

Energy consumed for transportation by type of energy across the scenarios is shown in Figure 3. For these scenarios in 2050, hydrogen consumption as a fraction of total energy consumed is 1% in the Hydrogen Challenging scenario, 3% in the Technology Neutral scenario and 14% in the Hydrogen Supportive scenario.

In the Hydrogen Supportive scenario, medium and heavy-duty trucks are projected to account for the majority of hydrogen consumed in transportation in 2050 (almost 80%). Marine and rail transportation are projected to account for approximately 22% of hydrogen consumed in transportation, but the modelling is less precise for those sub-sectors and additional research is recommended. Due to competition from electric vehicles, the modelling projects almost no hydrogen consumed for light duty vehicles. Hydrogen use in aviation was not modelled, due to lack of available information.



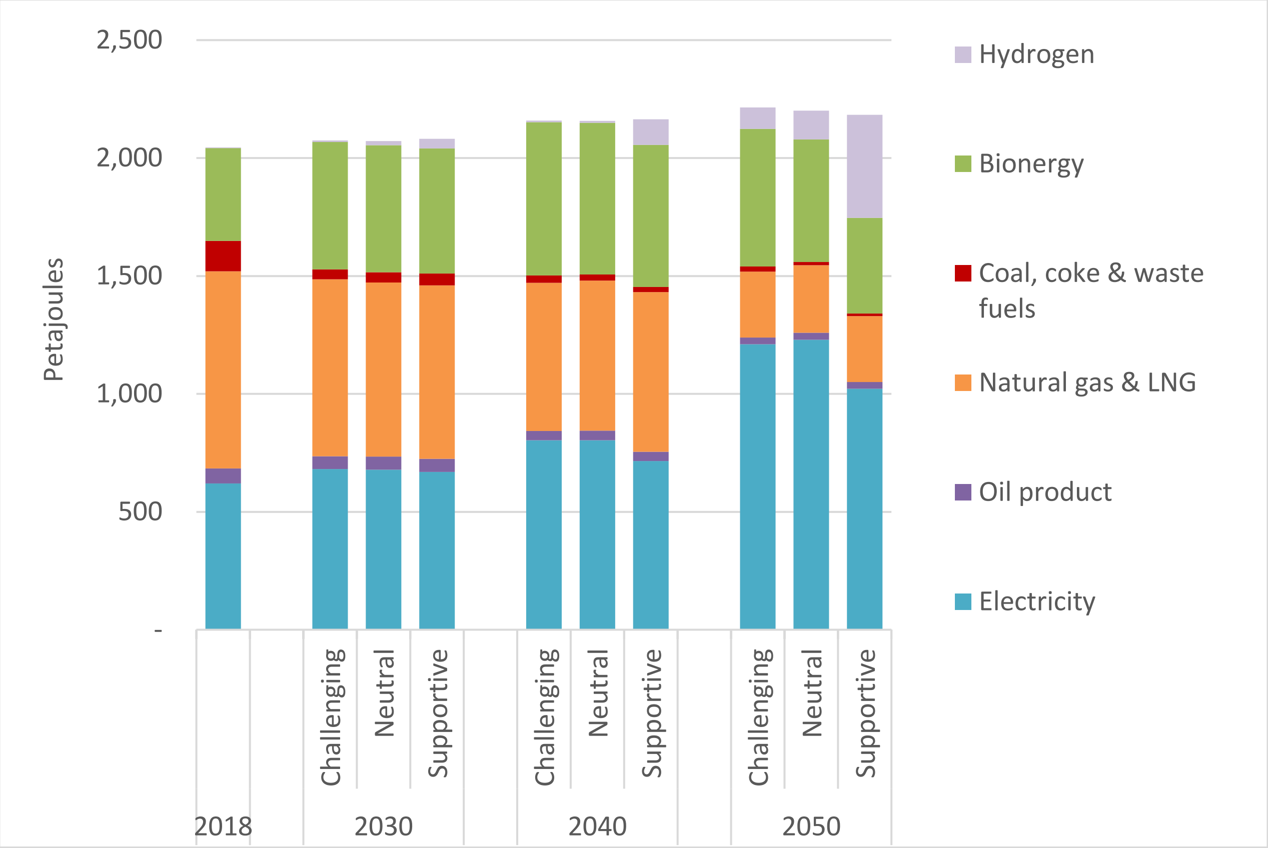
Note: 1 PJ of hydrogen corresponds to approximately 0.008 Mt of hydrogen (lower heating values).

Figure 3 Energy consumption in the Transportation Sector

Industry Sector

Hydrogen consumed for the industrial sector is projected to be limited through 2040 in the Hydrogen Challenging and Technology Neutral scenarios but increases to approximately 5% of total energy consumption in 2050 in both scenarios. The cost reductions included in the Hydrogen Supportive scenario are projected to allow hydrogen to be increasingly competitive with bioenergy and electricity in

2040. By 2050, electricity is projected to dominate energy use in the Hydrogen Supportive scenario, while hydrogen catches up with bioenergy and accounts for 20% of final energy consumed.



Note: 1 PJ of hydrogen corresponds to approximately 0.008 Mt of hydrogen (lower heating values).

Figure 4 Energy consumed in the Industrial Sector

Energy consumed for oil production and refining is excluded from Figure 4 but note that this sector accounts for the majority of hydrogen consumed in 2018 with hydrogen consumption declining over time due to lower volumes of oil production under net-zero GHG goals.

Heating for Buildings

The projections for hydrogen consumed for heating in buildings is low in most scenarios and years, except for the Hydrogen Supportive scenarios in 2050 (see Table 1). Unlike other sectors, hydrogen consumed in buildings, is projected to decrease from 2030 to 2040 in all three scenarios. The model projects that hydrogen consumed in buildings in these scenarios through 2040 will be from hydrogen blended with natural gas and delivered through the existing transmission and distribution system. This amount decreases from 2030 to 2040 due the projected uptake of heat pumps and corresponding decrease in gas consumed in buildings. By 2050, the model projects the build out of transmission pipelines carrying 100% hydrogen. However, the projections show only small uptake of pure hydrogen in buildings in 2050, except under the Hydrogen Supportive scenario, which includes cost reductions for heating equipment using hydrogen.

Table 1 Hydrogen consumption for heat in the Residential and Commercial sectors
(showing consumption in both PJ and Mt of hydrogen)

	2030		2040		2050		
	PJ	Mt	PJ	Mt	PJ	Mt	% of total energy
Challenging	5	0.05	4	0.03	0	0.00	0.0%
Neutral	14	0.12	2	0.02	3	0.03	0.1%
Supportive	41	0.34	32	0.27	149	1.24	5.4%

Additional Scenarios

ESMIA explored additional scenarios to consider hydrogen exports and other scenarios that were suggested during engagement with experts in the field. The scenarios are designed to reflect the several key uncertainties in the current understanding of hydrogen technologies, economic circumstances, and potential public or private sector actions. The uncertainties are grouped into contrasting scenarios for this report.

- *Hydrogen exports (hypothetical)* - Hydrogen export potential is a key consideration for Canadian public and private sectors. However, the uncertainty on exports is even greater than the domestic factors included in the modelling for the other scenarios. We refer to this scenario as hypothetical because the hydrogen production results are tightly linked to the input assumptions used to represent the global market. For this scenario, we set hypothetical prices for Canadian hydrogen exports based on values in Layzell et al. 2020.
- *Pure hydrogen regions (hypothetical)* – this scenario explores conditions where, through a combination of public and private sector actions, certain regions of the country specifically support hydrogen for space heat in buildings. We class this scenario as hypothetical because while studies are underway to explore the feasibility of pure hydrogen communities in Canada (Alberta Innovates (2023), the assessments are not concluded. We model this scenario by limiting the uptake of electricity heating source in certain regions and allowing up to 100% hydrogen in the existing distribution system. Hydrogen heating systems are available at reduced cost for this scenario, using the same values as the *Hydrogen Supportive* scenario. Any additional

transmission needs for transporting hydrogen would be met in the model through building new pipelines.

- *Gas Transmission Retrofit to H2 (hypothetical)* – this scenario considers future conditions that could permit the existing gas distribution and transmission systems to convert to using 100% hydrogen throughout Canada. This scenario is modeled by allowing any existing transmission pipelines to convert to carrying 100% hydrogen, accounting for the additional capital costs for such conversions and energy needs for additional compression requirements.

The Hydrogen Export scenario projects a significant increase in production, relative to either the Technology Neutral or the Hydrogen Supportive scenarios, but note this is based on an assumed price that Canada could receive for selling hydrogen.

The input parameters for both the Pure Hydrogen Regions and the Gas Transmission Retrofit scenarios lead to similar projections of increased hydrogen consumption, with the greatest increase for consumption in buildings, accounting for approximately 9% of total space heating energy use in buildings in 2050.

- Caveats: the increased hydrogen consumption relative to the Hydrogen Supportive scenario is driven by both model parameter changes – increased allowance for hydrogen blending and restricted use of electricity for space heating. The likelihood of these conditions has high uncertainty and the settings for the scenarios are hypothetical. In addition, the scenario is meant to explore the economic potential for conversions and is simplified by allowing parts of system to change incrementally. The modelling does not account for the costs to implement change, such as disruption in energy services during the pipeline conversions.

Discussion

By 2050, hydrogen is projected to play a role to support Canada in reaching its Net Zero GHG goal in all three core scenarios. The modelling projects hydrogen consumption in Canada in 2050, under Net Zero GHG emission aligned conditions, meeting 2% of total final energy consumption in the Hydrogen Challenging scenario, 3% in the Technology Neutral scenario and 12% Hydrogen Supportive scenarios. The range in these scenarios reflects the uncertainties over the next decades related to technology costs and performance and the amount of policy support for hydrogen.

These projections indicate that the potential size of the role depends strongly on the costs of producing and consuming hydrogen, which can be influenced by public sector policies.

By sector, industry and transportation are projected to have the largest potential for increased hydrogen consumption without cost reductions (in the Hydrogen Challenging and Technology Neutral scenarios). The buildings sector becomes a significant hydrogen consumer only in lower hydrogen cost settings of the Hydrogen Supportive scenario and only by 2050.

- Technology evolution from today's costs to that projected in the literature accounts for about 30% increase in consumption (comparing the Hydrogen Challenging to the Technology Neutral scenarios)
- Further technology evolution combined with policy support is projected to increase hydrogen consumption by nearly three times (Comparing the Hydrogen Supportive to the Technology Neutral scenarios).

The technologies projected to produce hydrogen change over time, based on hydrogen consumption requirements, and the support (of lack) for cost reductions as represented by the different scenarios Over time and with higher hydrogen consumption, production from equipment with lower GHG emissions replaces the production of current equipment. Production from biomass gasification with CCS plays a large role in 2050 in scenarios with greater hydrogen consumption. This result must be treated with caution though. In this analysis, producing hydrogen using biomass gasification with CCS is assumed to provide negative emissions due to accounting for sequestration credits during plant growth plus storing the CO_2 emissions released from biomass combustion. Further feasibility analysis is required for the GHG-accounting methods and for this technology, in particular.

Implications for Hydrogen Policy Development

Although not the focus of this hydrogen research, modelling and analysis, an obvious conclusion is that for Canada to reach Net-Zero GHG emissions by 2050 a large transformation of the energy system is required. Public and private sector will need to integrate this thinking in their strategies, including risk assessments, regardless of their roles in the hydrogen energy pathway.

- If Canada's goal of Net-Zero GHG emissions by 2050 is changed, with increased or decreased stringency, the results in this analysis will need to be revised.

With the goal of reaching Net-Zero GHG emissions at the least social costs, hydrogen production and consumption are projected to remain near current levels due to competition from other low (or negative) GHG options, unless hydrogen technologies achieve capital cost reductions and technology evolution.

- Such changes to hydrogen equipment would likely need to be supported by hydrogen-focused public and/or private sector actions in Canada and elsewhere, based on a current review of literature that projects costs and performance of future hydrogen equipment.
- The capital cost reductions tested here cover the full hydrogen energy path and with at least 20% capital cost reductions for hydrogen consuming equipment, combined with cost reductions for hydrogen production equipment, provisions for existing pipelines to carry hydrogen (blended with natural gas or pure) and the policies to reach Net Zero.[4]

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[4] For this modelling, any policies needed to reach Net Zero GHG emissions in 2050, beyond those currently implemented or announced with sufficient details, are represented by a cap on economy-wide GHG emissions. This is a modelling simplification for this project and not a policy direction or recommendation.

- Lower levels of policy support on any of these elements would lead to lower hydrogen production and consumption.

This analysis, by design, did not cover new hydrogen-specific policies and is not an impact analysis of government proposed policy directions. The results provide indications of the financial level of support that could be needed to increase hydrogen consumption and production in Canada, based on the assumptions in this project. Note the modelling includes representation of the details of current and announced policies, including the Federal fuel charge and Industrial climate pricing policies, Clean Fuel Regulation, Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles, Clean Technology Investment Tax Credit and Investment Tax Credit for Carbon Capture, Utilization and Storage. The proposed federal Investment Tax Credit for hydrogen production is not included.

The model results indicate potential role for Canada as a hydrogen exporter, depending on global hydrogen prices, which will be influenced by both demand for and supply costs of hydrogen in other countries.

The projections indicate hydrogen can play a role in supporting the achievement of Net-Zero GHG emissions in Canada, but its role in overall meeting Net-Zero emissions targets is as a supportive rather than dominant energy source for most end-uses, based on the assumptions in this analysis.

- Public or private sector actions (by Canada and others) will impact the extent of hydrogen's role.
- Goals for both hydrogen production and consumption should be clearly articulated as increasing both may be less beneficial.
- Government may consider stating goals on other roles for hydrogen, such as supporting existing energy infrastructure (gas pipelines) or providing new energy exports, separately from GHG emissions goals.

SECTION 1

2. Context and Assumptions

1.1. Context

The purpose of this project is to update the modelling, which was previously undertaken to inform the Hydrogen Strategy, to help inform the development of the first biennial Hydrogen Strategy Implementation Progress Report, and broader Government of Canada actions related to hydrogen.

Natural Resources Canada (NRCan) retained ESMIA Consultants (ESMIA) to provide energy system modelling to explore the potential for hydrogen to support pathways for Canada to achieve its goal of net zero emissions by 2050.

Net-zero emissions means that any GHG emissions released into the atmosphere are offset by carbon dioxide removals. Removals can include natural carbon sinks such as wetlands and forests, or sequestration using emerging technologies like carbon capture, use and storage (CCUS) (ECCC 2022c p. 4).

ESMIA's approach for this exploration involved using a detailed energy system model that finds the least-cost path to meeting Canada's economic needs while staying at or below the GHG emissions trajectory to meet net-zero emissions. The model is fuel and technology neutral – each opportunity for energy production and consumption over the time period is assessed through cost-competition across potential technologies represented in the model (subject to physical constraints on resource and technology availability). Energy production and consumption in the model results reflect a simulation of the economy evolving over time with millions of individual decisions on equipment purchases and retirement leading to an evolving technology mix. Hydrogen is one energy type that competes directly with all others.

For this study, we ran the model to explore possible energy futures using contrasting scenarios. The different scenarios to test the conditions that could support or detract from hydrogen's role in meeting net zero emissions and, importantly, quantify the magnitude of the impacts. **The scenarios are designed to test the conditions that impact potential hydrogen in Canada and must not be interpreted as representing any Government of Canada future energy policy vision or goals.**

Relative to other energy service models, NATEM's unique features are:

- It is an optimization model – it seeks the lowest cost set of technologies, from a social perspective.
- It has the most extensive technology database of any energy system model in Canada; and
- It uses partial equilibrium when solving account for economic impacts of different technology mixes.

Additional information on NATEM can be found in Section 1.4 and Annex A.

The modelling by ESMIA meets the needs of NRCan for hydrogen consideration by considering:

- multiple supply and demand sectors,
- explicit equipment characteristics (technology readiness, capital, operating costs, energy use, GHG emissions, lifespans),
- the regionally diverse[5] energy systems in Canada, and
- the time frame through 2050, with reporting in years 2030 and 2040.

All modelling requires simplifications and judgements on the level of details included. Caveats for this work, common to most energy system modelling, are:

- It represents directional analysis based on ESMIA’s collection of available information at the time of modelling. The project included meetings and feedback from federal and provincial government employees, academics and other researchers, and industry for review of input and requests for information updates but does not claim to be comprehensive.
- Representative technologies are used along with proxies for actions by the public or private sectors for modelling purposes. As work continues on hydrogen and net-zero GHG emissions goals, input assumptions and parameters will need further review and possibly adjustment as better information becomes available.
- Although life cycle assumptions were considered to the extent possible, the scope and time available did not enable a full life-cycle analysis in alignment with the Government of Canada lifecycle assessment model. In particular, the GHG emissions reported reflect GHGs emitted in Canada and do not account for GHGs emitted for production of commodities imported to Canada.
- This point in time modelling should not be considered outside the broader context of broader Hydrogen Strategy modelling and documentation.

See Section 1.3 on limitations particular to NATEM and this project.

1.2. Modelling Approach

The modelling approach for this study balances three key drivers:

- The transformation needed in Canada to meet Net Zero GHG emissions, recognizing the limitations of projections over multi-decade timeframes.
- The relative immaturity of hydrogen as an energy source and a trade commodity leading to a wide range potential development pathways; and
- The complexity of developing policies for technology development that are fair and avoid unintended consequences.

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[5] Although NATEM represents the economic structure and resources of each province/territory, providing regional results is out of scope for this project.

As agreed with NRCan, we used the following hybrid approach for this study.

"Bottom-up" technology and energy system model - The uncertainty on how the hydrogen system would develop in Canada is addressed through the energy system representation in NATEM that accounts for the necessary physical and economic flows of such a system. The pathway and technology choices that ESMIA input to NATEM are the potential steps for creating the hydrogen energy system and the model chooses the most effective combination of steps in each scenario.

Limited representation of detailed and comprehensive Hydrogen policies/actions - the potentially complex design of hypothetical policies is not included in this work. Instead, simplified representations of the impacts of the policies tested are input to the model. The model results are then discussed in terms of possible policy settings (such as tax credits, production subsidies, grants, and research and development goals for technologies), with order of magnitude quantification, noting that future policy designs will reflect the values of society and those actors implementing the policies. For example, one model parameter is a capital cost subsidy and there are many different policy settings that could lead to a reduced capital cost for hydrogen technologies. The analysis does not include assessing the individual potential policies. Note that throughout the project, ESMIA tested the impacts of different types and levels of model parameter and shared the results through meetings with the NRCan technical authority and many other stakeholders. These model runs informed the set of actions included in the scenarios for this work.

"Top Down" GHG constraint - the Net Zero GHG requirement is met by setting a GHG constraint for the model that ensures Canada's goal is met by 2050. The selection and modelling of a multitude of potential policies that could be applied for the full economy needed to meet this goal are beyond the timelines available for this work. Using an optimization model and an economy-wide GHG constraint inherently assumes that the majority of decision-makers are aligned on this goal and that public and private sector actions seek cost-effective policies and actions.

1.2.1. Hydrogen's Technology Development and Modelling

Hydrogen has been used in Canada for years but in limited applications and lacks widespread infrastructure for transportation. Recently however, interest and research has led to an expansive literature and multiple feasibility studies in Canada. ESMIA uses such public literature to define representative technologies, but we note that not all studies can be reviewed and included in this report. To check our approach, ESMIA shared the NATEM's set of representative technologies for hydrogen and the model framework for the hydrogen system with a set of technical experts[6] for

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[6] As reported in Annex E, experts invited to participate in this review are from the following areas: Federal government (40), Provincial government (32), Academic and Non-government Organizations (11), Private sector (41).

feedback, which has led to updates to NATEM's technology database. See section 3 for more information on the technologies and representation.

1.2.2. Hydrogen Policy Representation

The objective of the analysis is to explore the potential of hydrogen to contribute to net zero pathways. Input to the Government of Canada from NRCan's hydrogen working groups[7] indicated that developing a wide-spread hydrogen system in Canada in the next 20 years is likely to require public sector support. Actions by the United States government also indicate a need for public support. In particular, the United States implemented the Inflation Reduction Act in August 2022 which offers tax credits for hydrogen production, energy storage (including hydrogen), clean vehicles and alternative fuel stations (The White House 2022). The United States has set research goals and provided funding since 2021 for advancing clean hydrogen production with the Hydrogen Shot initiative (US Office of Energy Efficiency & Renewable Energy (no date)).

Canada has also developed programs that support hydrogen production and use. Many sectoral and cross-sectoral pricing policies that aim to reduce GHG emissions will provide benefits (or lower costs) to hydrogen consumption due to its zero GHG combustion. Programs providing investments for hydrogen projects include the Clean Fuels Fund, Zero Emission Vehicle Infrastructure, Strategic Innovation Fund – Net Zero Accelerator, and others. These programs are mostly project specific with goals of advancing technology performance. Canada is expected to announce a Clean Hydrogen Investment Tax credit in Spring 2023, but the details were not available in time for this analysis.

ESMIA represented major existing and announced (if sufficient information available) energy and climate policies, including hydrogen-specific policies in NATEM. See Section 3.1 for the list of policies included and approach, which aligns with ECCC modelling (ECCC 2022b).

Both the Canadian and US hydrogen-specific policies appear to be focused mostly on research and subsidies[8]. ESMIA's scenarios (see Section 3.1) also test out actions or policies of this type (subsidies and research), but we provide only a few examples to test order of magnitude impacts. We do not specify exact policy or program details for potential new government action. This follows from the objective to explore options rather than having a pre-determined policy to assess.

1.2.3. Net Zero GHG Emissions

This analysis explores the potential for hydrogen to help Canada meet its goal of Net Zero GHG emissions by 2050. See the text box below that describes modelling by the Government of Canada

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[7] Available by request from NRCan.

[8] By hydrogen-specific policies we consider those that support the production or consumption of hydrogen as a commodity, rather than policies aimed at low GHG solutions.

regarding the path to Net Zero. Modelling in the United States and elsewhere have shown the extensive changes, including the use of negative emissions technologies,[9] needed by developed countries to meet Net Zero GHG goals (for example, Lawson et al 2021, IEA 2021). The Canadian Energy Regulator (CER) has been developing scenario analysis consistent with Canada achieving net zero GHG emissions by 2050. The report release is expected in Spring 2023 but was not available at the time of ESMIA's analysis (CER 2022).

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[9] Negative emissions technologies contribute to carbon-dioxide removals from the atmosphere and consequently generate negative emissions, for example direct-air capture (DAC) and bioenergy with carbon capture and storage (BECCS). Natural climate solutions, such as reforestation, are also negative emissions options.

What does Net Zero GHG emissions in Canada mean?

Excerpts from Canada's Long-Term Strategy (LTS) Submission to the United Nations Framework Convention on Climate Change (ECCC 2022c)

In June 2021, the Canadian Net-Zero Emissions Accountability Act (the Act) received Royal Assent, legislating Canada's 2030 NDC[10] and target of net-zero emissions by 2050 (p. 2).
Canada's LTS uses a "top-down" approach where emissions are capped at net-zero by 2050 and the model determines the most economically desirable path to achieve this, based on the enabling assumptions (p 19). The LTS presents illustrative [approaches to 2050 based on modelled] scenarios that consider key enabling conditions that could play an important role in reducing emissions across all sectors of the economy: widespread electrification, increased use of renewable and alternative fuels, and increased use of engineered CO2 removal technologies, such as carbon capture and storage (CCS) technologies. (This report] is not policy prescriptive, and does not identify the range of policies, measures and regulations that would be undertaken (p. 3).

Table 4: Canada Emissions by Sector in 2020 and 2050 in MtCO2e – All scenarios

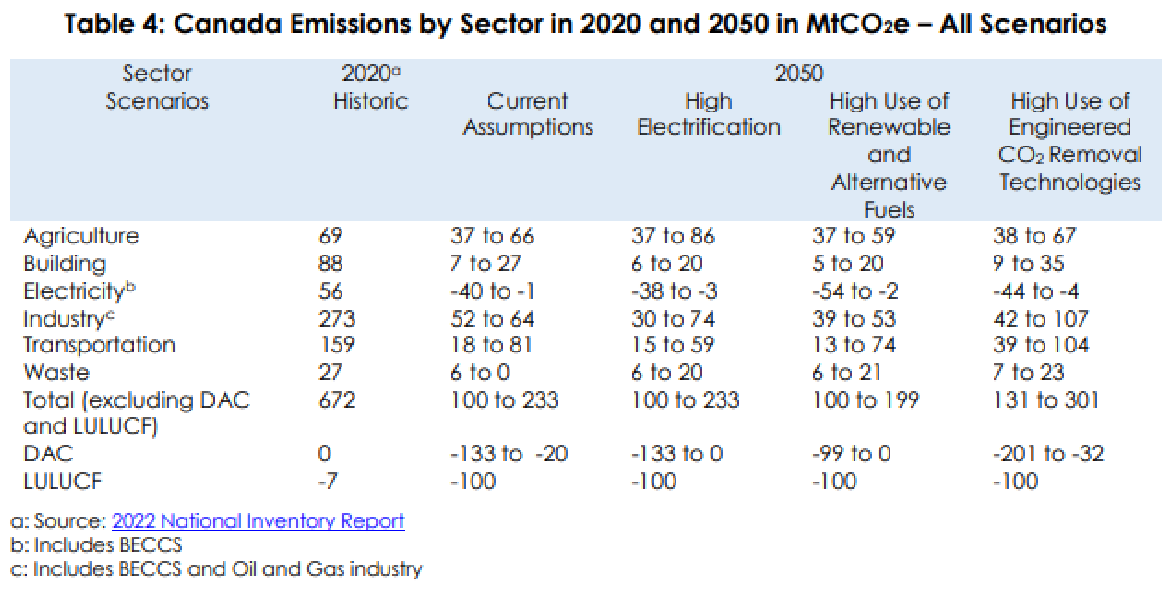

Table 4: Canada Emissions by Sector in 2020 and 2050 in MtCO$_2$e – All Scenarios

Sector Scenarios	2020[a] Historic	2050 Current Assumptions	High Electrification	High Use of Renewable and Alternative Fuels	High Use of Engineered CO$_2$ Removal Technologies
Agriculture	69	37 to 66	37 to 86	37 to 59	38 to 67
Building	88	7 to 27	6 to 20	5 to 20	9 to 35
Electricity[b]	56	-40 to -1	-38 to -3	-54 to -2	-44 to -4
Industry[c]	273	52 to 64	30 to 74	39 to 53	42 to 107
Transportation	159	18 to 81	15 to 59	13 to 74	39 to 104
Waste	27	6 to 0	6 to 20	6 to 21	7 to 23
Total (excluding DAC and LULUCF)	672	100 to 233	100 to 233	100 to 199	131 to 301
DAC	0	-133 to -20	-133 to 0	-99 to 0	-201 to -32
LULUCF	-7	-100	-100	-100	-100

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

p. 34

Key Takeaways
Canada's LTS modelling demonstrates first, that widespread electrification of sectors— such as industry, buildings, and transportation—will likely be essential for reaching net zero emissions. To achieve this, large increases in electricity generation from non-emitting sources (e.g., hydropower, wind, solar, and nuclear) would be required. Second, energy efficiency measures beyond electrification across the economy are likely to be crucial, with total energy use in the industry, buildings, and transportation sectors decreasing in all scenarios, despite a growth in population and output. Third, clean, alternative fuels such as bioenergy and hydrogen could play important roles in

the pathway to net-zero emissions, especially in areas that are difficult to electrify, but electricity would likely dominate these fuels in most scenarios. Fourth, fossil fuel demand in Canada is found to decrease across all scenarios. Lastly, modelling results suggest that the usage of negative emissions technologies have a role to play in a net zero emissions context. Residual emissions are likely to occur in sectors like transportation and industry, which are more challenging to decarbonize. **To account for these emissions, removals from a combination of BECCS and DAC are found to play key roles in all modelled scenarios, with the exception of two modelled runs where it is projected that net-zero emissions could be achieved without DAC.**

ESMIA employed a similar approach as the LTS modelling, with a focus on conditions that could impact hydrogen production and consumption within the Net Zero GHG emissions goal. For ESMIA's modelling, we applied a constraint on national GHG emissions that is the same for all scenarios. This GHG constraint drives much of the large energy system evolution over the 2030 to 2050 period. The large-scale change in energy system evolution in our results is similar to other modelling analysis for Canada (see text box).

The GHG constraint is shown in Figure 5, along with Canada's actual emissions from 2005 to 2020 for context. The modelling approach is to:

- Calibrate the model to actual GHG emissions in 2020, the most recent year available. Source is Canada's National Inventory Report 2022 (ECCC 2022d);
- For 2021 to 2035, match the GHG constraint to emissions reported in the For Additional Measures case of ECCC's latest forecast, *Canada's Eighth National Communication and Fifth Biennial Report on Climate Change.* (ECCC 2022b);[11]
- For 2050 emissions, assume that 28 Mt CO2e will be captured through actions that are not included in NATEM. NATEM excludes LULUCF emissions. This assumption was provided by ECCC based on analysis for their GHG forecast and extending through 2050 (personal communication, email to Alison Bailie from Government of Canada on March 3, 2023); and
- For 2036 to 2049, we assumed an annual linear decline in emissions to 2050.

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[10] NDC – Canada's enhanced Nationally Determined Contribution (NDC) is the 2030 greenhouse gas (GHG) emissions reduction target of 40-45 per cent below 2005 levels.

[11] ESMIA develops its own reference case projections for Canada but is using Canada's official submission to the UNFCCC as the basis for the work here.

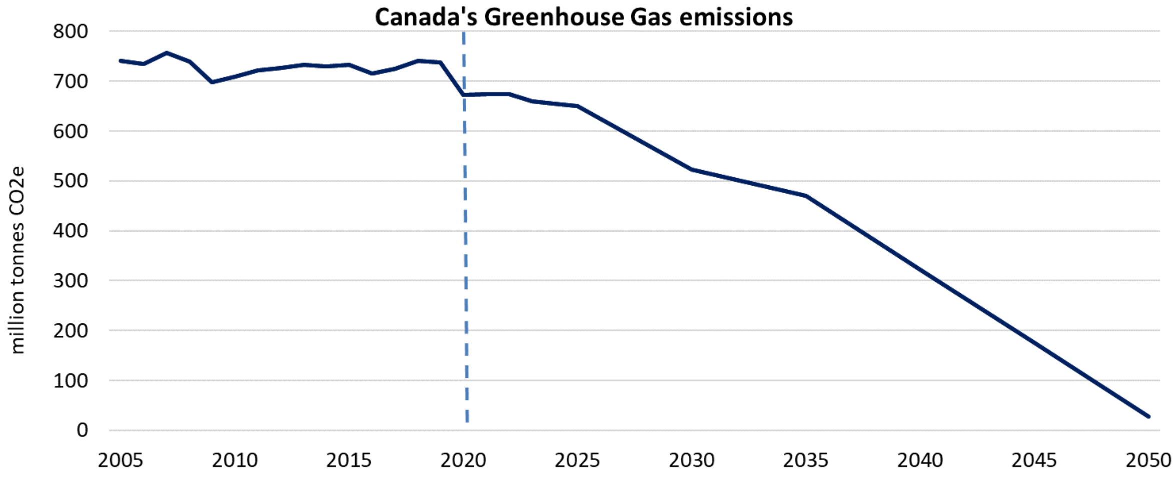

Figure 5 Canada's GHG emissions for this analysis
(2005 to 2020 are actual reported values, 2021 to 2050 represent the constraint input to the model)

1.3. Modelling Limitations and Further Research

As noted in the caveats in Section 1.1, this project uses the information that ESMIA was able to collect within the timeline of this project for input and assessment in the NATEM. Only a limited set of scenarios could be included in the resources available. Further analyses of hydrogen options are expected in the future as NRCan continues to assess progress through biennial Hydrogen Strategy Progress Reports.

The most important limitations for this study are:

- The scenarios explore actions that could result from government policies (such as capital cost reductions) through a combined economic and environmental (GHG) lens. But detailed policy designs that would be needed for full assessment of particular policies were beyond project scope.
- Detailed macroeconomic modelling approach has not been applied to provide a comprehensive and consistent list of macro economic variables across all sectors. Indicators have been used to estimate possible number of jobs created by the hydrogen economy across scenarios, but caution is advised on the narrow focus and large uncertainties.
- Not all the feedback received about key technology assumptions could be included – due to the lack of consensus, and the project timeline, especially for performing multiple model iterations.
- Some hydrogen-related technologies are missing. While NATEM includes the most comprehensive list of technologies, there are always new technologies that could be added in the database and that are part of future work. This study excludes:
    - Retrofit of gas-based appliances to hydrogen appliances and new hydrogen appliances for the building sector (other than space heating boilers),

    - Electricity generation via hydrogen-fuelled turbines (electricity generation from hydrogen fuel cells is included as a technology option). Consequently, the role for hydrogen as a seasonal grid balancing option in jurisdictions with limited other options could be underestimated.
    - Some emerging hydrogen production pathways such as methane pyrolysis and anion exchange membrane (AEM) electrolysis.
- Possible hydrogen leakages across the value chains are not considered.
- Spatial disaggregation within NATEM is limited to the 13 Canadian jurisdictions, but not below (intra-jurisdictional level). Providing results for individual provinces and territories is beyond the project scope.
- The study timeframe did not allow ESMIA to perform detailed sensitivity analysis on all uncertain parameters, amongst those suggested by stakeholders are:
    - technical attributes of technologies such as efficiency, construction time, lifespans, capacity factors, etc.
    - carbon capture rates for specific technologies,
    - cost and potential for upgrading existing gas transmission and distribution network to pure hydrogen,
    - international energy demands and prices for hydrogen and ammonia as well as for fossil fuels, renewable energy, materials (iron and steel, etc.),
    - amount of GHG reductions coming from natural solutions and consequently not part of the GHG target on the other sectors,
    - fugitive emissions along the gas and hydrogen supply chains,
    - respective roles for methanol, ammonia and LOHC, as well as their techno-economic attributes for an optimal market penetration, and
    - buildout rates for the electricity generation capacity mix in relation with potential lack of workforce or imported material.
- Social acceptability constraints of technologies or policies were not investigated in detail.

1.4. The North American TIMES Energy Model (NATEM)

For this project, the Canadian module of the North American TIMES Energy optimization Model (NATEM) was used. NATEM-Canada represents the entire integrated energy system, as well as non-energy emitting sectors for the 13 Canadian provincial and territorial jurisdictions. The unique aspects of each province and territory are included in the model by calibrating all energy to existing resources and future potential. Commodity flows and GHG emissions are calibrated to existing data sources up to 2020, capturing the existing electricity, natural gas and oil supply and distribution systems. The development opportunities in each province and territory are also represented by, for example, non-renewable and renewable resource availability over time.

Note: Biomass availability is restricted in NATEM to reflect sustainable sources, using ESMIA's best reflection of available information. The definition of sustainable biomass is an area of evolving knowledge and only limited review was within the scope of this project.

The model provides a rigorous analytical basis for deriving least-cost solutions for meeting economic needs, social policies and GHG mitigation targets. NATEM-Canada is part of a larger framework covering all North America. Our comprehensive database of technologies for Canada, makes this framework ideal for exploring net-zero targets. See Annex A for a brief overview.

The inherent flexibility with NATEM provides a large range of energy and climate policy-relevant investigations. NATEM model's results have been used by decision makers from public and private organizations and results have been accepted in leading peer-reviewed journals.

1.5. Economic Context

The macroeconomic variables, gross domestic product and population growth that were used for all scenarios were obtained by request from the Canada's Energy Regulator (CER), who provided ESMIA with preliminary projections for inclusion in this report.[12] The values are not direct inputs into the NATEM model, but rather are used to derive a series of initial demands for energy services.

While it is preferred that the economic growth and energy prices come from the same case study, CER was unable to provide an updated set of energy prices for a Net Zero case in the timeframe required for our modelling. ESMIA chose to use CER projections as a base for our work, which required aggregating preliminary CER macro-economic projections from 2023 with the world oil and gas prices from CER's 2021 Evolving Policies case.

World oil & gas prices that are used in all our scenarios for export prices are provided in Table 2, using prices from the CER's 2021 Energy Futures, Evolving policies case.

Table 2. Projections for World Energy Prices (CAD22$/GJ)

	2020	2025	2030	2035	2040	2045	2050
Crude oil - Brent	8.89	12.77	11.52	10.80	10.09	9.38	8.67
Crude oil - WTI	8.44	11.86	10.60	9.89	9.18	8.47	7.75
Crude oil - WCS	5.56	9.01	7.75	7.04	6.33	5.62	4.90
Natural gas	2.22	3.76	3.88	4.08	4.28	4.35	4.42

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[12] Canadian Energy Regulator (2023). Personal communication provided to ESMIA. CER plans to publish updated projections in its Energy Futures report to be released in 2023.

Liquified natural gas	6.35	7.89	8.01	8.21	8.41	8.47	8.54

Source: Converted from CER - Canadian Energy Regulator (2021). Canada’s Energy Future 2021, Evolving Policies.

SECTION 2

3. Hydrogen in NATEM

This section covers the representation of hydrogen in NATEM, including how hydrogen production and consumption technologies are represented in the many sectors. We also provide a summary of technology characteristics and the references that ESMIA used as input for technology attributes.

2.1. Hydrogen in NATEM's Energy System

NATEM covers the full energy system from resource extraction to energy use by consumers (see Annex A). Technologies exist at commercial or near commercial stages for a wide range of hydrogen pathways and we have included representative technologies throughout the system as shown in Figure 6 and with more detail in Annex C.

Hydrogen production paths include:

- Centralized production of hydrogen
  - Steam methane reforming or Autothermal reforming using natural gas
    - with or without carbon capture and sequestration (CCS)
  - Electrolysis
    - Alkaline,
    - Polymer electrolyte membrane (PEM), and
    - Solid oxide electrolyzer cell (SOEC).
  - Coal or biomass gasification,
    - with or without CCS.
- Centralized ammonia production
  - Fossil fuel, with or without CCS
  - Electrolysis
- Decentralized hydrogen production
  - Steam methane reforming using natural gas
  - Electrolysis (PEM)

The following sectors have hydrogen-consuming technologies as options:

- Transportation - personal and freight by road, rail or marine
- Industrial uses, including ammonia production, iron and steel production, chemicals and steam boilers available in several industries
- Oil refineries
- Feedstock for synthetic fuels
- Electricity generation – centralized or de-centralized
- Residential space heating
- Commercial space heating

NATEM ensures that infrastructure is built to convert, distribute, and store hydrogen and provides several technology options for each service.

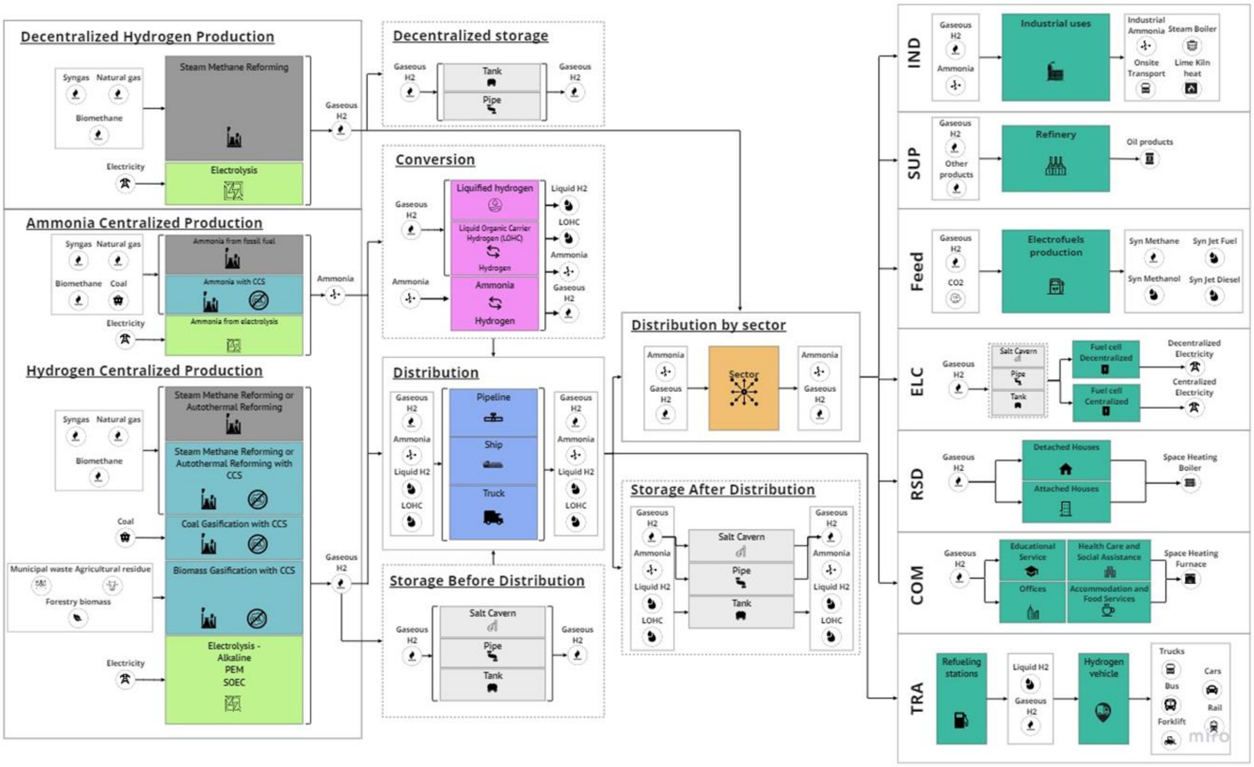

Figure 6 Hydrogen representation in NATEM

As noted previously, NATEM seeks a least-cost solution across the entire energy system, representing competitive markets where the production and consumption of hydrogen will depend on its financial appeal relative to all other technology options, recognizing the physical constraints on resources and technology implementation.   Although Figure 6shows only hydrogen options, each step of the energy system includes potential competition between fuels and technologies (see section 2.2 for descriptions of select competing low carbon technologies).

Exports – NATEM includes export options for hydrogen. The model optimizes exports based on the commodity price, i.e., when revenues from exports exceed domestic production costs. There are no prescribed demands from international markets by default (or lower or upper limits on export volumes in modelling terms) but could be added in future analysis.

2.2. Hydrogen and Competing Low Carbon Technologies

NATEM includes over 290 technologies in the hydrogen production and use pathways in this study. See Annex B for diagrams depicting the number and types of technology choices. ESMIA's database for this project used references that are available to the public and are reported in the References section at the end of the report.

The main references used for are provided in Table 3. Note that ESMIA often uses multiple sources for one representative technology to compile all the information needed for technology attributes and the full set of sources is provided in the References.

Table 3 Key references for technology attributes (non-comprehensive)

Type of technology	Key reference
Hydrogen Production	- International Energy Agency (2019). IEA G20 Hydrogen report: Assumptions. - Element Energy Ltd (2018). Assumptions for the Hydrogen Supply Chain Evidence Base. - TEQ (2020). Revue de littérature technico-économique de l'hydrogène : de la production à l'utilisation. - National Renewable Energy Laboratory (2018). H2A: Hydrogen Analysis Production Case Studies. Version 3.2018
Liquefaction/Conversion/ Reconversion	- International Energy Agency (2019). IEA G20 Hydrogen report: Assumptions.
Transmission and distribution	- International Energy Agency (2019). IEA G20 Hydrogen report: Assumptions. - Element Energy Ltd (2018). Assumptions for the Hydrogen Supply Chain Evidence Base.
Storage	- International Energy Agency (2019). IEA G20 Hydrogen report: Assumptions. - Ahluwalia R.K. et al. (2019). System Level Analysis of Hydrogen Storage Options.
E-fuel	- International Energy Agency (2021). Global hydrogen review 2021 - Braynolf S. et al (2018). Electrofuels for the transport sector: A review of production costs.
Transportation	- International Energy Agency (2019). IEA G20 Hydrogen report: Assumptions. - Lajevardi S. M. (2019). An Examination of Heavy-duty Trucks Drivetrain Options to Reduce GHG Emissions in British Columbia. - Zhao H. et al (2018). A Comparison of Zero-Emission Highway Trucking Technologies.
Electricity from Fuel cell	- Saggiorato N. et al (2017). A Total Cost of Ownership Model for Low Temperature PEM Fuel Cells in Combined Heat and Power and Backup Power Applications.

Industrial and commercial	- IEA. (2021). ETP Clean Energy Technology Guide. - Hy4Heat (2019) Conversion of Industrial Heating Equipment to Hydrogen. - Hy4Heat (2020) Understanding Commercial Appliances.

Notes: See References section below for the comprehensive list of sources used by ESMIA for this study.

NATEM also includes representation of the full energy system requirements for delivering electricity and natural gas to consumers, including hydrogen producers. Like hydrogen, the representation includes financial costs (capital and operating costs, economic life, financing costs), construction time, energy performance, and any constraints on availability, such as assumed year available.

For electricity generation, NATEM includes the following technologies, with technologies available only when permitted and commercially available:

Biomass
- Dedicated Solid Biomass central
- Dedicated Solid Biomass central + CCS (90%)
- Dedicated wood pellet central
- Landfill Gas Internal Combustion Engine

Coal
- Ultra-supercritical Pulverized Coal
- Integrated Gasification Combined Cycle
- Ultra-supercritical Pulverized + CCS (30%)
- Ultra-supercritical Pulverized + CCS (90%)
- Coal + Biomass
- Ultra-supercritical Pulverized coal Cofire with biomass

Geothermal
- Hydrothermal Dual Flash Steam Geothermal
- Hydrothermal Binary Cycle Geothermal
- Enhanced Geothermal Near-Hydro Flash
- Enhanced Geothermal Near-Hydro Binary
- Enhanced Geothermal Systems Deep Flash
- Enhanced Geothermal Systems Deep Binary

Hydro
- Large conventional dam
- Small conventional dam
- Adaptation of a Large non powered dam
- Adaptation of a Small non powered dam
- Small Run-of-river
- Large Run-of-river

Natural gas
- Simple cycle Combustion gas turbine
- Combined Cycle Gas turbine
- Combined cycle Gas turbine + CCS (90%)

Nuclear
- Advanced Reactor
- Small Modular Reactor

Ocean
- Ocean Thermal Energy Conversion Medium
- Ocean Thermal Energy Conversion Large
- Tidal Stream
- Wave Energy Conversion

Oil
- Reciprocating Diesel Engine
- Reciprocating Heavy fuel oil Engine

Solar
- Photovoltaic 1 axis — level 1, 2, 3
- Concentrating Solar Tower
- Photovoltaic 1 axis + 200 MW Storage

Wind
- Onshore Medium Conventional Wind turbine
- Onshore small Conventional Wind Turbine
- Onshore Large Conventional Wind Turbine
- Offshore Fix foundation Wind turbine
- Offshore Floating Wind turbine

Solar - distributed
- Decentralized Residential Rooftop Solar
- Decentralized Commercial Rooftop Solar

Wind - distributed
- Decentralized Residential Wind Onshore
- Decentralized Commercial Wind Onshore

SECTION 3

4. Results: Core Scenarios

Three core scenarios were explored in detail to consider the potential for hydrogen as an energy pathway for Canada in meeting its Net Zero GHG emission goal. The core three scenarios (Technology Neutral, Hydrogen Supportive and Hydrogen Challenging) focus on Canadian demand and supply. Additional scenarios are provided in Section 5 that explore elements with higher uncertainty, such as the future hydrogen export market and the extent that the existing gas transportation network can be used for moving hydrogen.

This section describes the three core scenarios and provides the results of NATEM modelling including hydrogen production by technology type, consumption by energy demand sector, including sub-sectors for transportation. We also report the impacts beyond the physical hydrogen production and demand including reporting changes to electricity generation, plus indicators for investment and avoided greenhouse gas emissions.

3.1. Scenario Descriptions

To develop comparable results, all scenarios are subject to the following modelling constraints:

1. Canada's GHG emissions meet Net Zero emissions in Canada in 2050, and follow the same trajectory for annual emissions from now until 2050 (see Section 1.2)
2. Technology choice is determined by the model using its least social cost algorithm.
3. The demands for all goods and services must be met; each scenarios uses the same exogenous input for these demands, but the model will adjust the values based on price elasticities for a limited set of goods and services.

The scenarios are designed to reflect several key uncertainties in the current understanding of hydrogen technologies, economic circumstances and potential public or private sector actions. The uncertainties are grouped into representative scenarios for this report. Below are the scenario descriptions (Table 4) and summaries of the input parameters (Table 5).

Table 4 Descriptions of Core Scenarios

Scenario 1 - Technology neutral - This scenario determines the energy system in Canada that reaches the Net Zero GHG emission goals at the lowest social cost. Fuels and technologies compete to meet the needs of the economy (section 1.5) and the GHG trajectory (Section 1.2). The technology parameters reflect a neutral approach to the range of values in the literature. This scenario assumes no new policies, so the proposed Investment tax credit for hydrogen production is excluded.[13] In developing its technology database, ESMIA reviews hundreds of reports, journal articles and trade publications. When faced with a range of costs, energy consumption or other input values, our base input for technologies generally represents values that are supported in multiple sources and are not

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[13] The modeling for this report was concluded by March 10, 2023, prior to details being announced for the proposed Investment tax credit.

outliers in the research. These are the assumptions applied in the *Technology Neutral* scenario. Annex C provides the assumptions used for hydrogen and electricity generation technologies.

Potential policies or actions – This scenario is based on current and announced polices plus a requirement for Canada to meet net-zero GHG emissions by 2050. It reflects the environment with no new hydrogen-specific policies but meeting net-zero by 2050 will require policy change beyond this study scope (see Section 2).

Scenario 2 - Hydrogen supportive – For this scenario we chose parameters from external literature that were in the range that we expected would lead to more supportive conditions for hydrogen in the energy system. We assume additional actions occur to reduce capital costs even further – such actions could be on-going support from federal or provincial governments or greater impacts of research and learning-by-doing than currently anticipated. A small subsidy on hydrogen production is also provided in this scenario.

The allowable blend for hydrogen with natural gas that is permitted for transport in the current gas pipeline system and for use in gas appliances and equipment is higher than in the Hydrogen Neutral scenario but note that the value used is a proxy. Several studies are assessing this opportunity and limits on blending are not yet known and will depend on specific regional considerations that could not be researched and integrated for this project.

NOTE THIS IS NOT INTENDED TO REFLECT ANY SPECIFIC POLICY AND IS NOT AN ASSESSMENT OF CANADA’S PROPOSED INVESTMENT TAX CREDIT. The settings are used to test a supportive environment for hydrogen in Canada.

Potential policies or actions –

Many types of policies could lead to the reductions in capital costs modeled in this scenario. The most obvious is an investment tax credit that begins before 2025 and applies to either or both hydrogen production and hydrogen end-use technologies through 2050. Note however that one goal of tax credits is to spur technology development and ideally the policy would allow the government to reduce credits if capital costs fall more rapidly in the future than projected here.

Scenario 3 - Hydrogen challenging – For this scenario we chose parameters from external literature that were in the range that we expected would lead to challenging conditions for hydrogen in the energy system. For example, we assume that capital cost reductions due to research and learning-by-doing are limited beyond what is currently forecast for costs in 2025. We also assume that hydrogen blending with natural gas is limited.

Potential policies or actions – this scenario would reflect a situation where policy does not support technology development for hydrogen and allowable blending standards are set at lower levels than in the *Technology Neutral* scenario.

Table 5. Summary of input parameters of Technology Neutral, Hydrogen Challenging and Hydrogen Supportive scenarios

	Technology Neutral	Hydrogen Challenging	Hydrogen Supportive
Hydrogen technology cost assumptions	Reference (see Annex C)	Costs do not decline after reference values projected for year 2025	Optimistic (see Annex C)
Allowed H2 blend in natural gas pipelines for use in existing appliances and technology	Maximum 13% of gas volume allowed*	Maximum 2% of gas volume allowed*	Maximum 20% of gas volume allowed*
Actions that reduce hydrogen capital costs (for example, government policies or stronger technology evolution)	None	None	Capital costs are 20% below optimistic for all hydrogen-consuming technologies. For hydrogen production, capital costs are reduced below optimistic by - 6% for SMR+CCS - 7.5% for ATR+CCS - 30% for electrolysis (See Annex C) Also applied a $1.5/kg subsidy for all hydrogen production.
Limits on growth in electricity system	None	None	Capacity increase limited to 20% every 5 years
Biomass CCS constraints (maximum percent of total H2 centralized production from BECCS)**	Biomass sequestration not limited	Biomass sequestration not limited	Biomass sequestration limited at 35% max by 2035, 75% by 2050
Price for H2 exports (2022$ CAD)***	$2/kg H2	$2/kg H2	$2/kg H2

Note: * for hydrogen blending, the scenario parameter is the maximum, model determines the blend amount that meets least cost objectives and GHG and other constraints.

** Constraints for hydrogen produced through biomass with CCS are applied in the Hydrogen Supportive scenario to reflect concerns that ESMIA heard in meetings for this project, regarding technology and social acceptance risks for this technology (see Section 3.2). Other scenarios have lower hydrogen production and ESMIA did not apply constraints on hydrogen from BECCS for those. All scenarios have limits on total biomass resource availability to reflect sustainability concerns (see Section 1.4)

*** This price was used in a 2020 Transition Accelerator report (Layzell et al 2020) but is not based on supply-demand assessment for global hydrogen. ESMIA deliberately chose a conservatively low value as an export price proxy in these core scenarios. See additional scenarios in Section 5 for tests of higher export price values.

Assumptions that are constant across scenarios are:

- The social discount rate is set at 4% until 2040 and 3% afterwards.
- Federal policies reflect the approach and outcomes of the for additional measures case of ECCC's Fifth Biennial report (ECCC 2022b). ESMIA matched the GHG outcome of the Fifth Biennial report and also represented the key details of the following policies:
    - Federal fuel charge / backstop carbon price
    - Output-based performance standard
    - Quebec cap and trade
    - Clean Fuel Regulation (SOR/2022-140)
    - Zero-emissions vehicle sales mandate (federal)
    - Clean Electricity Regulations
    - Federal Oil and Gas GHG emissions cap
    - Methane from oil and gas 75% reduction
    - Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles (iMHZEV)
    - Clean Technology Investment Tax Credit
    - Investment Tax Credit for Carbon Capture, Utilization and Storage

Some policies were not implemented at the point of modeling for this project, such as the Clean Electricity Regulation and the Oil and Gas GHG emissions cap and ESMIA developed parameters based on modelling of climate plans by ECCC (ECCC 2022a and ECCC 2022b).

3.2. Hydrogen Production

Figure 7 shows both hydrogen and ammonia production by technology type for the first three scenarios.

In 2018, over 3 million tonnes (Mt) of hydrogen were produced in Canada, primarily (97%) from Steam Methane Reforming (SMR) using natural gas and process gas (Okunlola, A, et al., 2021). In 2030, the Hydrogen Challenging and Technology Neutral scenarios show uptake of SMR without CCS along with Autothermal Reforming (ATR) with CCS and a small amount of electrolysis using Polymer Electrolyte Membrane (PEM) technology. The Hydrogen Supportive scenario has more PEM production and ATR with CCS, and less SMR without CCS.

By 2050, when Canada meets its net zero goals, SMR production without CCS will not be feasible and the equipment that is producing hydrogen today will need to retire or be retrofit. The three scenarios differ in terms of both total production and the mix of production technologies. Total production is determined by demand as described in the next sections. ATR with CCS that was installed by 2030 is still producing at almost the same capacity in 2050 but additional hydrogen needs are met by new PEM electrolysis combined with biomass gasification with CCS. Producing hydrogen using biomass gasification with CCS is assumed to provide negative emissions due to accounting for sequestration credits during plant growth plus storing the CO_2 emissions released from biomass combustion.[14]

Caveat: Current modelling projects that achieving net-zero targets will require net negative emission options to compensate for the hard-to-abate sectors such as some industrial process and agriculture process emissions (based on the actual knowledge around existing and emerging technologies and based on the options included in the NATEM model). There are important limitations related to that net negative emissions options that should be noted. There are reasons for the projected increasing use of bioenergy; primarily as it is viewed as being CO_2 neutral, with CO_2 emitted during combustion considered to be equal to CO_2 absorbed during tree growth. However, there is a lag in the temporal aspects of bioenergy production from the forest sector, as CO_2 releases are immediate when burning wood-based biomass, while corresponding absorption from the atmosphere occurs progressively over future decades of tree growth (also referred to as carbon debt). This accounting method is the one used by most governments today in preparation of their national GHG inventories and submissions to the United National Framework Convention on Climate Change-UNFCCC). Second, there are important technology risks because the hydrogen pathway using biomass gasification with CCS is currently not available (to ESMIA's knowledge) at the commercial scale or even at the project scale in Canada. Currently, we limit BECCS availability to after 2030.

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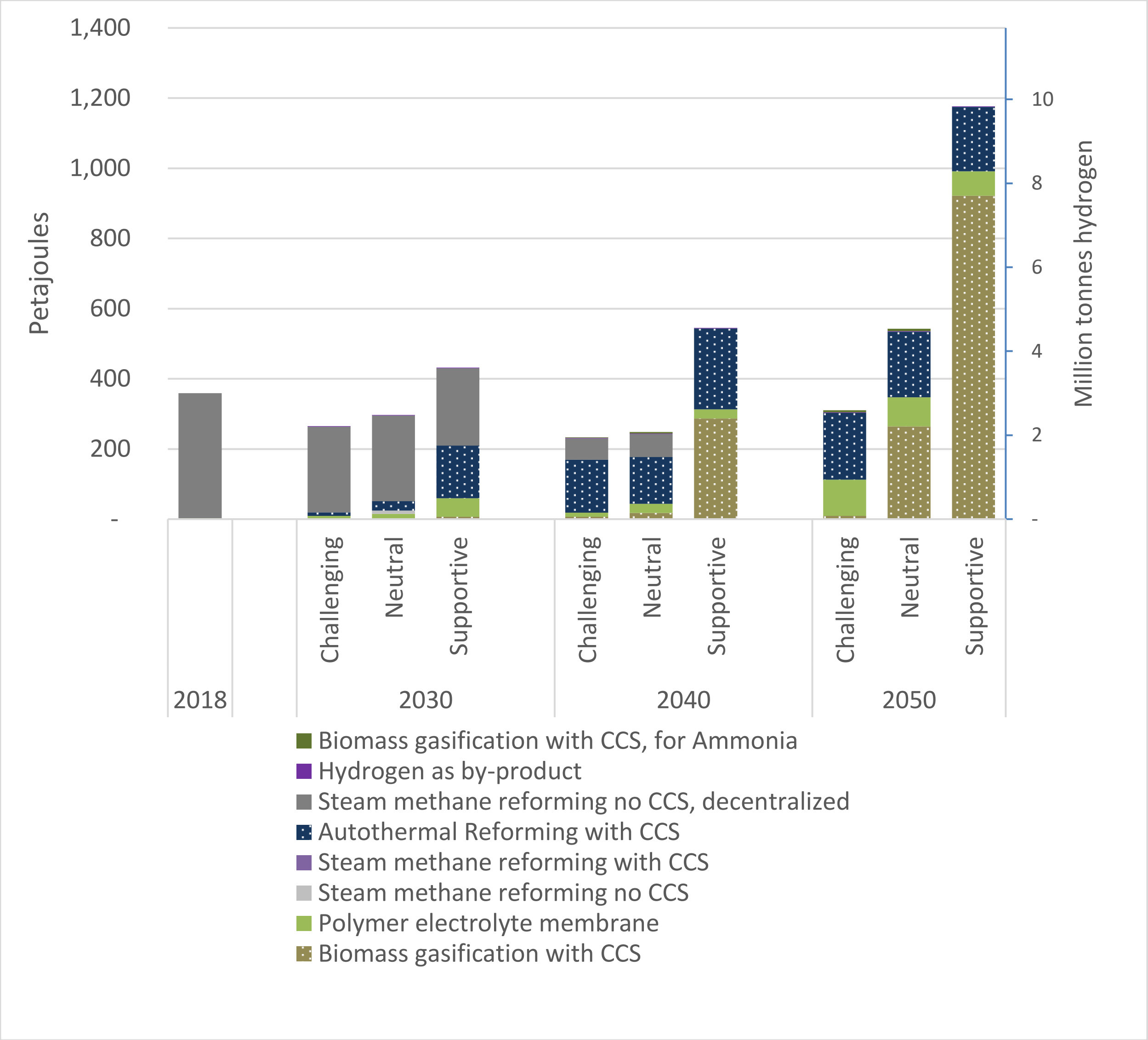
[14] Biomass availability is restricted in NATEM to reflect sustainable sources, using ESMIA's best reflection of available information. The definition of sustainable biomass is an area of evolving knowledge and only limited review was within the scope of this project.



Notes: Technologies are centralized production of hydrogen unless otherwise noted.
Hydrogen energy is converted from petajoules to million tonnes using the factor 120.1 PJ/Mt.

Figure 7 Hydrogen and Ammonia Production by technology type, 2030, 2040 and 2050 (PJ), existing and new production.

3.3. Aggregated Hydrogen Consumption

Hydrogen consumed by sector is shown in Figure 8. In the Technology Neutral scenario, hydrogen consumption is projected to reach 3.3 Mt in 2050.[15] While only about 10% higher than in 2018, consumption declines from oil production while increasing for transportation and other industries. The Supportive scenario shows strong growth in hydrogen consumption, where it reaches about 9 Mt.

Currently and in 2030, domestic consumption of hydrogen is dominated by oil production and refining with some use of blended hydrogen in buildings and in transportation in the Hydrogen Supportive scenario, due to lower costs for production and demand-side technologies. Demand decreases through 2040 as the oil production and refining sector has lower use and there is less use of blended hydrogen due to increased electrification and lower overall gas demand for buildings and industry. Demand for pure hydrogen occurs mostly after 2040 through industrial demand. This lag is reasonable due to long lived equipment in this sector. In the Hydrogen Supportive scenario, hydrogen demand for transportation is apparent by 2030 and accounts for similar demand as the industrial sector. The buildings sector also contributes to hydrogen demand in this scenario, due to the lower capital costs for production and demand technologies. The capital costs in this scenario are set lower than other scenarios to account for either policies or technology evolution over time. Across these scenarios and years, hydrogen for export is close to zero by design with a conservative export price at $2/kg (see additional scenarios in Section 4 for exploration of hydrogen exports).

Sections 3.4 to Section 3.6 will show the contribution of hydrogen to total energy consumption for the transportation, industrial and buildings sector with more detail by type of service.

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[15] Losses in transporting and storing hydrogen account for the difference between the projected total hydrogen and production values.

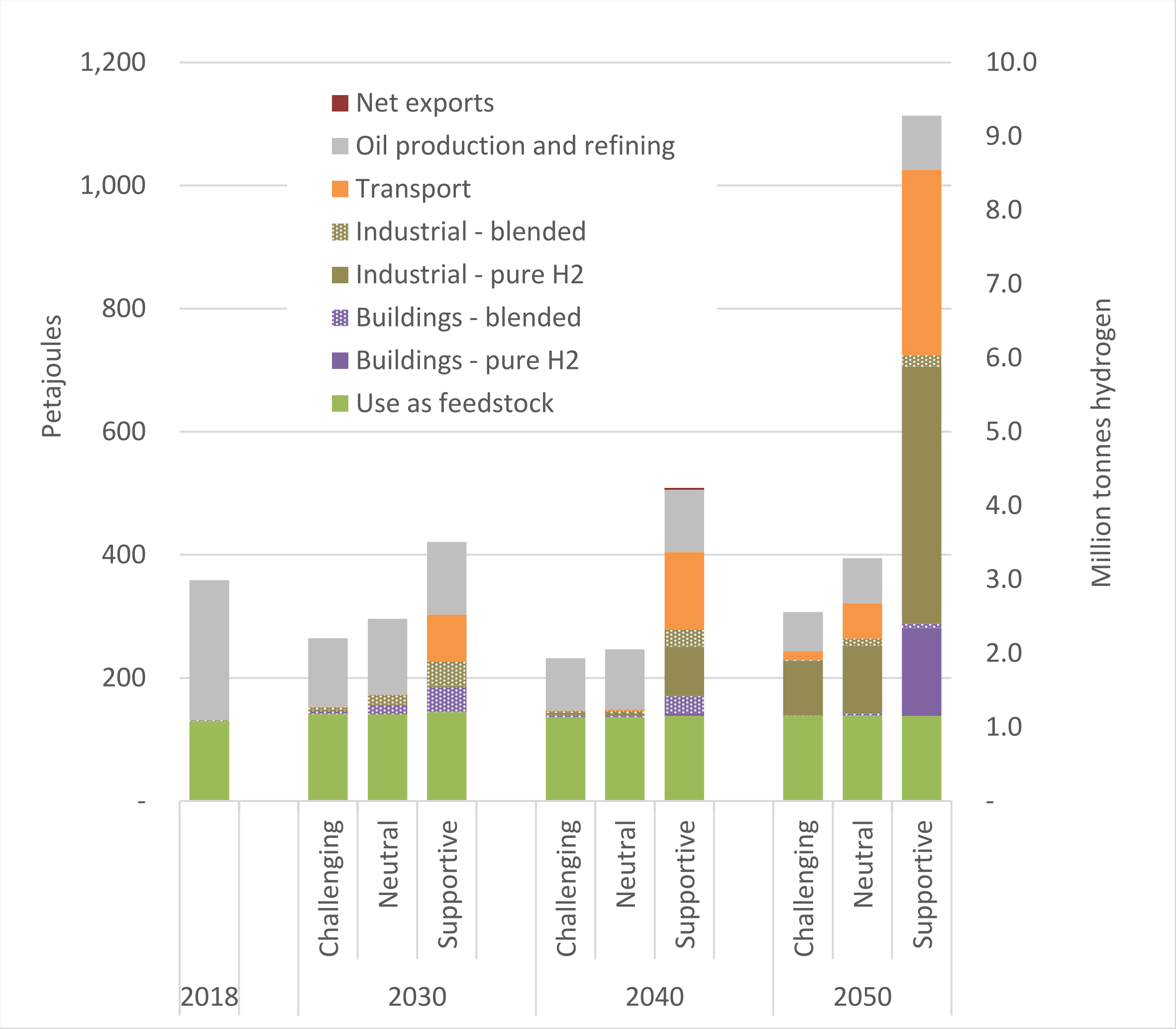


Figure 8 Hydrogen Consumption by Sector

3.3.1. Hydrogen Prices

Hydrogen prices are calculated in the model based on marginal costs at any given time, including costs of system expansion (for example, capital cost of production facilities). Thus, prices are highest when demand approaches or exceeds supply. The table below provides average marginal prices across all demand sectors, over the year. As would be expected, prices are lowest in the Supportive scenario, due to the reduction in capital costs. The price increase from 2030 to 2050 can be explained by the increasing cost of decarbonization, due to increasingly strict emissions constraints and decreasing returns on production. (For example, the best value sites for electrolysis would be in locations with cheap electricity and abundant renewables. As the hydrogen sector expands, the best value sites will be used up and lower value sites will be used.) Moreover, hydrogen production competes with other energy types and associated technologies, increasing prices along with further decarbonization.

Nevertheless, an average price range of $3/kg to $4.3/kg is projected for 2050, suggesting that while low carbon hydrogen will be more expensive than current grey hydrogen prices, the price remains competitive on a per energy basis with traditional fuels used today (for example, a gasoline price of $1.5/L is equivalent to $0.17/kWh whereas a hydrogen price of $4/kg is equivalent to $0.12/kWh). The observed hydrogen prices also explain why a very limited amount of hydrogen has been dedicated for export in these scenarios, since the export price was set at $2/kg. The analysis suggests that in the neutral scenario, an export market price of $3/kg or higher is required in 2040, and $4/kg or higher for 2050. (The Export scenario, where export prices were set higher and production increases as a consequence, confirms this conclusion.)

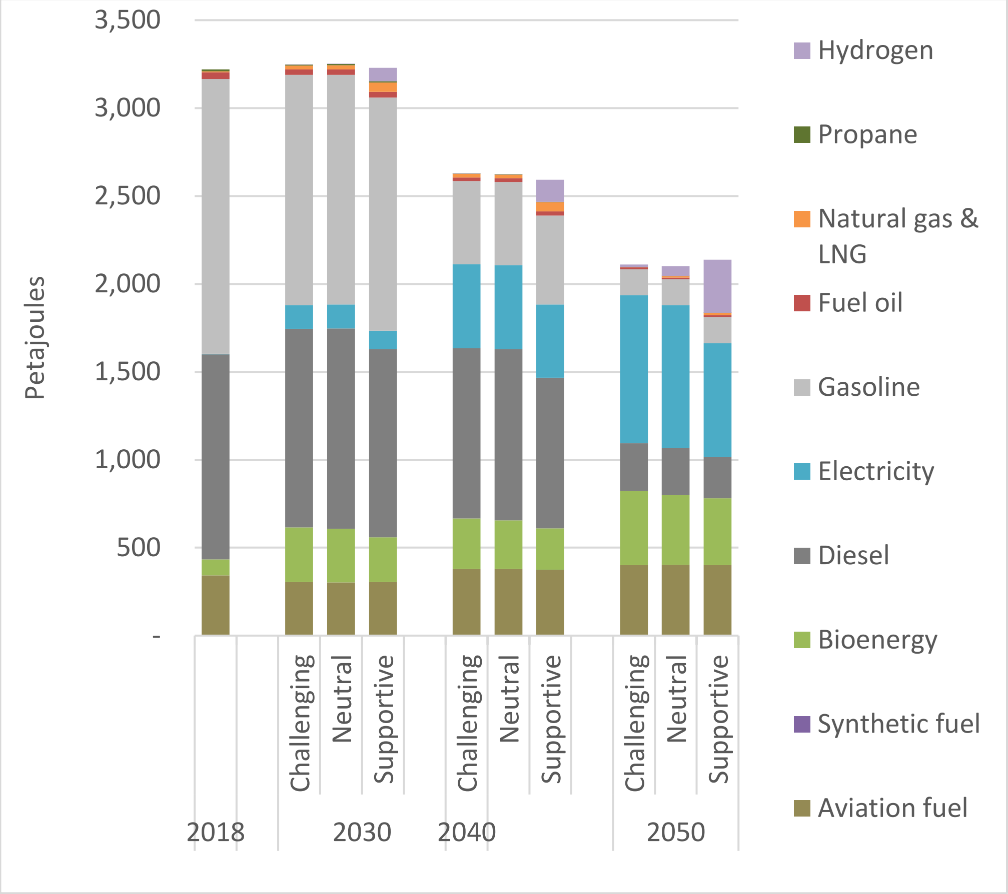
Table 6 Average Hydrogen Prices ($/kg)

	Neutral	Challenging	Supportive
2030	2.03	1.77	1.71
2040	2.90	2.77	2.24
2050	3.79	4.33	3.03

3.4. Transportation Sector

Energy consumed for transportation by type of energy across the scenarios is shown in Figure 9. For these scenarios in 2050, hydrogen consumption as a fraction of total energy consumed is 1% in the Hydrogen Challenging scenario, 3% in the Technology Neutral scenario and 14% in the Hydrogen Supportive scenario.

Due to competition from electric vehicles, there is almost no hydrogen consumed for light duty vehicles. Hydrogen use in aviation was not modelled, due to lack of available information. The following sub-sectors explore hydrogen use by the other transportation sub-sectors.



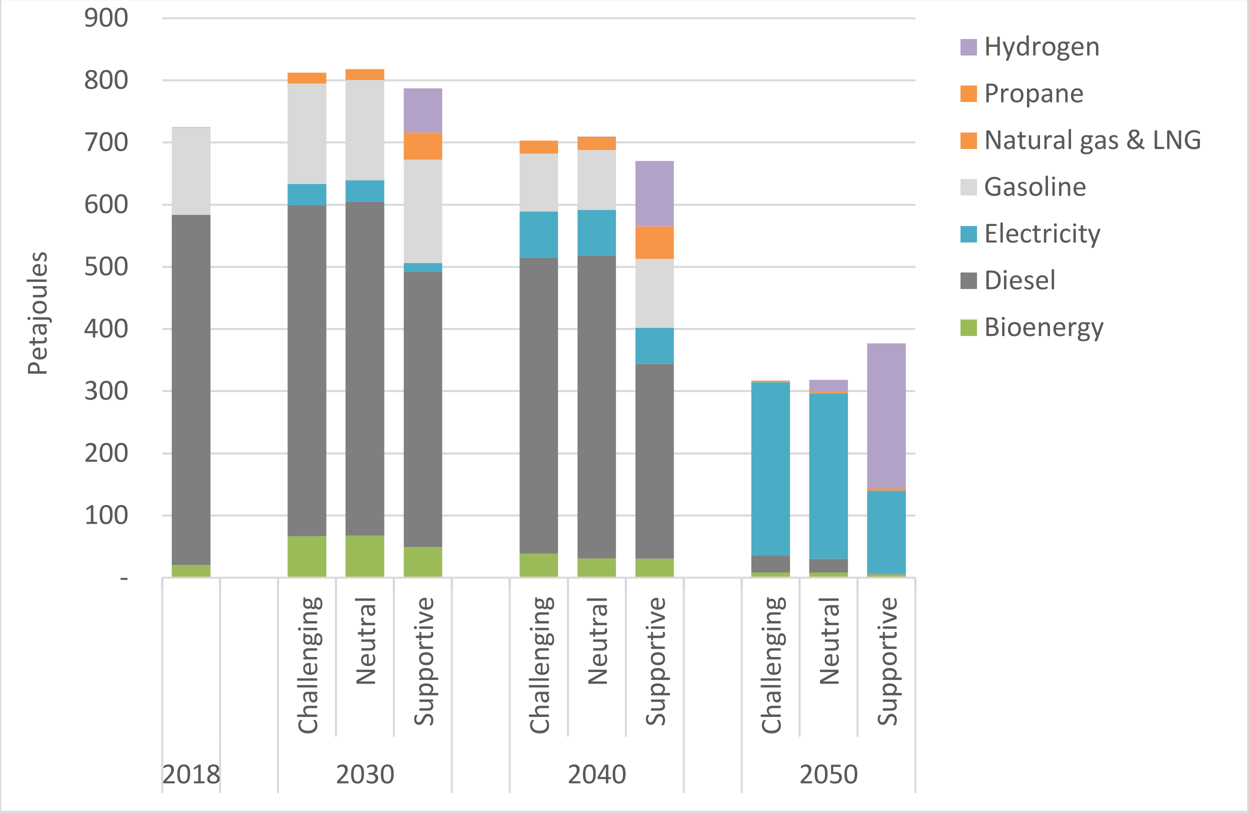
Note: 1 PJ of hydrogen corresponds to approximately 0.008 Mt of hydrogen (lower heating values).

Figure 9 Energy consumption in the Transportation Sector

3.4.1. Medium and Heavy-Duty Trucks

Under the Hydrogen Challenging and Technology Neutral scenarios, limited uptake occurs for hydrogen in medium and heavy-duty trucks, with diesel remaining dominant through 2040 then electric transport taking over in 2050 for meeting Net Zero goals. The lower costs for hydrogen production and consumption technologies in the Hydrogen Supportive scenarios make a large difference in this end-use, with hydrogen becoming the dominant energy consumed by 2050.

The decrease in overall energy consumption in 2040 and 2050 reflects the much higher energy efficiency of electric transportation relative to fossil fuel and hydrogen energy efficiency.



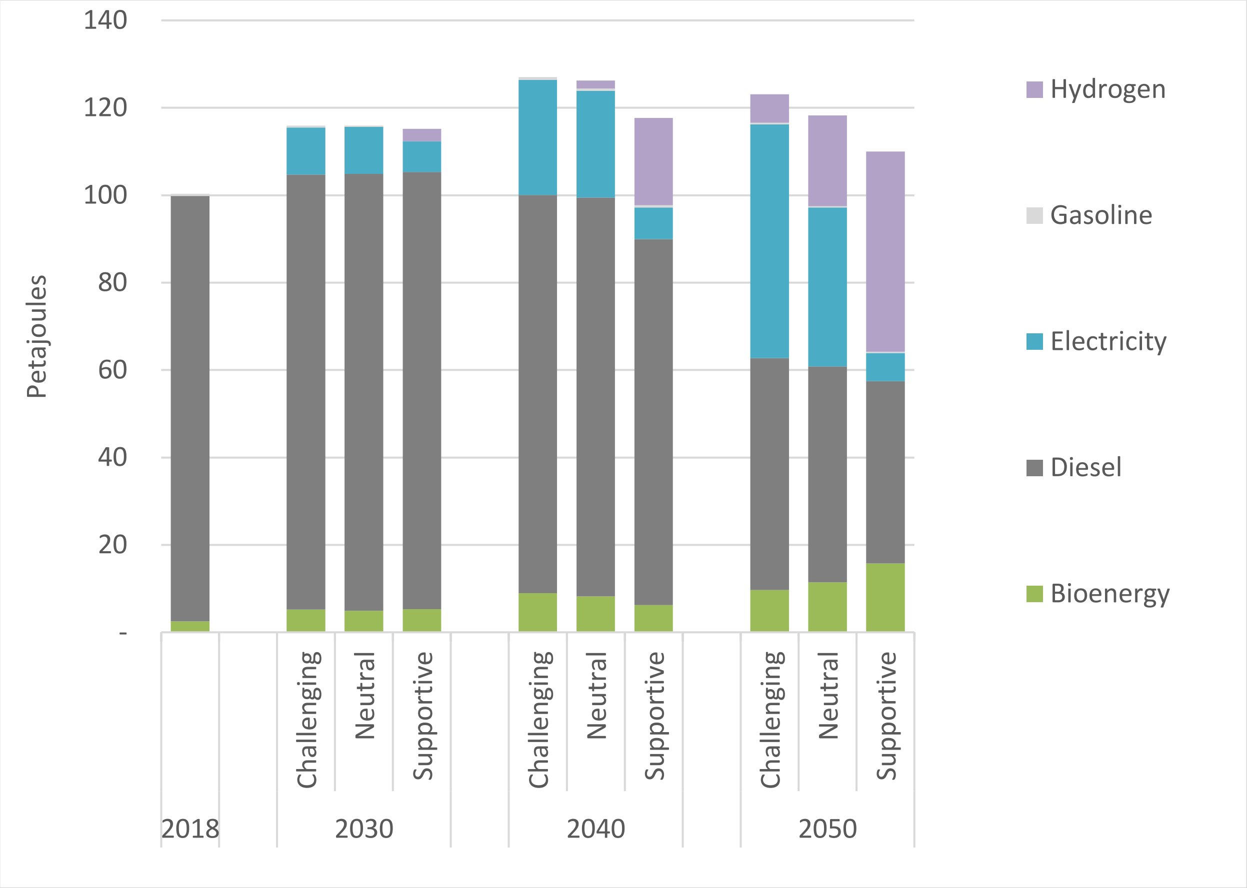
Note: 1 PJ of hydrogen corresponds to approximately 0.008 Mt of hydrogen (lower heating values).

Figure 10 Energy consumed by Medium and Heavy-Duty Trucks

3.4.2. Rail and Marine

Hydrogen consumed for rail transportation is limited through 2040 in the Hydrogen Challenging and Technology Neutral scenario but increases in the Technology Neutral scenario by 2050. The cost reductions included in the Hydrogen Supportive scenario are projected to allow hydrogen to outcompete electricity in 2050. Some diesel remains in this sector in all scenarios, as the modelling indicates that mitigation options for rail transport are higher cost than other end-uses.

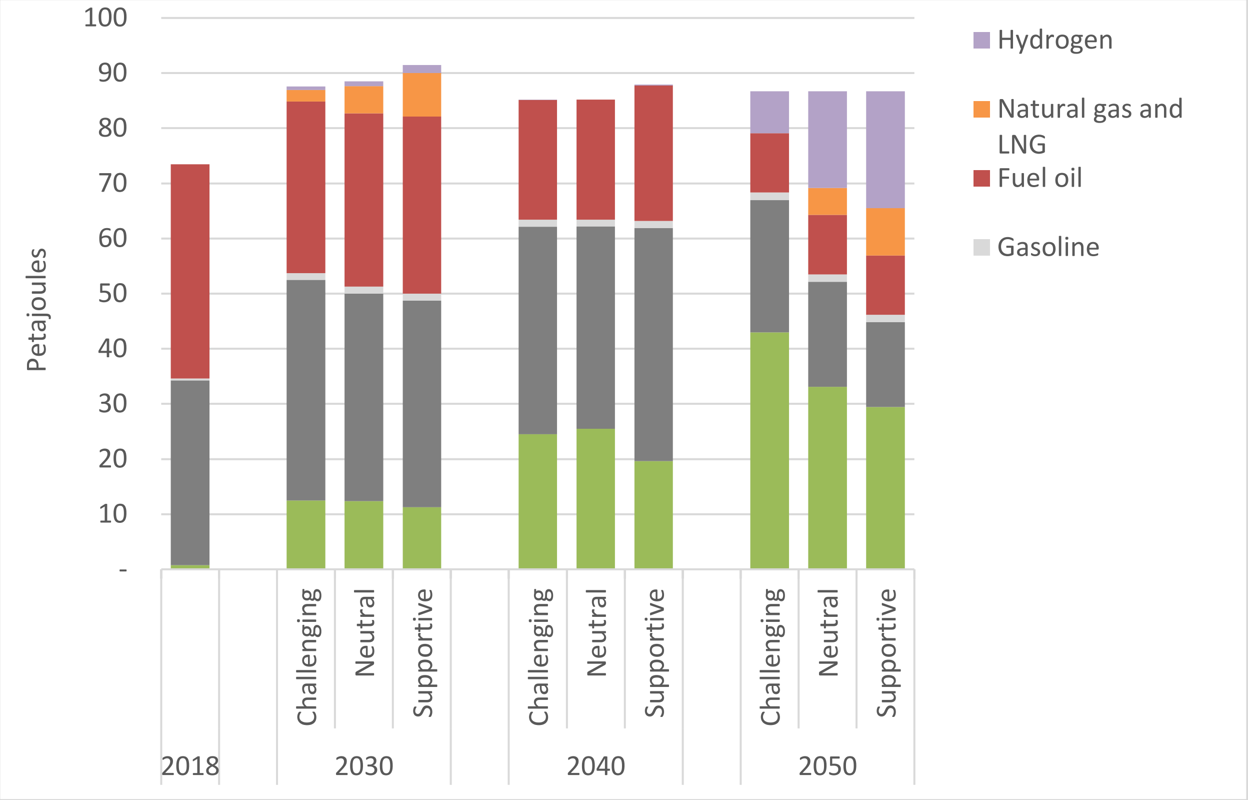
Caveat: While all road transport segments are modelled explicitly through detailed technologies with specific and well documented techno-economic attributes, the rail and marine transport modes are modelled using generic technologies with average attributes. Consequently, the optimization is more driven by the respective fuel prices than the capital costs of technologies.



Note: 1 PJ of hydrogen corresponds to approximately 0.008 Mt of hydrogen (lower heating values).

Figure 11 Energy Consumed for Rail Transportation

For marine transportation, the main competition for low carbon energy is between hydrogen and bioenergy. Bioenergy consumption increases across years in all scenarios and there is very little hydrogen consumed prior to 2050. In the year 2050, hydrogen consumption becomes material and dominates over diesel, fuel oil and natural gas in the Technology Neutral scenario, but bioenergy remains dominant.

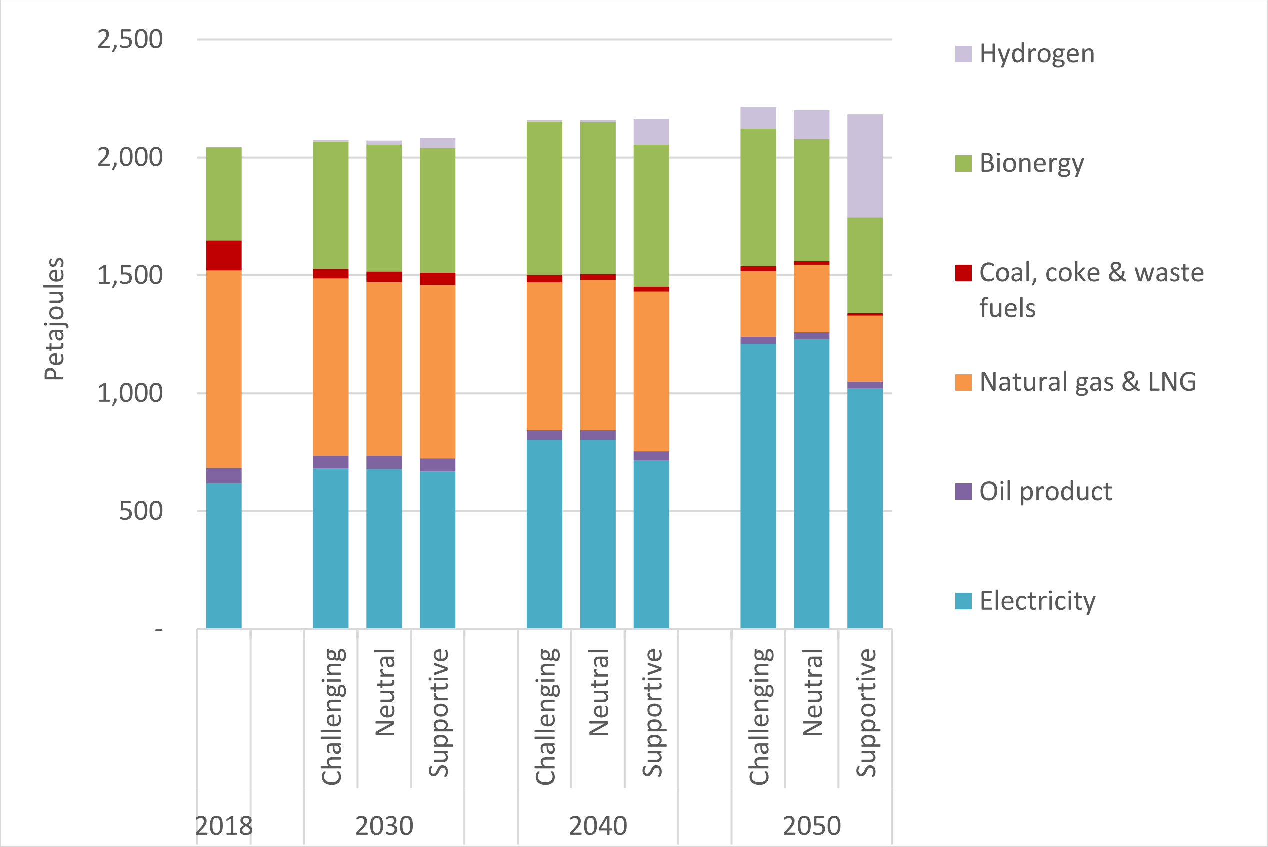


Note: 1 PJ of hydrogen corresponds to approximately 0.008 Mt of hydrogen (lower heating values).

Figure 12 Energy Consumed for Marine Transportation

3.5. Industry Sector

Hydrogen consumed for the industrial sector is projected to be limited through 2040 in the Hydrogen Challenging and Technology Neutral scenarios but increases to approximately 5% in 2050 in both scenarios. The cost reductions included in the Hydrogen Supportive scenario are projected to allow hydrogen to be increasingly competitive with bioenergy and electricity in 2040. By 2050, electricity is projected to dominate energy use in the Hydrogen Supportive scenario, while hydrogen catches up with bioenergy and accounts for 20% of final energy consumed.



Note: 1 PJ of hydrogen corresponds to approximately 0.008 Mt of hydrogen (lower heating values).

Figure 13 Energy consumed in the Industrial Sector

Energy consumed for oil production and refining is excluded from Figure 13 but was shown previously, in Figure 8. This sector accounts for the majority of hydrogen consumed in 2018, but its hydrogen consumption declines over time due to lower volumes of oil production under net-zero GHG goals. Hydrogen consumption is projected to respond to the changes in costs across the scenarios as expected, with the Hydrogen Supportive scenario having the highest consumption of the three scenarios in 2050.

3.6. Heating for Buildings

The projections for hydrogen consumed for heating in buildings are shown in Table 7. Consumption is low in most scenarios and years, except for the Hydrogen Supportive scenarios in 2050, but shows a different pattern compared to other sectors. In buildings, hydrogen consumption is projected to decrease from 2030 to 2040 in all three scenarios. The model projects that hydrogen consumed in buildings in these scenarios through 2040 will be from hydrogen blended with natural gas and delivered through the existing transmission and distribution system. This amount decreases from 2030 to 2040 due the projected uptake of heat pumps. By 2050, the model projects the uptake of transmission lines carrying 100% hydrogen. The projections show only small uptake of pure hydrogen in buildings in 2050, except under the Hydrogen Supportive scenario, which includes cost reductions for heating equipment using hydrogen.

Table 7 Hydrogen consumption for heat in the Residential and Commercial sectors
(showing consumption in both PJ and Mt of hydrogen)

	2030		2040		2050		
	PJ	Mt	PJ	Mt	PJ	Mt	% of total energy
Challenging	5	0.05	4	0.03	0	0.00	0.0%
Neutral	14	0.12	2	0.02	3	0.03	0.1%
Supportive	41	0.34	32	0.27	149	1.24	5.4%

In the Hydrogen Supportive scenario, hydrogen is projected to supply over a million tonnes of heating energy for buildings in 2050, accounting for over 5% of the total energy consumed in buildings.

3.7. Electricity Generation

The projections show almost no hydrogen used for electricity generation in these scenarios (not even visible in Figure 14). This area needs further study to determine whether the low uptake is due to model limitation or reflective of the competitiveness of renewables sources for electricity generation to meet the GHG constraint, especially the inefficiency of producing hydrogen then consuming it for electricity. Many provinces are completing their own electricity generation modelling studies and this may be an area for even greater collaborative research in the future (see for example, AESO 2022, IESO 2022).

ESMIA notes that the version of NATEM used for this analysis does not include an hour-by-hour dispatch representation due to the condensed project timeline. A version with that feature, which could explore additional opportunities for hydrogen as storage, will be available for future analysis.

Projected electricity generation by type of energy is provided in Figure 14. Electricity generation is projected to more than double from 2018 to 2050. This growth reflects the Net Zero constraint applied in the modelling and, with opportunities for the electricity system to decarbonize, electricity consumption becomes a competitive option in many end-uses. The impact of the different levels of hydrogen consumption appears in the projections for 2050. The Hydrogen Supportive scenario, with the highest levels of projected hydrogen consumption, has the lowest electricity demand with wind generation being most impacted by the change in demand.

Generation from fossil fuels (coal, natural gas and fuel oil) is projected to decline to provide approximately 3% of total generation in 2040 and less than 1% in 2050. This is consistent with the goals of the proposed Clean Electricity Regulation. Wind generation is projected to have the greatest increase with solar also becoming more significant while solar generation increases to a smaller degree. Wind and solar combined are projected to provide 30% of total generation in 2040 in all scenarios. In 2050, the portion is projected to increase to 50% for the Hydrogen Challenging and Technology Neutral scenarios and 40% for the Hydrogen Supportive scenario, due to lower overall electricity demand stemming from decreased electrification of end-uses.

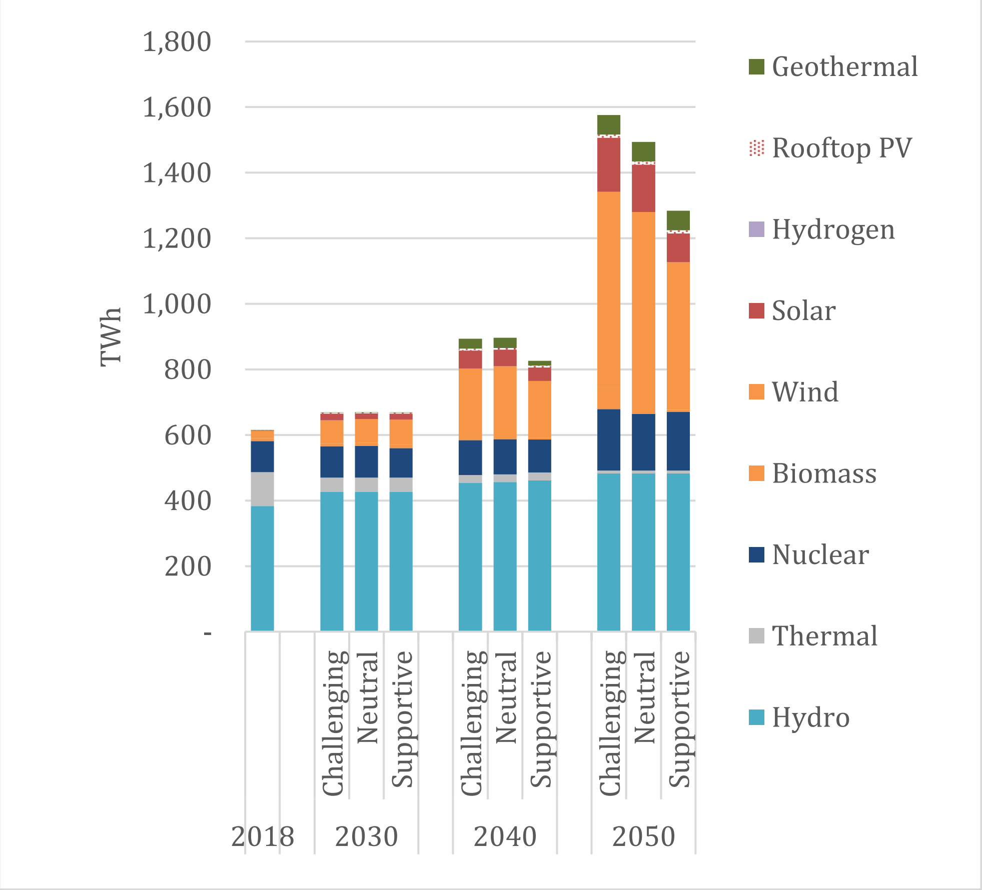


Figure 14 Electricity generation by type, core scenarios

Changes to electricity capacity follow the same general pattern as the generation shown in Figure 14, except that wind and solar capacity grow faster due to their lower capacity factors. In 2050, total capacity is projected to reach over 500 GW in the Hydrogen Challenging and Technology Neutral scenarios, and 425 GW in the Hydrogen Supportive scenario.

3.8. Impacts of the Hydrogen Scenarios

The following section considers the impacts of the different hydrogen scenarios, *from NATEM's partial economic viewpoint* (i.e., macro-economic changes limited to the energy sectors as well as sectors with large non-energy GHG emissions). The results show the impacts due to changes in hydrogen production and/or consumption, but not entire economy-wide impacts. This approach, while limited, allows for more direct comparison with estimates from the *Hydrogen Strategy* (Canada 2022), which reported the hydrogen-focused results only.

Caveat – Changes in investment, jobs and GHG emissions from non-hydrogen energy pathways were not estimated for this study.

3.8.1. Investment and Jobs

Figure 15 shows the investments by year, which are determined by the assumed technology costs (Annex C) and the purchases of the different technology types projected by the model. These values only include investments for hydrogen equipment, as noted in the introduction to this section. The Transport and Distribution portion of the costs is larger for the Hydrogen Supportive scenario in 2050 because this scenario has a larger share of pure hydrogen being used, rather than the hydrogen blended with natural gas. The core scenarios assume that pure hydrogen will require new transmission pipelines for delivery, see Additional Scenarios (Section 4) for alternatives to this assumption.

As a general approximation for the number of jobs associated with the investments to produce and deliver hydrogen, ESMIA followed the same approach as in the 2020 Hydrogen Strategy (Canada 2020). The revenue for companies producing and transporting hydrogen was estimated assuming that revenue would cover a return on investment, assumed to be 10 percent for this calculation, and also accounting for assumed lifespan of the equipment. The number of jobs is a basic calculation using the revenue estimate and the jobs multiplier reported in the Hydrogen Strategy (6.7 jobs for each million $ of revenue).

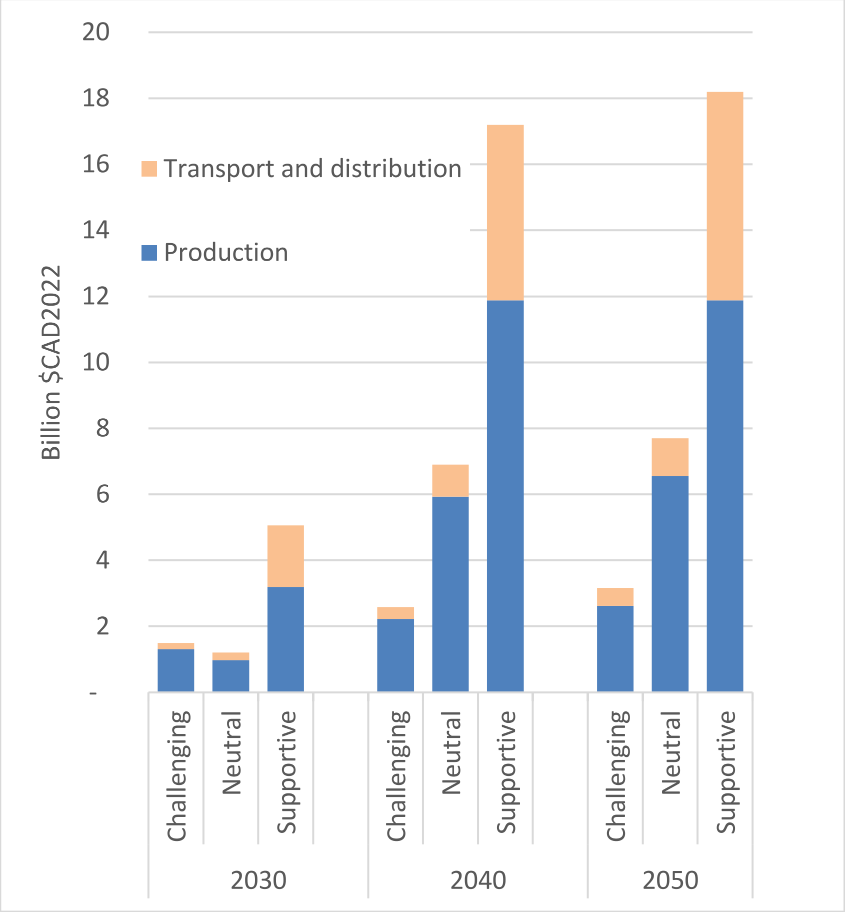


Figure 15 Investments for hydrogen production and delivery

Based on this calculation, in 2050 the investments in hydrogen production and transport are projected to support roughly 14,000 jobs in the Hydrogen Challenging scenario, 23,000 in the Technology Neutral scenario and 70,000 in the Hydrogen Supportive scenario (direct, indirect, and resulting jobs).

Caveat: As with the 2020 Hydrogen Strategy, the estimates should be seen as indicative of the order of magnitude of the number of jobs supported and are subject to many uncertainties and unpredictable changes in economics and technologies. Job changes due to investment changes in the rest of the economy are not estimated.

3.8.2. GHG Emissions

A foundation of this analysis is the project’s requirement to meet Net Zero GHG emissions by 2050. Our approach to defining this and the impact of this requirement are discussed in section 1.2.1 and in the results above. The approach leads to all scenarios meeting the same total, economy-wide GHG emissions regardless of the hydrogen consumption. If hydrogen was not consumed at the amount projected for any scenario, another low carbon energy would be used, or more negative emissions technologies would be required. The GHG emissions vary across years and by sector, as shown in Figure 16.

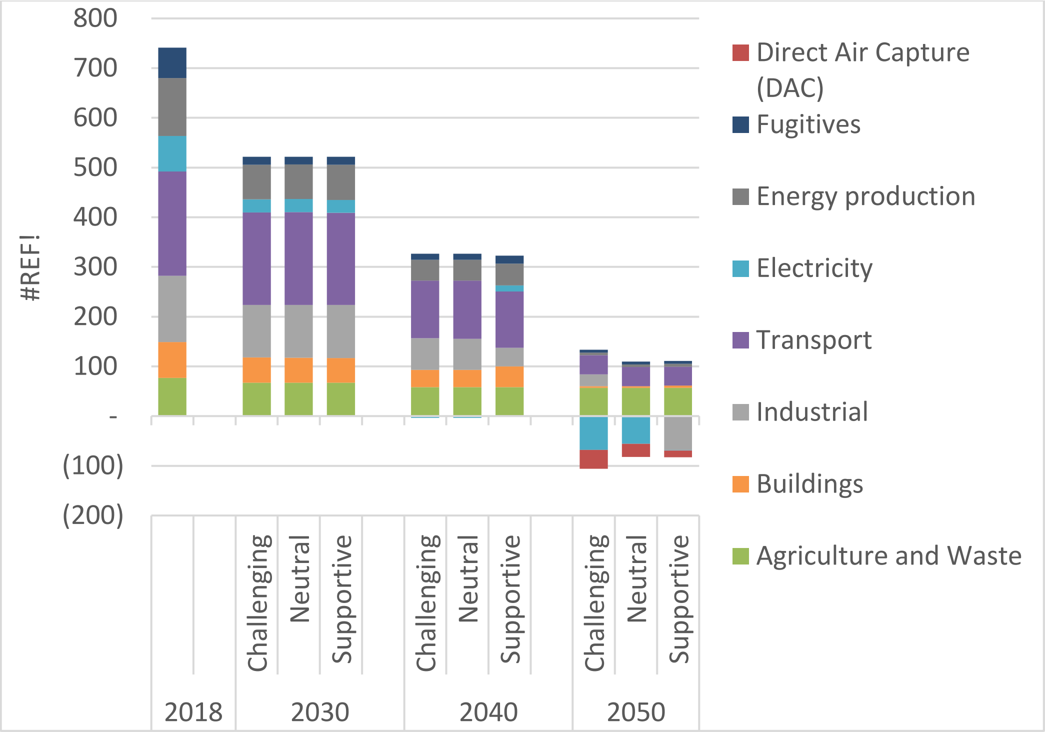


Figure 16 Total Greenhouse Gas (GHG) Emissions by sector

In keeping with the reporting in the 2020 Hydrogen Strategy (Canada 2020), we have calculated an estimate for the GHG reductions due to hydrogen consumption in Canada. We do this by estimating the GHG intensity of the fuels likely to be displaced when hydrogen is consumed. We used a NATEM model run with the same input parameters as the scenarios for this analysis, but without the GHG constraints. The results provided a GHG intensity (Mt CO_2e/PJ) for fossil fuel use by sector and, assuming hydrogen would mostly displace fossil fuels, we calculated avoided GHG emissions (see Table 8).

Table 8 GHG emissions avoided, attributed to hydrogen consumption (Mt CO2 eq)

	2030	2050
Challenging	8	12
Neutral	10	18
Supportive	18	69

SECTION 4

5. Results: Additional Scenarios

ESMIA explored additional scenarios to consider hydrogen exports (as per the project scope) and other scenarios that were suggested during engagement with experts in the field. These additional scenarios are grouped together for the purpose of concise reporting. The common element across the additional scenarios is the larger uncertainties for the input parameters for these scenarios. ESMIA can generate the same level of detail as in Section 4 but to limit repetition in this report, we discuss the key results of these scenarios, and provide only the charts for hydrogen production by type and hydrogen consumption by sector, rather than the full set of charts. Charts are in section 4.3.

4.1. Scenario Descriptions

The scenarios are designed to reflect the several key uncertainties in the current understanding of hydrogen technologies, economic circumstances, and potential public or private sector actions. The uncertainties are grouped into representative scenarios for this report. Below are the scenario descriptions (Table 9) and summaries of the input parameters (Table 10).

Table 9 Descriptions of Additional Scenarios

Scenario 4 - Hydrogen exports (hypothetical) - Hydrogen export potential is a key consideration for Canadian public and private sectors. However, the uncertainty on exports is even greater than the domestic factors included in the modelling for the other scenarios. We refer to this scenario as hypothetical because the hydrogen production results are tightly linked to the input assumptions used to represent the global market. For this scenario, we set hypothetical prices that Canadian hydrogen exports could sell at, based on values in Layzell et al. 2020. ***Potential policies or actions*** – this scenario could reflect efforts by the federal or provincial governments to develop trade deals for hydrogen, or by private companies.
Scenario 5 – Pure hydrogen regions (hypothetical) – This scenario explores conditions where, through a combination of public and private sector actions, certain regions of the country specifically support hydrogen for space heat in buildings pure hydrogen communities. This could reflect, for example, strategies considered by the different region's electricity system for avoiding combinations of high power demands and low wind and solar supply, such as could occur in cold winters in Alberta if electricity accounted for a large portion of space heating. The scenario also adds an option to retrofit the existing gas transmission system to transport 100% hydrogen, but this is regionally restricted, acknowledging that the pipeline system across Canada has a mix of vintages and materials, which will impact the cost or feasibility of this option. Converting existing pipelines, transmission and distribution, to 100% hydrogen has an assumed cost (see Annex C). Hydrogen heating systems are available at reduced cost for this scenario, using the same values as the Hydrogen Supportive scenario. ***Potential policies or actions*** – this scenario reflects changes to the standards for distribution pipelines to carry 100% hydrogen, involving the Canadian Standards Association. Limiting electricity heating in the model reflects policies that restrict purchases of electric heating equipment without backup

sources or consumer preferences to avoid electric heating. This scenario includes the technology cost reductions in the *Hydrogen Supportive* scenario so the same potential policies would apply here.

Scenario 6 – Gas Transmission Retrofit to H2 (hypothetical) – this scenario considers future conditions that could permit the existing gas distribution and transmission systems to convert to using 100% hydrogen, anywhere in Canada. This scenario is also considered hypothetical due to lack of consensus and existing studies on the feasibility of this large-scale conversion (Topolski, K et al (2022). This scenario is modeled by allowing existing transmission pipelines to convert to carrying 100% hydrogen, accounting for the additional capital costs for such conversions and energy needs for additional compression requirements (see Annex C for costs).

Caveats –This scenario allows but does not require conversion of gas transmission systems to carry 100% hydrogen. It is meant to explore the economic potential for conversions and is simplified by allowing parts of system to change incrementally. The modelling does not account for the costs to implement change, such as disruption in energy services during the pipeline conversions.

Potential policies or actions – Standards for the transmission pipelines would need to be developed to permit these conversions, requiring further study and testing on the logistics, technology requirements, and pipeline materials (Alberta Innovates 2023, NREL 2022). This scenario includes the technology cost reductions in the *Hydrogen Supportive* scenario so the same potential policies would apply here.

Table 10. Summary of input parameters of Exports, Regional and Gas Transmission Retrofit scenarios.

	Hydrogen Exports	Regional Hydrogen	Gas Transmission Retrofit
Hydrogen technology cost assumptions	Reference (see Annex C)	Optimistic (see Annex C)	Optimistic (see Annex C)
H2 blend allowed in natural gas pipelines	Maximum 13% of gas volume allowed*	Maximum 20% of gas volume allowed with no additional costs* In Alberta only, existing pipelines can be retrofit to carry 100% hydrogen. Assumed costs for the retrofit are included in Annex C.	Maximum 20% of gas volume allowed with no additional cost * Everywhere, existing pipelines can be retrofit to carry 100% hydrogen. Assumed costs for the retrofit are included in Annex C.
Actions that reduce hydrogen capital costs (for example, government policies or stronger technology evolution)	None	Capital costs are 20% below optimistic for all hydrogen-consuming technologies.	Capital costs are 20% below optimistic for all hydrogen-consuming technologies.

		For hydrogen production, capital costs are reduced below optimistic by - 6% for SMR+CCS - 7.5% for ATR+CCS - 30% for electrolysis (See Annex C) Also applied a $1.5/kg subsidy for all hydrogen production.	For hydrogen production, capital costs are reduced below optimistic by - 6% for SMR+CCS - 7.5% for ATR+CCS - 30% for electrolysis (See Annex C) Also applied a $1.5/kg subsidy for all hydrogen production.
Limits on growth in electricity system	None	None	None
Biomass CCS constraints (maximum percent of total H2 production allowed from BECCS)	Biomass sequestration not limited	Biomass sequestration not limited	Biomass sequestration not limited
Limits to heat pumps for heating	No	Yes, for cold weather regions with low solar and wind availability during the winter. In Alberta, Saskatchewan and Manitoba, heat pumps are limited to a maximum of 25% of space heating demand for buildings.	Yes, for cold weather regions with low solar and wind availability during the winter. In Alberta, Saskatchewan and Manitoba, heat pumps are limited to a maximum of 25% of space heating demand for buildings.
Price for H2 exports (in 2022$)	2030 – $3.5/kg 2040 – $5/kg 2050 – $5/kg	$2/kg H2	$2/kg H2

Note: * for hydrogen blending, the scenario parameter is the maximum, model determines the blend amount that meets least cost objectives and GHG and other constraints.

4.2. Discussion

4.2.1. Hydrogen Export (hypothetical)

For the *Hydrogen Export scenario*, the key uncertainties relate to the global market demand and supply and the resulting trade price for the commodity or the price agreements that Canadian companies set up in contracts with international companies for hydrogen supply. The key input parameter is the price that Canada can expect when exporting hydrogen and we used values from the Transition Accelerator's

2020 report, *Towards Net-Zero Energy Systems in Canada: A Key Role for Hydrogen* (Layzell, D et al (2020) as guidance. But we note that the prices used here ($3.5/kg H2 in 2030 increasing to $5/kg H2 in 2040 and later) are a test to determine response of the modeled system, rather than an outcome of global markets analyses.

In the *Hydrogen Export scenario*, Canada is projected to produce almost 14 million tonnes of hydrogen in 2050 (1,640 PJ) with domestic consumption of 2.9 million tonnes. Compared to the Technology Neutral scenario, this shows a significant increase in production but slightly less domestic consumption.

4.2.2. Regional Hydrogen Scenario (hypothetical)

The Regional scenario was suggested at a point in the project where there was limited opportunity for the level of research needed to develop the input parameters beyond hypothetical values. This scenario explores conditions where, through a combination of public and private sector actions, certain regions of the country specifically support pure hydrogen for space heat in buildings. The scenario also adds an option to retrofit the existing gas transmission system to transport 100% hydrogen, but this is regionally restricted, acknowledging that the pipeline system across Canada has a mix of vintages and materials, which will impact the cost or feasibility of this option.

The input parameters use the Hydrogen Supportive settings plus restrict the uptake of heat pumps equipment in Alberta, Saskatchewan, and Manitoba and, in Alberta only, allow existing gas pipelines to be retrofit, at a cost, to convey 100% hydrogen (see Table 10). Due to uncertainties on physical limits on the use of existing gas transmission pipelines to transport hydrogen, other scenarios require the model to build new transmission for hydrogen transportation needs. ESMIA received feedback both in favour of this option and concerned regarding feasibility.

These parameters lead to projections of increased hydrogen consumption, approximately 10% higher overall than in the Hydrogen Supportive scenario in 2050, with the greatest increase for consumption in buildings (almost 60% increase in hydrogen consumed in buildings relative to the Hydrogen Supportive Scenario and accounting for approximately 9% of total space heating energy use in buildings in 2050, see Table 11).

Caveat: the increased hydrogen consumption relative to the Hydrogen Supportive scenario is driven by both model parameter changes – increased allowance for hydrogen blending and restricted use of electricity for space heating. Additional model runs could help separate the impacts, but the further research questions remain regarding the model parameters:

- Is significant deterioration in heat pump performance in Canadian weather conditions likely or, alternatively, are there other reasons for limiting electric space heating equipment?
- Where would such restrictions make sense?

4.2.3. Gas Transmission Retrofit to H2 Scenario (hypothetical)

The Gas Transmission Retrofit scenario was suggested at a point in the project where there was limited opportunity for the level of research needed to develop the input parameters beyond hypothetical values. This scenario has the same parameters as the Regional Scenario, except that option to retrofit existing pipelines, at an assumed cost, to be able to carry 100% hydrogen, is allowed anywhere in Canada.

The main reason for modeling this hypothetical scenario was to test the impact on hydrogen consumption due to adding this option, with the other conditions, such as meeting Net Zero and competing technologies in place. The results show that hydrogen consumption does not change significantly from the Regional Hydrogen Scenario, increasing by less than 2%.

Comparing the results of the Regional Hydrogen and Gas Transmission Retrofit scenarios indicates that the cost of hydrogen new hydrogen transmission pipelines (rather than lower costs of retrofits), in regions outside of Alberta, has less impact on increasing hydrogen consumption than the impact of avoiding electric equipment for heating. Potential reasons for avoiding electric space heating (performance, electricity system operations, consumer behaviour) should be researched.

Caveat: The modelling here does not fully address the physical needs for retrofitting the pipeline system, including the co-ordination, costs, and timing of rolling out this level of change to the existing energy transportation system.

Table 11 Hydrogen consumed for heat in the Residential and Commercial sectors.
(showing consumption in both PJ and Mt of hydrogen)

	2030		2040		2050		
	PJ	Mt	PJ	Mt	PJ	Mt	% of total energy
Regional	50	0.41	56	0.47	231	1.92	8.8%
GasTransRetrofit	52	0.43	58	0.48	237	1.98	9.0%

4.2.4. Hydrogen Prices

Hydrogen prices are calculated in the model based on marginal costs at any given time, including costs of system expansion (for example, capital cost of production facilities). Thus, prices are highest when demand approaches or exceeds supply. The table below provides average marginal prices across all demand sectors, over the year. In the Export scenario, domestic hydrogen prices fall below the set export price by about 30%, which explains why a large quantity of hydrogen is produced for export in this scenario. For all three scenarios, hydrogen prices fall at an average of about $3.6/kg in 2050.

Table 12 Average hydrogen prices for additional scenarios ($/kg)

	Export	Regional	GasTransRetrofit
2030	1.91	1.75	1.71
2040	3.53	2.31	2.19
2050	3.60	3.65	3.64

4.3. Key Charts for the Additional Scenarios

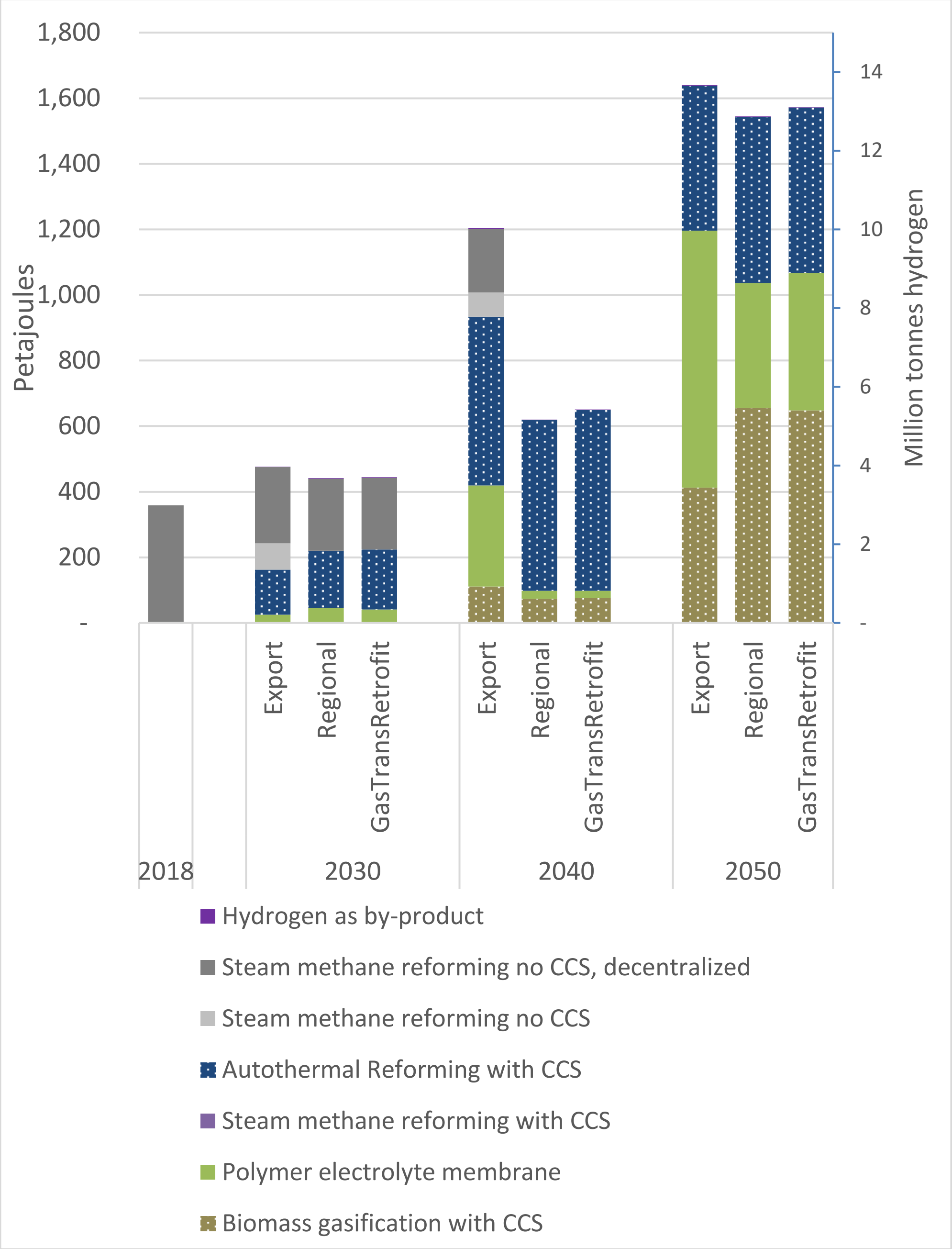


Figure 17 Hydrogen production for additional scenarios

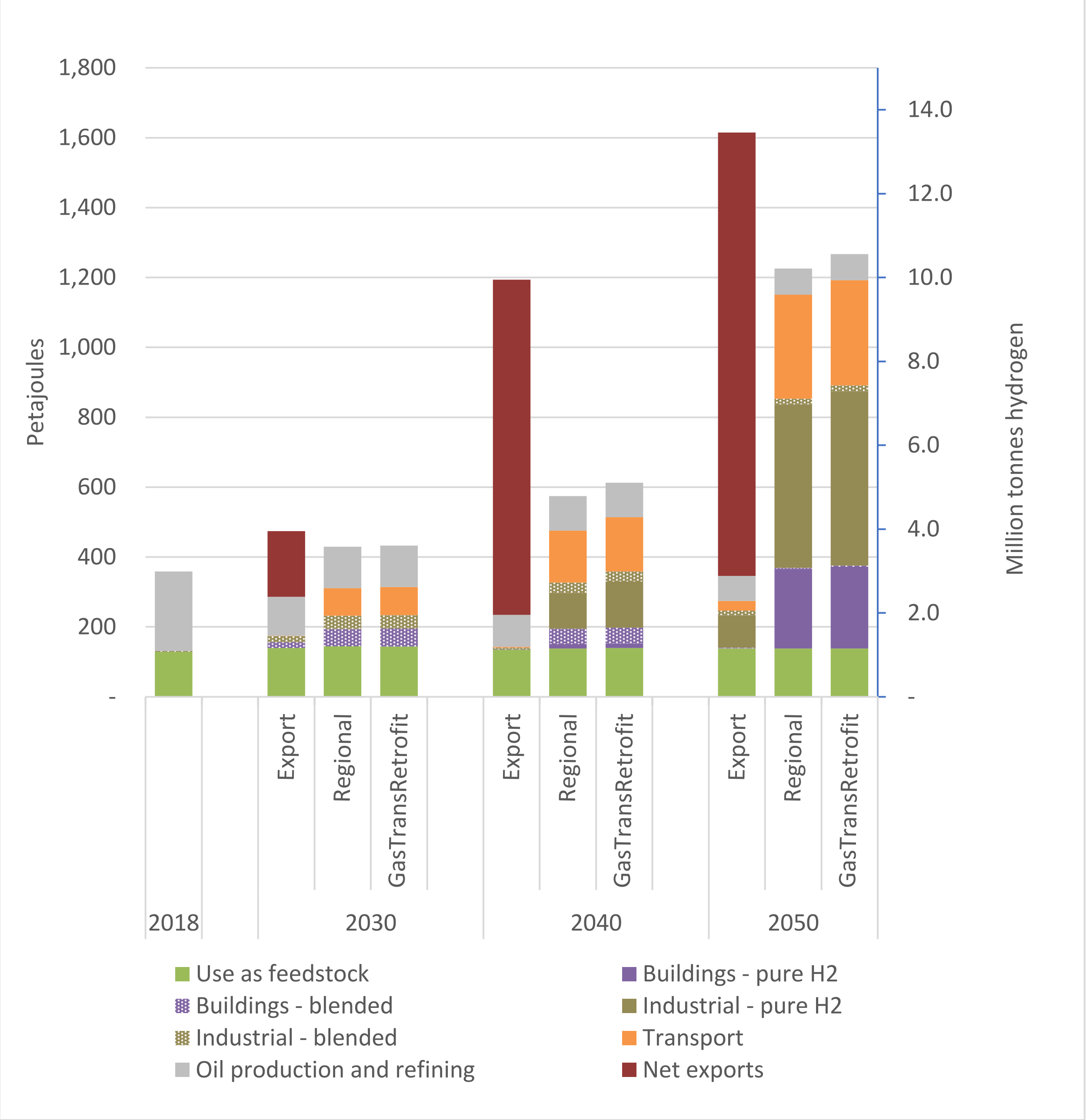


Figure 18 Hydrogen consumption for additional scenarios

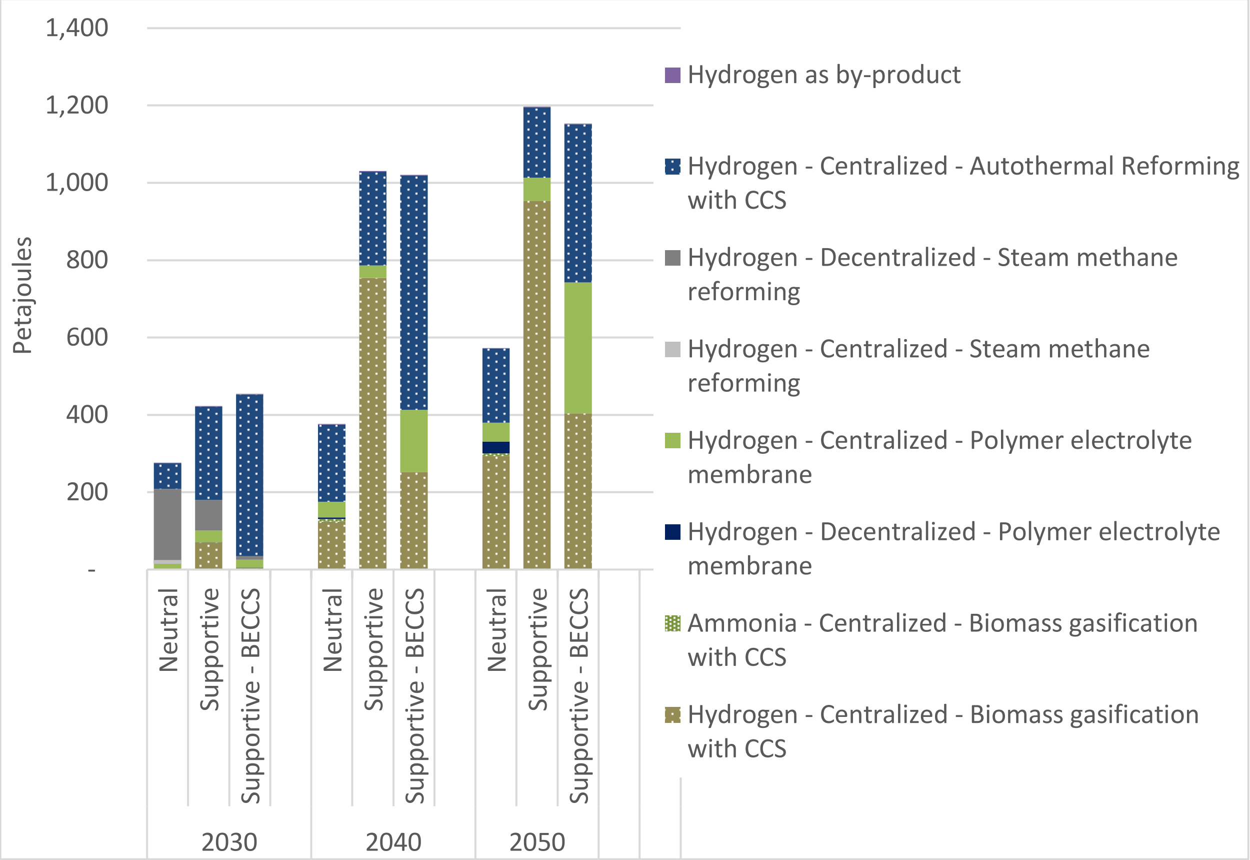
4.4. Sensitivity to Limits on Biomass Energy with CCS

An additional scenario was completed to assess sensitivity of hydrogen production to limiting biomass energy-based carbon capture and storage.

The “Supportive - BECCS” scenario, which was based on the capital cost reduction and other parameters of the Supportive scenario, limited the potential for centralized hydrogen production through biomass with carbon capture to 35% in 2050, due to debate around biomass-based carbon capture and storage (BECCS) relating to its impact on land use and lifecycle emissions.

Figure 19 shows that overall projections for hydrogen production decreases by about 6% in 2050 compared to the Supportive scenario, and production shifts primarily to centralized electrolysis along with an increase in centralized natural-gas-based production pathways. In contrast, hydrogen production increases by 12% in 2040, with a significant increase in natural gas-based production. We believe this reversal in the production trend is caused by the increasingly strict GHG emissions cap and shifting of emissions from other sectors to the hydrogen sector and vice versa. The corresponding decrease in hydrogen consumption affects mostly pure commercial uses, where demand drops by over 50% in 2050, and pure industrial use of hydrogen, where demand drops by 14% in 2050. In 2040, the hydrogen consumption increases mostly from pure industrial uses.

Overall, the results show that limiting BECCS is not a key driver for total amount of hydrogen consumption and production, however, it will naturally have a large impact on the choice of production technologies that are developed.



Note: 1 PJ of hydrogen corresponds to approximately 0.008 Mt of hydrogen (lower heating values).

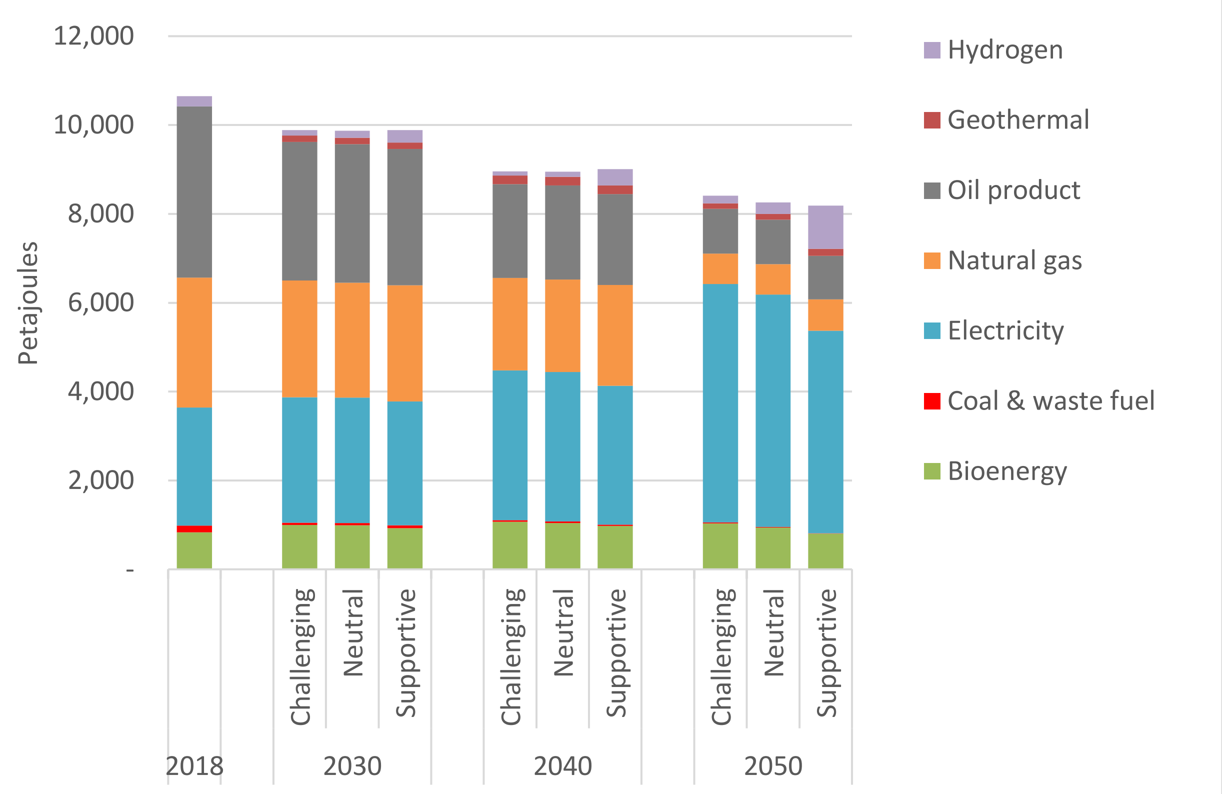
Figure 19 Hydrogen production by type, Hydrogen Supportive with BECCs limit sensitivity.

SECTION 5

6. Discussion

5.1. Hydrogen Consumption in Canada

The modelling results in Figure 20 show projected hydrogen consumption in Canada in 2050, under Net Zero GHG emission aligned conditions, meeting 2% of total final energy consumption in the Hydrogen Challenging scenario, 3% in the Technology Neutral scenario and 12% Hydrogen Supportive scenarios. The range in these scenarios reflects the uncertainties over the next decades related to technology costs and performance and the amount of policy support for hydrogen. All results here assume least-cost optimization over the time period.



Note: 1 PJ of hydrogen corresponds to approximately 0.008 Mt of hydrogen (lower heating values).

Figure 20 Total final energy consumed by energy type, three core scenarios.

By 2050, hydrogen is projected to play a role to support Canada in reaching its Net Zero GHG goal in all three core scenarios. These projections indicate that the potential size of the role depends strongly on the costs of producing and consuming hydrogen, which can be influenced by public sector policies.

- Reminder that the Hydrogen Supportive scenario includes capital cost subsidies in the range of 30% for hydrogen with the lowest GHG intensity, less subsidies for higher GHG intensive hydrogen. It also applies a production-based reduction effectively reducing variable costs by a $1.5/kg subsidy.
- Importantly for consumption in Canada, the Hydrogen Supportive scenario also includes capital cost reduction for equipment that consumes hydrogen, of approximately 20%, and allows higher blending rates with natural gas in the existing gas pipeline system.

By sector, industry and transportation are projected to have the largest potential for increased hydrogen consumption without cost reductions (in the Hydrogen Challenging and Technology Neutral scenarios). The buildings sector becomes a significant hydrogen consumer only in lower hydrogen cost settings of the Hydrogen Supportive scenario and only by 2050.

Cost reductions through support for technology evolution or direct subsidies are projected to have measurable impact on hydrogen consumption.

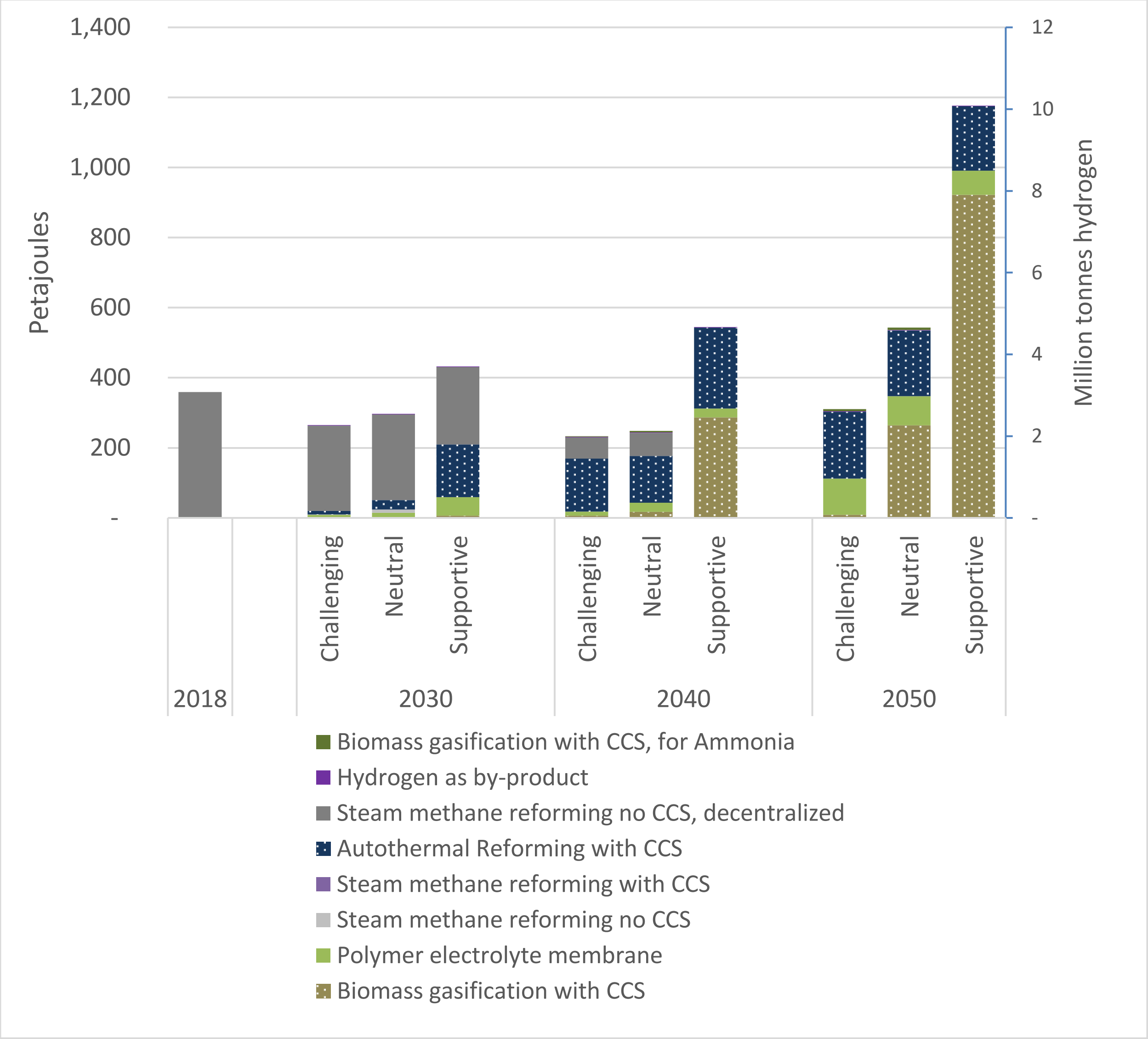
- Technology evolution from today's costs to that projected in the literature accounts for about 30% increase in consumption (comparing the Hydrogen Challenging to the Technology Neutral scenarios)
- Further technology evolution combined with policy support is projected to increase hydrogen consumption by nearly three times (Comparing the Hydrogen Supportive to the Technology Neutral scenarios).

5.2. Hydrogen Production in Canada

Figure 21 shows both hydrogen and ammonia production by technology type for the core three scenarios. The technologies projected to produce hydrogen change over time, based on hydrogen consumption requirements, and the support (of lack) for cost reductions.

Currently, most hydrogen is produced with SMR without CCS and this technology is projected to remain dominant in 2030, along with ATR with CCS and a small amount of electrolysis using PEM technology. By 2050 Canada's net-zero goal is projected to drive significant changes in production technology: SMR production without CCS will not be feasible; ATR with CCS that was installed by 2030 still produces at almost the same capacity in 2050; additional hydrogen needs are met by new PEM electrolysis combined with biomass gasification with CCS.

Producing hydrogen using biomass gasification with CCS is assumed to provide negative emissions due to accounting for sequestration credits during plant growth plus storing the CO_2 emissions released from biomass combustion. There are important caveats regarding these credits and technology, see Section 3.2.



Notes: Technology are centralized production of hydrogen unless noted in its name in the legend
Hydrogen energy is converted from petajoules to million tonnes using the factor 120.1 PJ/Mt.

Figure 21 Hydrogen and Ammonia Production by technology type, 2030, 2040 and 2050 (PJ)

5.3. Implications for Hydrogen Policy Development

Although not the focus of this hydrogen research, modelling and analysis, an obvious conclusion is that for Canada to reach Net-Zero GHG emissions by 2050 a large transformation of the energy system is required. Public and private sector will need to integrate this thinking in their strategies, including risk assessments, regardless of their roles in the hydrogen energy pathway.

- If Canada’s goal of Net-Zero GHG emissions by 2050 is changed, with increased or decreased stringency, the results in this analysis will need to be revised.

With the goal of reaching Net-Zero GHG emissions at the least social costs, hydrogen production and consumption are projected to remain near current levels without additional capital cost reductions and technology evolution due to competition from other low (or negative) GHG options.

- Such changes to hydrogen equipment could be supported by public and/or private sector actions in Canada and elsewhere.

This analysis, by design, did not cover specific policies and is not an impact analysis of government proposed policy directions (see Section 1.2). The results provide indications of the financial level of public sector support that could be needed to increase hydrogen consumption and production in Canada, based on the assumptions in this project.

- The capital cost reductions tested here are approximately 20% capital cost reductions for hydrogen consuming equipment, combined with cost reductions for hydrogen production equipment, provisions for existing pipelines to carry hydrogen (blended with natural gas or pure) and the policies to reach Net Zero.
- Lower levels of policy support on any of these elements would lead to lower hydrogen production and consumption.

The model results indicate potential role for Canada as a hydrogen exporter, with caveats as noted in the report related to global hydrogen prices, which are influenced by both demand for and supply costs of hydrogen in other countries.

The projections indicate hydrogen can play a role in supporting the achievement of Net-Zero GHG emissions in Canada, but its role in overall meeting Net-Zero emissions targets is small, based on the assumptions in this analysis.

- Public or private sector actions (by Canada and others) will impact the extent of hydrogen’s role.
- Goals for both hydrogen production and consumption should be clearly articulated as increasing both may be less beneficial.
- Government may consider stating goals on other roles for hydrogen, such as supporting existing energy infrastructure (gas pipelines) or providing new energy exports, separately from GHG emissions goals.

ANNEX A

Annex A – The North American TIMES Energy Model (NATEM)

For this project, we used the Canadian module of its North American TIMES Energy Model (NATEM). NATEM-Canada describes the entire integrated energy system, as well as non-energy emitting sectors of the 13 Canadian jurisdictions, and provide a rigorous analytical basis for identifying least-cost solutions to achieve energy and climate objectives without compromising economic growth. NATEM-Canada is part of a larger framework covering the whole North American continent. It includes a large number of technologies allowing to reach deep decarbonisation levels (including net-zero targets by 2050).

An economy-wide and dynamic optimization approach

Optimization models of energy-economy-environmental (E3) systems such as NATEM provide a rigorous analytical basis for studying the transition toward a clean energy future in a detailed multi-regional, multi-sector and multi-fuel framework.

- Optimization models provide a very detailed representation of the technological changes required in the long term, as well as their costs, to meet growing demands and/or to reach specific goals.
- In addition, they provide important additional features compared with other types of energy system models, such as simulation models. They endogenously provide an optimal configuration of the energy sector which makes it possible to satisfy the total demand for energy services at lower cost, while respecting system constraints (resource limitations, renewable targets, GHG taxes or mitigation targets, energy policies, etc.). These models are typically projected to very long-term horizon, which makes it possible to study the structural changes within the energy sector. In addition, the linear programming approach quickly solves very complex problems.
- The TIMES optimization model generator in particular is the most advanced and widespread; it is used by numerous teams in 70 countries. It is a rigorous methodology, well documented[16] and which is constantly improved through an international collaboration network (ETSAP-International Energy Agency).
- NATEM is an application of the TIMES model generator for North America and represents the most detailed optimization model covering the Canadian energy systems.

NATEM is a dynamic least-cost optimization model based on the linear programming approach, and as such contains three components.

- The first component (objective) corresponds to minimizing the net total discounted cost (e.g. 3-5% is typically used in deep decarbonisation studies) of the entire energy system. A single optimization, which searches for the maximal net total surplus, simulates market equilibrium for each commodity (energy, material, demand). Maximizing the net total surplus (i.e. the sum of producers' and consumers' surpluses) is operationally done by minimizing the net total cost of the energy system.
- The second component (variables) corresponds mainly to future investments and activities of technologies at each time period, amount of energy produced or consumed by technologies, as well as energy imports and exports. An additional output of the model is the implicit price (shadow price)

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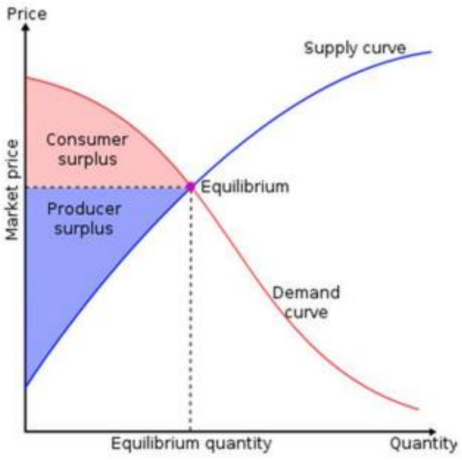
[16] Loulou R, Goldstein G, Kanudia A, Lehtila A, Remme U. (2016). Documentation for the TIMES Model. Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA). Retrieved from http://iea-etsap.org/index.php/documentation.

of each energy form, material and emission, as well as the reduced cost of each technology (reduction required to make a technology competitive).

- The third component (constraints) corresponds to various limits (e.g. amount of energy resources available) and obligations (e.g. energy balances throughout the system, useful energy demand satisfaction) to be respected.

Computing partial equilibrium on energy markets with elastic demands to capture feedback from the economy to the energy system



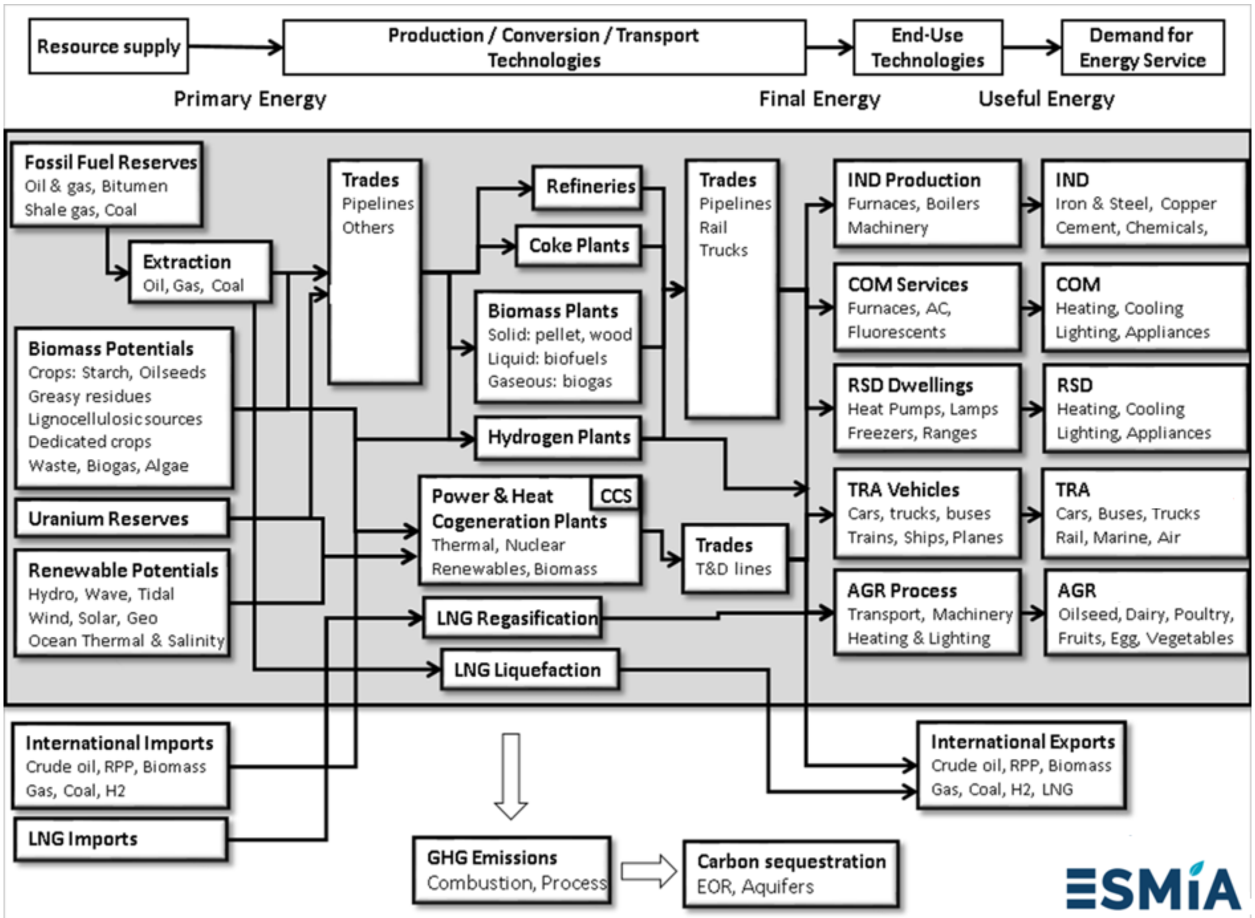
By default, TIMES assumes competitive markets for all commodities, unless specified differently by the modeller, with perfect foresight. The model computes both the flows of energy (materials and pollutants) and their prices, in such a way that the suppliers of energy produce exactly the amounts that the consumers are willing to buy. The total economic surplus is maximized when all markets are in equilibrium (or total system cost is minimized). Energy services are elastic to their own prices, capturing the main feedback from the economy to the energy system.

A detailed representation of North American energy systems

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 pollutant coefficients. It thus 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 covers the energy system from extraction, processing, final then useful energy and included exports and imports, see simplified representation below.



An extremely rich technology database for all 13 Canadian jurisdictions

NATEM describes the entire integrated energy system of the 13 Canadian jurisdictions, including inter-jurisdictional flows of energy commodities and transportation infrastructure, as well as non-energy emitting sectors such as industrial processes, agriculture and waste.

- The model database describes 475 such commodities in each jurisdiction, as well as more than 4,500 explicit technologies.
- NATEM is driven by 65 end-use demands for energy services, projected to the 2060 horizon in physical units (e.g., passengers- and tons- kilometres for transport segments).

- Demands for energy services are currently projected through 2060 using a coherent set of socio-economic projections (GDP, population, industrial gross outputs, etc.) from national and provincial sources. Other factors are considered for adjustments such as future announced projects.
- For the energy supply side, NATEM captures all sectors including electricity and heat generation in many details. Other supply sectors include fossil fuel extraction, upgrading and transport, uranium extraction and transport, petroleum refining, bioenergy production, natural gas liquefaction and exports, hydrogen supply chain, renewable natural gas production and upgrading, etc.
- Primary energy resources include conventional and unconventional fossil fuels reserves (oil, gas, and coal), renewable potential (hydro, geothermal, wind, solar, tidal and wave), uranium reserves and biomass (various solid, liquid and gaseous sources).
- Carbon capture options are available in the electricity, hydrogen, oil upgrading, and industrial sectors. Sequestration potential exists for enhanced oil recovery, in oil and gas fields (onshore and offshore) and in deep saline aquifers. Direct air capture is also covered.
- The model is currently solved for the 2016-2060 timeframe. These projections rely on time periods of variable and flexible length, shorter at the beginning (1 to 2 years) and longer (5 years) at the end of the horizon. Besides, each time period is divided into flexible and hierarchical annual time slices. There are currently sixteen time slices representing four seasons a year (spring, summer, fall and winter) and four intraday periods (day, night, morning peak, evening peak).
- The model tracks all GHGs, including carbon dioxide (CO2), methane (CH4), nitrous oxide (N20), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3) from all sectors of the national inventories, except land use, land-use change and forestry (LULUCF).

NATEM is currently used in several research and consulting projects in Canada.

A powerful decision-making tool that is regularly used to inform climate action in North America

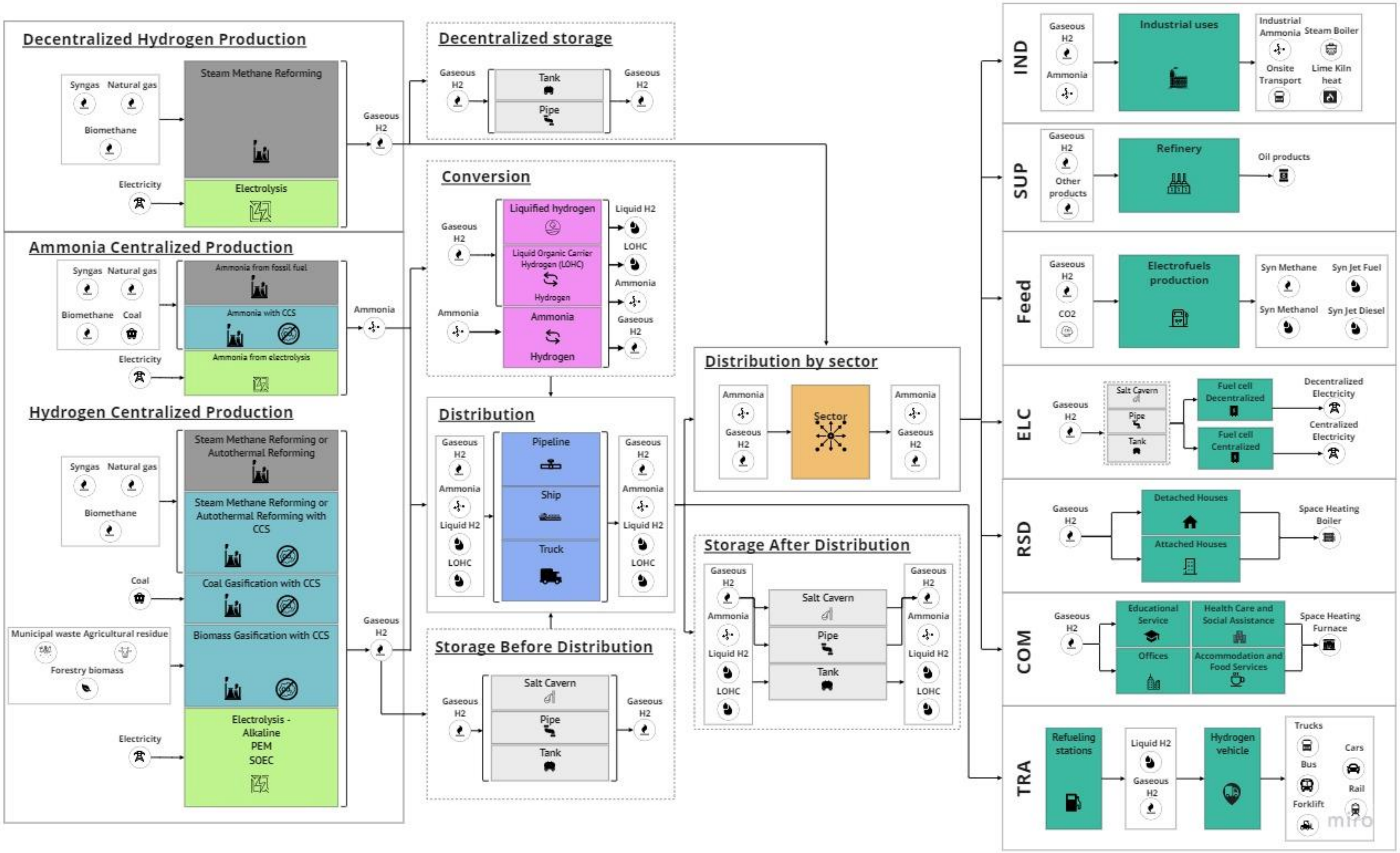
NATEM represents most major low-carbon technologies that are envisaged being available for at least the first half of the 21st century. By capturing the substitution of low-carbon for high-carbon technologies in response to their relative costs, as well as emissions constraints and/or carbon prices, the NATEM model simulates mitigation. It enables capturing in particular substitutions of energy forms (e.g., switching to low-carbon fuels) and energy technologies (e.g., use of battery-electric vehicles instead of vehicles equipped with an internal combustion engine running on conventional fuels) to comply with renewable electricity or climate policy targets. NATEM also has the capability of estimating the price-based response of these energy service demands to the changing conditions of scenarios in which mitigation occurs via a set of demand price elasticities.

NATEM predominantly works by specifying either a GHG price (e.g., a carbon tax) or a GHG limit (e.g., a carbon cap, target, constraint) in one or several regions, or alternatively for all regions simultaneously. Additionally, the following further policies and measures can be implemented: subsidies or taxes on specific technologies, renewable portfolio standards, minimum renewable content in conventional fuels, phase out programs and moratoria on energy types (e.g., nuclear or coal), investment growth rate projections, etc.

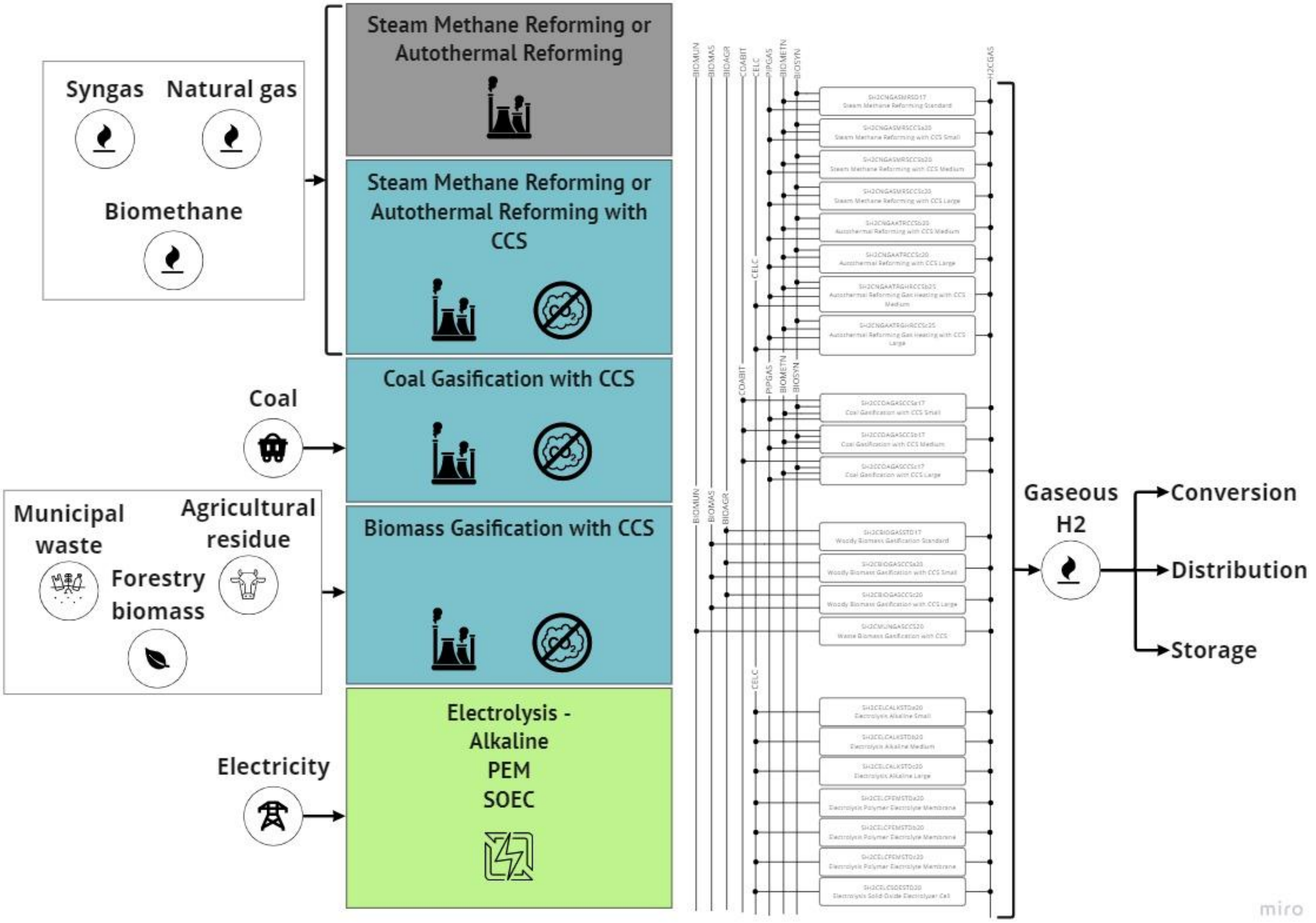
This allows NATEM to perform a number of energy and climate policy-relevant investigations. NATEM has been used to assess the implications of meeting ambitious GHG mitigation goals on the energy system configuration and cost, under many different economic and technical assumptions. NATEM model's results have been used by decision makers from public and private organizations to : i) draft climate action plans, with optimal sequences for the introduction of mitigation measures, ii) identify strategic research priorities to reduce mitigation costs, while contributing to economic development, iii) prepare Canadian energy outlooks including net-zero scenarios, iv) prepare technological roadmaps, v) evaluate the economic and environmental impacts of energy projects, vi) analyze energy security issues. Results on different topics were also validated in numerous peer-reviewed journals.

Annex B – Hydrogen in NATEM

The following charts are examples, non-exhaustive of hydrogen representation in NATEM. Not all hydrogen technologies are included here.


Decentralized Hydrogen Production
Syngas
Natural gas
Biomethane
Steam Methane Reforming
Electricity
Electrolysis
Gaseous H2
Ammonia Centralized Production
Syngas
Natural gas
Biomethane
Coal
Ammonia from fossil fuel
Ammonia with CCS
Electricity
Ammonia from electrolysis
Ammonia
Hydrogen Centralized Production
Syngas
Natural gas
Biomethane
Steam Methane Reforming or Autothermal Reforming
Steam Methane Reforming or Autothermal Reforming with CCS
Coal
Coal Gasification with CCS
Municipal waste Agricultural residue
Forestry biomass
Biomass Gasification with CCS
Electricity
Electrolysis - Alkaline PEM SOEC
Gaseous H2
Decentralized storage
Gaseous H2
Tank
Pipe
Gaseous H2
Conversion
Gaseous H2
Ammonia
Liquified hydrogen
Liquid Organic Carrier Hydrogen (LOHC)
Hydrogen
Ammonia
Hydrogen
Liquid H2
LOHC
Ammonia
Gaseous H2
Distribution
Gaseous H2
Ammonia
Liquid H2
LOHC
Pipeline
Ship
Truck
Gaseous H2
Ammonia
Liquid H2
LOHC
Storage Before Distribution
Gaseous H2
Salt Cavern
Pipe
Tank
Gaseous H2
Distribution by sector
Ammonia
Gaseous H2
Sector
Ammonia
Gaseous H2
Storage After Distribution
Gaseous H2
Ammonia
Liquid H2
LOHC
Salt Cavern
Pipe
Tank
Gaseous H2
Ammonia
Liquid H2
LOHC
IND
Gaseous H2
Ammonia
Industrial uses
Industrial Ammonia
Steam Boiler
Onsite Transport
Lime Kiln heat
SUP
Gaseous H2
Other products
Refinery
Oil products
Feed
Gaseous H2
CO2
Electrofuels production
Syn Methane
Syn Jet Fuel
Syn Methanol
Syn Jet Diesel
ELC
Gaseous H2
Salt Cavern
Pipe
Tank
Fuel cell Decentralized
Fuel cell Centralized
Decentralized Electricity
Centralized Electricity
RSD
Gaseous H2
Detached Houses
Attached Houses
Space Heating Boiler
COM
Gaseous H2
Educational Service
Health Care and Social Assistance
Offices
Accommodation and Food Services
Space Heating Furnace
TRA
Refueling stations
Liquid H2
Gaseous H2
Hydrogen vehicle
Trucks
Cars
Bus
Rail
Forklift
miro

Hydrogen Centralized Production



Syngas

Natural gas

Biomethane

Steam Methane Reforming or Autothermal Reforming

Steam Methane Reforming or Autothermal Reforming with CCS

Coal

Coal Gasification with CCS

Municipal waste

Agricultural residue

Forestry biomass

Biomass Gasification with CCS

Electricity

Electrolysis -
Alkaline
PEM
SOEC

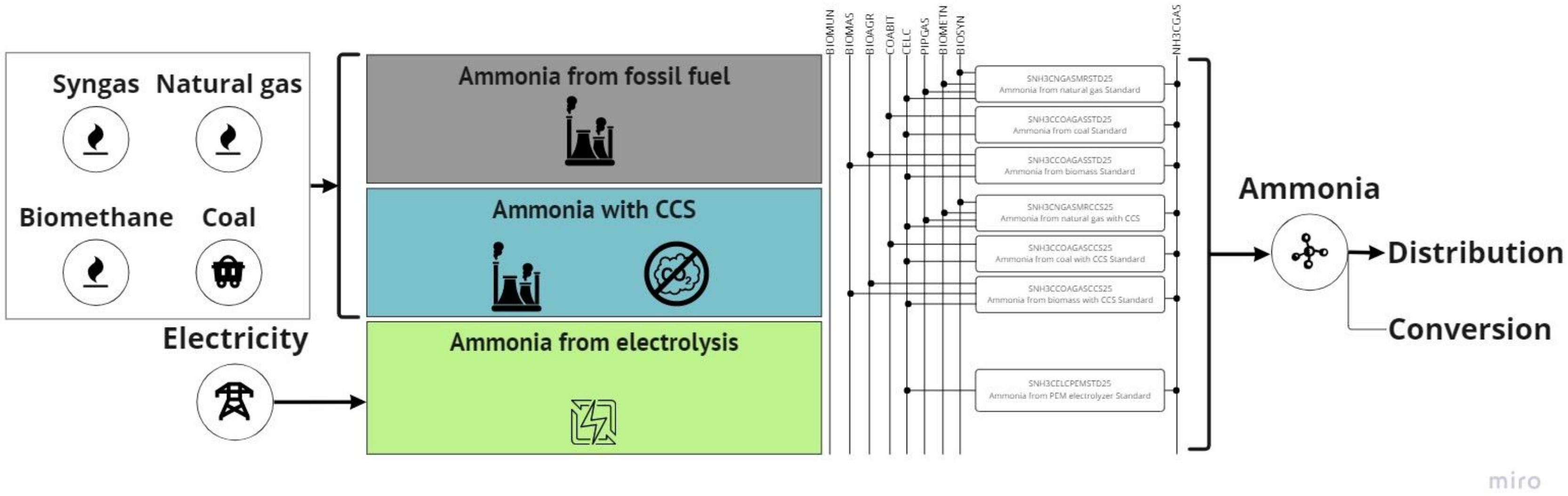
Gaseous H2

Conversion

Distribution

Storage

Ammonia Centralized Production



Syngas

Natural gas

Biomethane

Coal

Electricity

Ammonia from fossil fuel

Ammonia with CCS

Ammonia from electrolysis

BIOMUN

BIOMAS

BIOAGR

COABIT

CELC

PIPGAS

BIOMETN

BIOSYN

NH3CGAS

SNH3CNGASMRSTD25
Ammonia from natural gas Standard

SNH3CCOAGASSTD25
Ammonia from coal Standard

SNH3CCOAGASSTD25
Ammonia from biomass Standard

SNH3CNGASMRCCS25
Ammonia from natural gas with CCS

SNH3CCOAGASCCS25
Ammonia from coal with CCS Standard

SNH3CCOAGASCCS25
Ammonia from biomass with CCS Standard

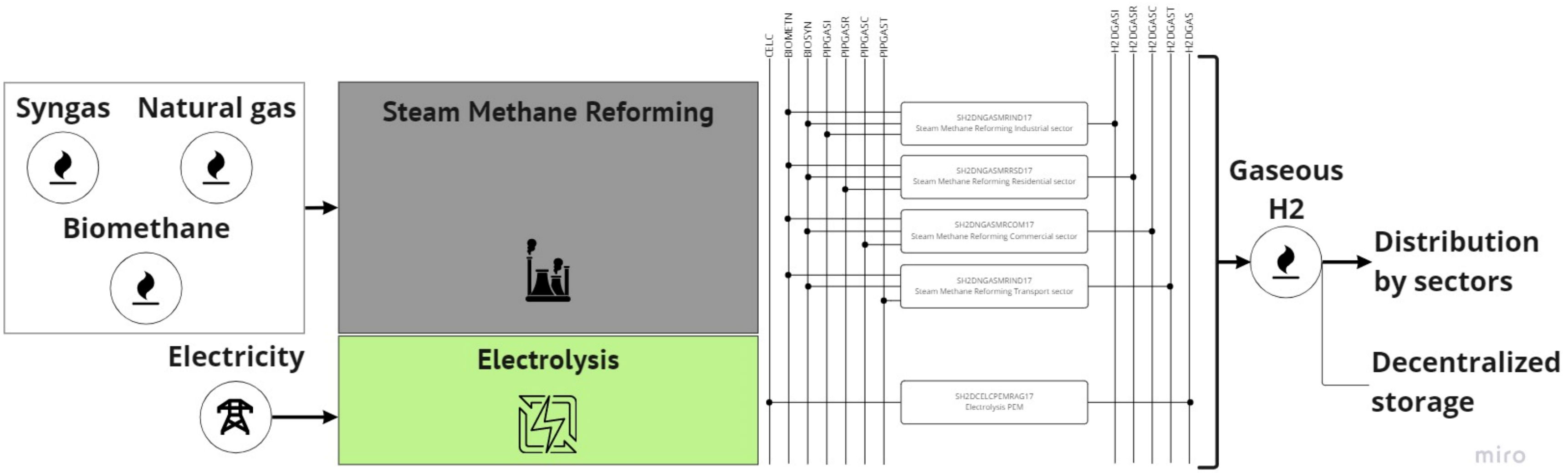
SNH3CELCPEMSTD25
Ammonia from PEM electrolyzer Standard

Ammonia

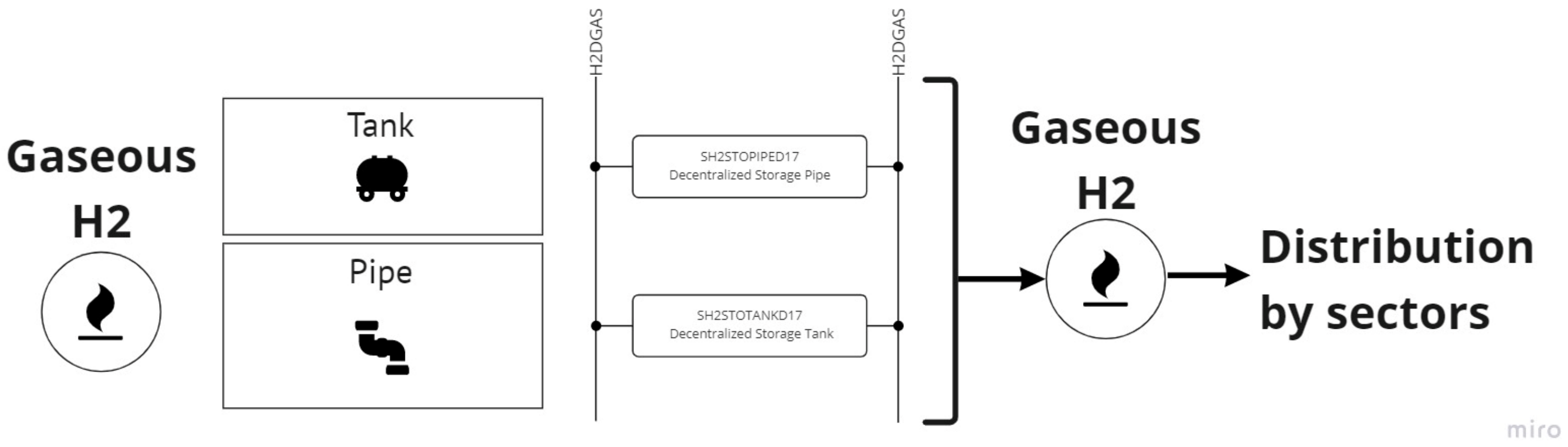
Distribution

Conversion

Decentralized Hydrogen Production



Decentralized storage



Gaseous H2

Tank

Pipe

H2DGAS

SH2STOPIPED17
Decentralized Storage Pipe

SH2STOTANKD17
Decentralized Storage Tank

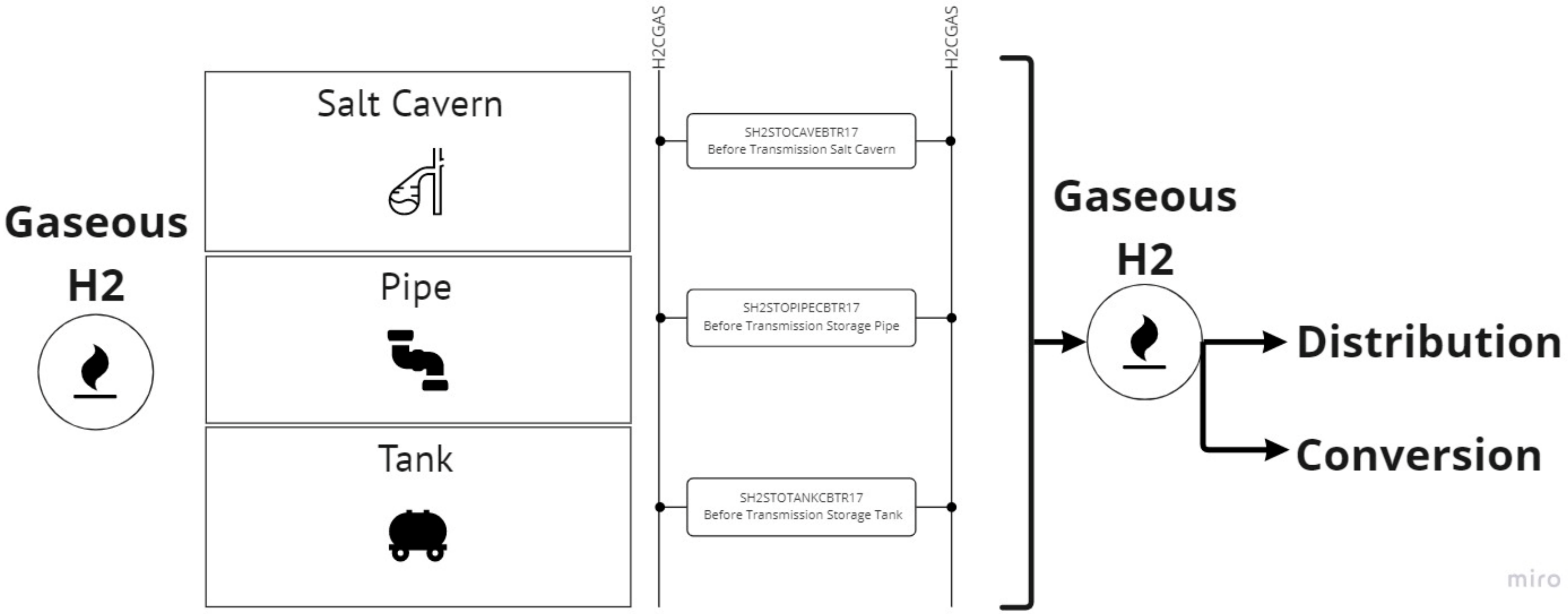
H2DGAS

Gaseous H2

Distribution by sectors

miro

Storage Before Distribution



Gaseous H2

Salt Cavern

Pipe

Tank

H2CGAS

SH2STOCAVEBTR17
Before Transmission Salt Cavern

SH2STOPIPECBTR17
Before Transmission Storage Pipe

SH2STOTANKCBTR17
Before Transmission Storage Tank

H2CGAS

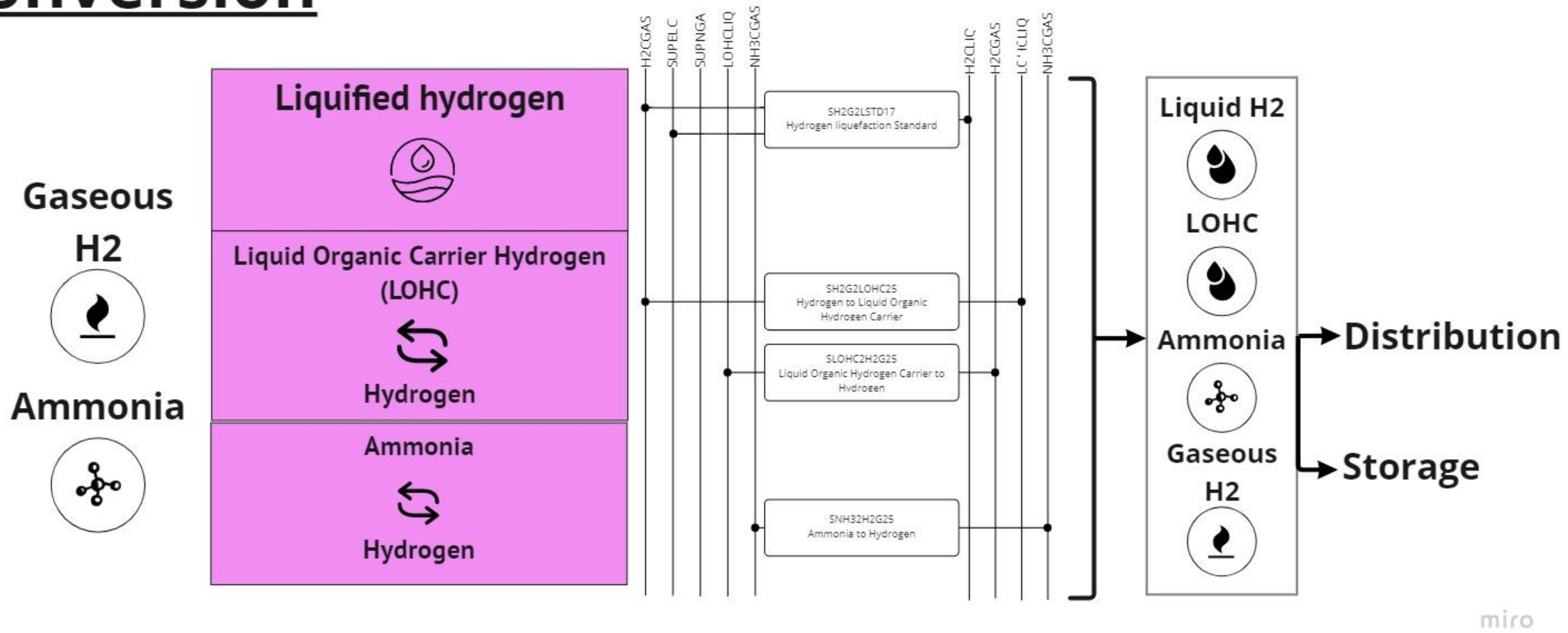
Gaseous H2

Distribution

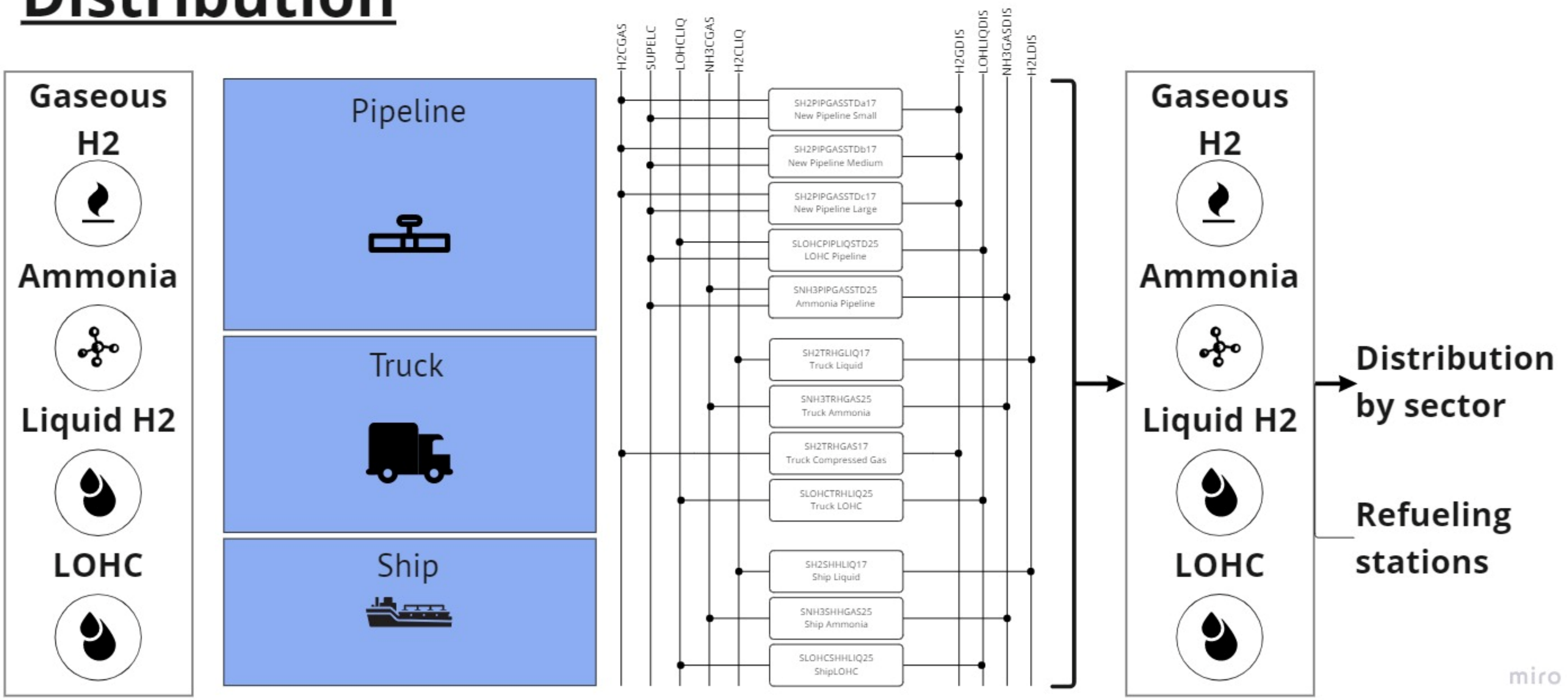
Conversion

miro

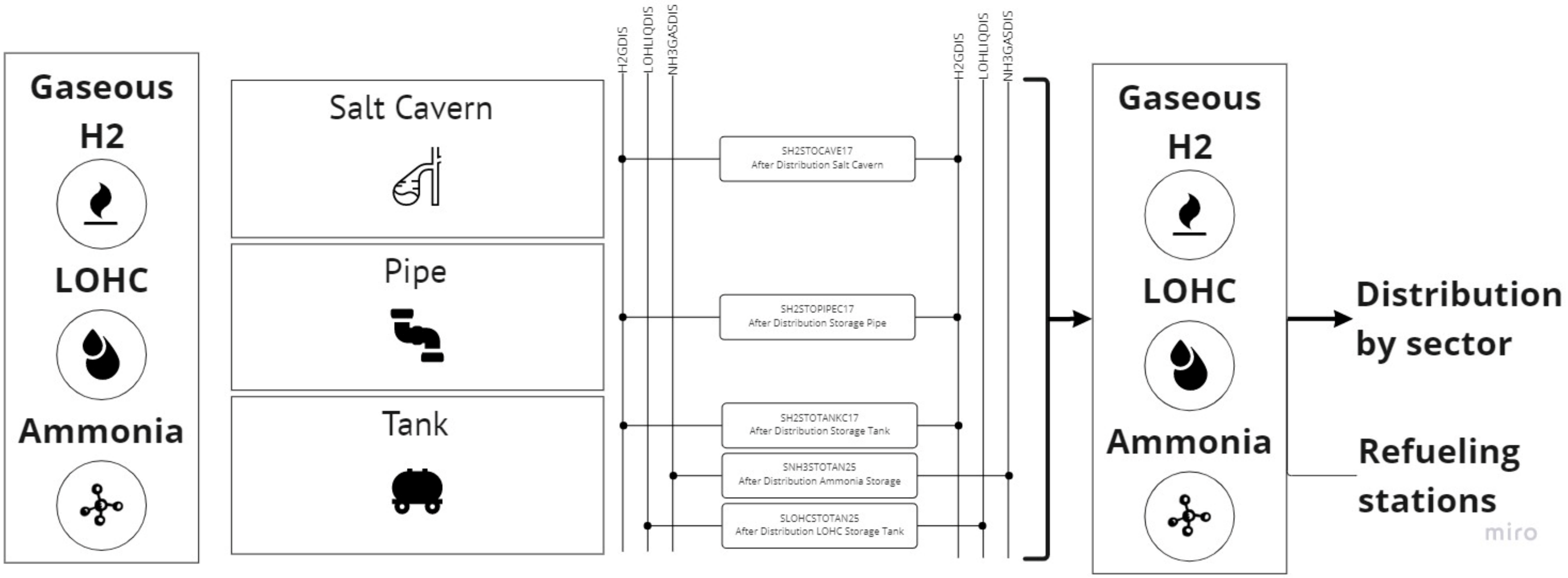
Conversion


Gaseous H2
Ammonia
Liquified hydrogen
Liquid Organic Carrier Hydrogen (LOHC)
Hydrogen
Ammonia
Hydrogen
H2CGAS
SUPELC
SUPNGA
LOHCLIQ
NH3CGAS
SH2G2LSTD17
Hydrogen liquefaction Standard
SH2G2LOHC25
Hydrogen to Liquid Organic Hydrogen Carrier
SLOHC2H2G25
Liquid Organic Hydrogen Carrier to Hydrogen
SNH32H2G25
Ammonia to Hydrogen
H2CLIC
H2CGAS
LC'ICLIQ
NH3CGAS
Liquid H2
LOHC
Ammonia
Gaseous H2
Distribution
Storage
miro

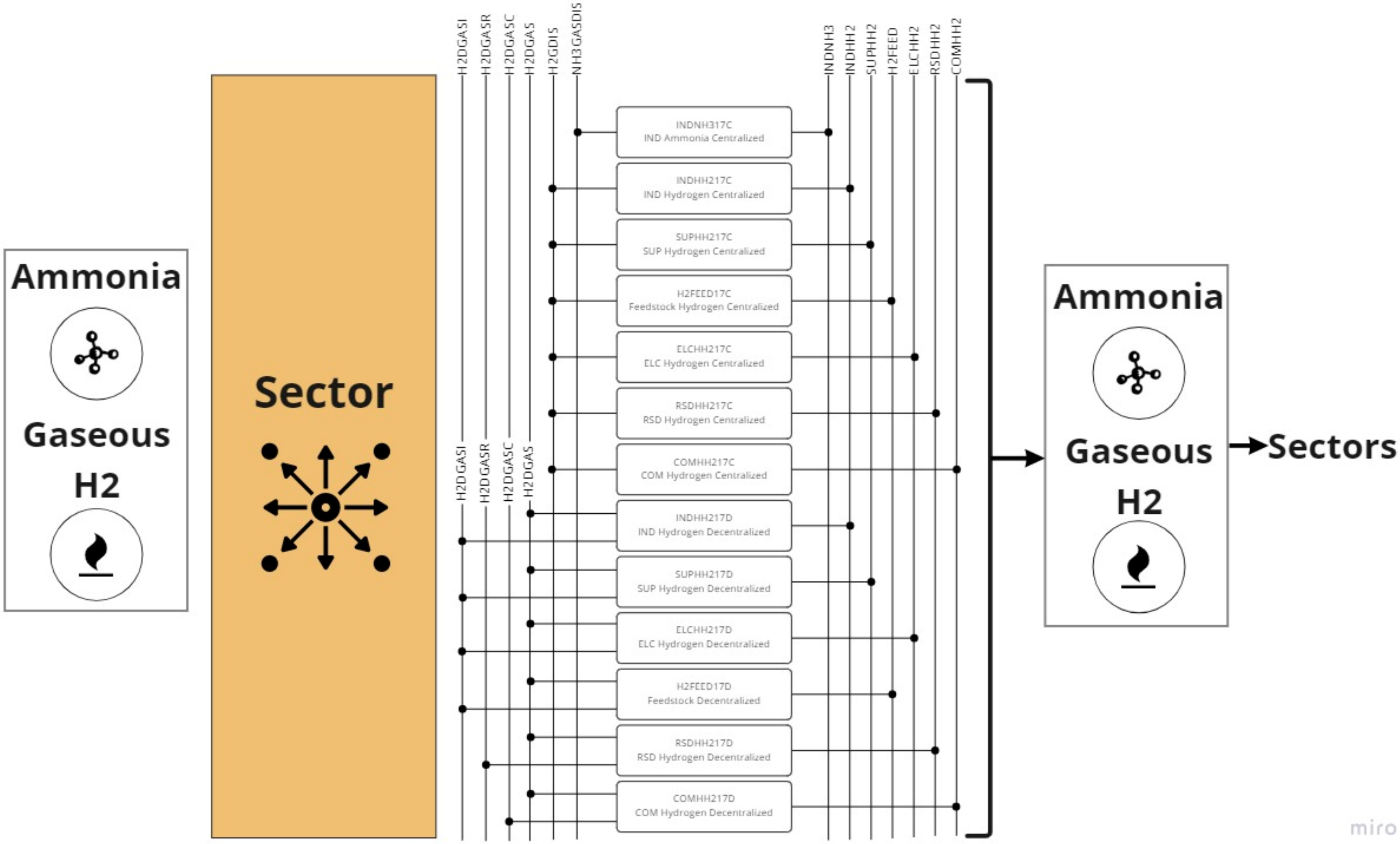
Distribution



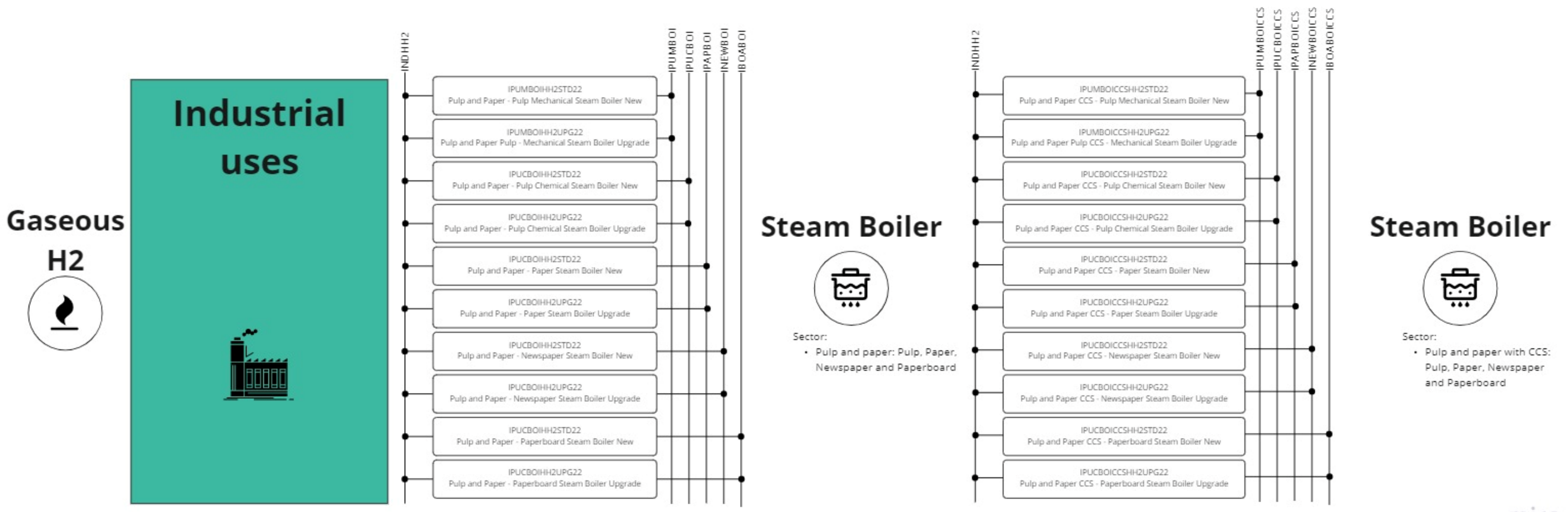
Storage After Distribution



Distribution by sector



Industrial sector



Gaseous H2

Industrial uses

INDHH2

IPUMBOIHH2STD22
Pulp and Paper - Pulp Mechanical Steam Boiler New

IPUMBOIHH2UPG22
Pulp and Paper Pulp - Mechanical Steam Boiler Upgrade

IPUCBOIHH2STD22
Pulp and Paper - Pulp Chemical Steam Boiler New

IPUCBOIHH2UPG22
Pulp and Paper - Pulp Chemical Steam Boiler Upgrade

IPUCBOIHH2STD22
Pulp and Paper - Paper Steam Boiler New

IPUCBOIHH2UPG22
Pulp and Paper - Paper Steam Boiler Upgrade

IPUCBOIHH2STD22
Pulp and Paper - Newspaper Steam Boiler New

IPUCBOIHH2UPG22
Pulp and Paper - Newspaper Steam Boiler Upgrade

IPUCBOIHH2STD22
Pulp and Paper - Paperboard Steam Boiler New

IPUCBOIHH2UPG22
Pulp and Paper - Paperboard Steam Boiler Upgrade

IPUMBOI
IPUCBOI
IPAPBOI
INEWBOI
IBOABOI

Steam Boiler

Sector:
- Pulp and paper: Pulp, Paper, Newspaper and Paperboard

INDHH2

IPUMBOICCSHH2STD22
Pulp and Paper CCS - Pulp Mechanical Steam Boiler New

IPUMBOICCSHH2UPG22
Pulp and Paper Pulp CCS - Mechanical Steam Boiler Upgrade

IPUCBOICCSHH2STD22
Pulp and Paper CCS - Pulp Chemical Steam Boiler New

IPUCBOICCSHH2UPG22
Pulp and Paper CCS - Pulp Chemical Steam Boiler Upgrade

IPUCBOICCSHH2STD22
Pulp and Paper CCS - Paper Steam Boiler New

IPUCBOICCSHH2UPG22
Pulp and Paper CCS - Paper Steam Boiler Upgrade

IPUCBOICCSHH2STD22
Pulp and Paper CCS - Newspaper Steam Boiler New

IPUCBOICCSHH2UPG22
Pulp and Paper CCS - Newspaper Steam Boiler Upgrade

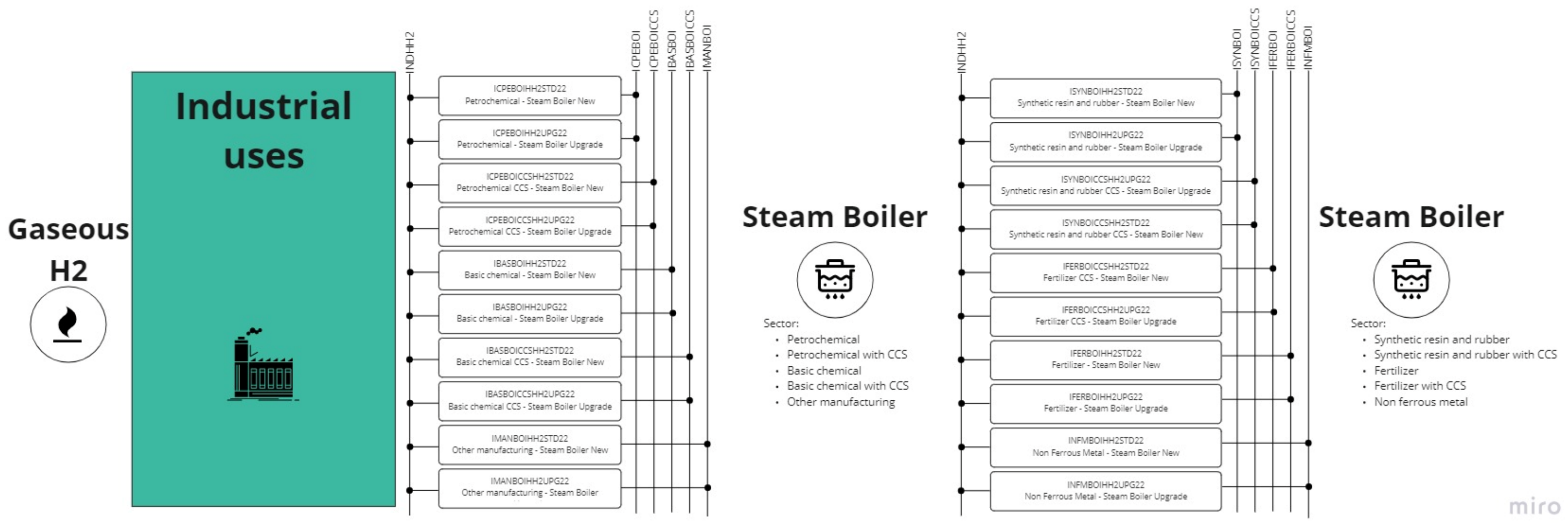
IPUCBOICCSHH2STD22
Pulp and Paper CCS - Paperboard Steam Boiler New

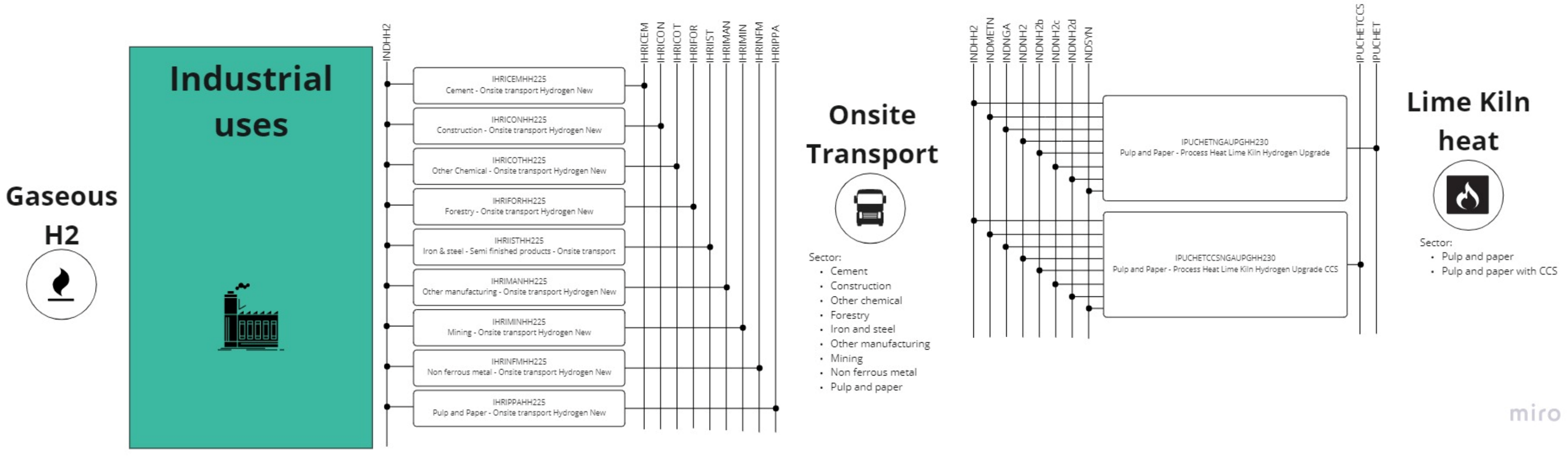
IPUCBOICCSHH2UPG22
Pulp and Paper CCS - Paperboard Steam Boiler Upgrade

IPUMBOICCS
IPUCBOICCS
IPAPBOICCS
INEWBOICCS
IBOABOICCS

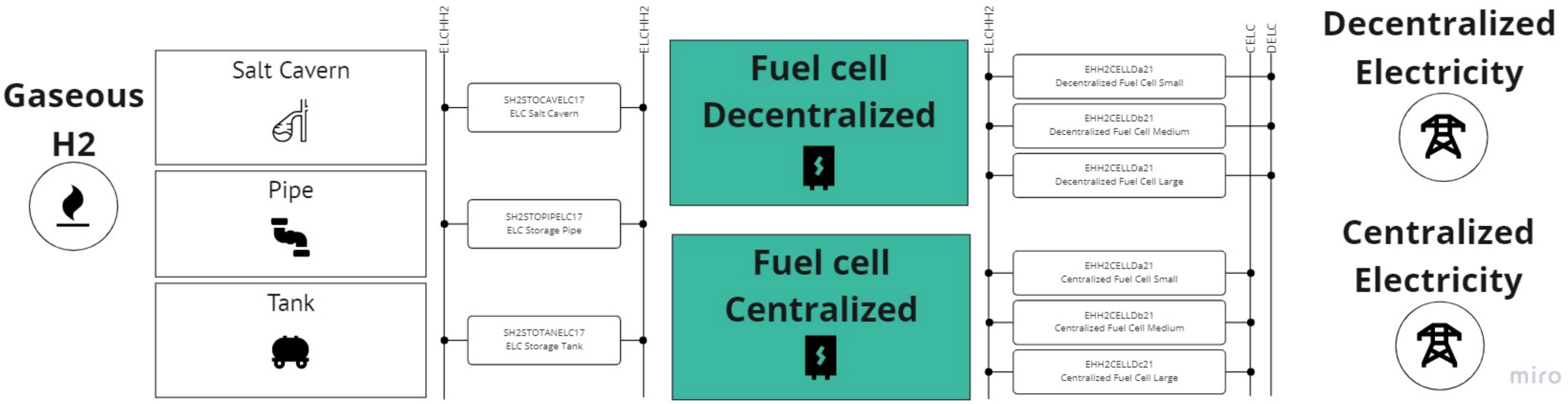
Steam Boiler

Sector:
- Pulp and paper with CCS: Pulp, Paper, Newspaper and Paperboard

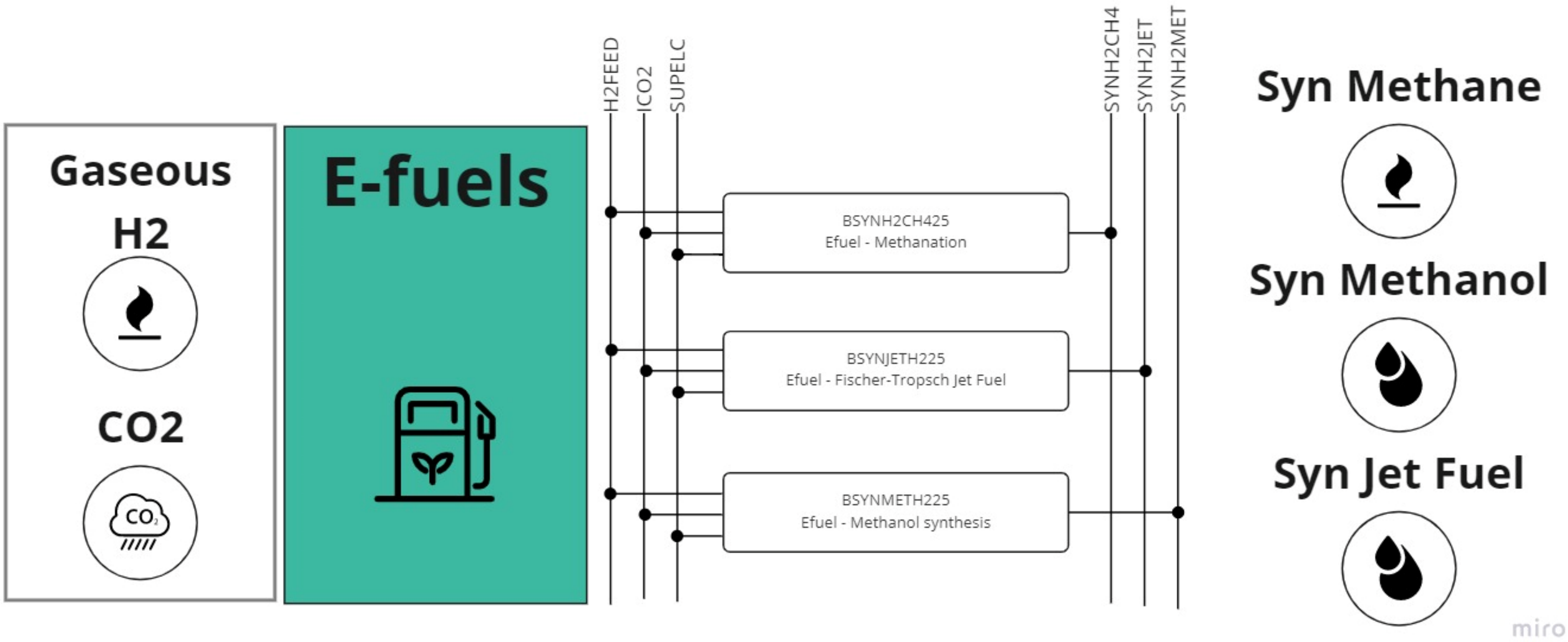

Gaseous H2
Industrial uses
INDHH2
ICPEBOI
ICPEBOICCS
IBASBOI
IBASBOICCS
IMANBOI
ICPEBOIHH2STD22
Petrochemical - Steam Boiler New
ICPEBOIHH2UPG22
Petrochemical - Steam Boiler Upgrade
ICPEBOICCSHH2STD22
Petrochemical CCS - Steam Boiler New
ICPEBOICCSHH2UPG22
Petrochemical CCS - Steam Boiler Upgrade
IBASBOIHH2STD22
Basic chemical - Steam Boiler New
IBASBOIHH2UPG22
Basic chemical - Steam Boiler Upgrade
IBASBOICCSHH2STD22
Basic chemical CCS - Steam Boiler New
IBASBOICCSHH2UPG22
Basic chemical CCS - Steam Boiler Upgrade
IMANBOIHH2STD22
Other manufacturing - Steam Boiler New
IMANBOIHH2UPG22
Other manufacturing - Steam Boiler
Steam Boiler
Sector:
Petrochemical
Petrochemical with CCS
Basic chemical
Basic chemical with CCS
Other manufacturing
INDHH2
ISYNBOI
ISYNBOICCS
IFERBOI
IFERBOICCS
INFMBOI
ISYNBOIHH2STD22
Synthetic resin and rubber - Steam Boiler New
ISYNBOIHH2UPG22
Synthetic resin and rubber - Steam Boiler Upgrade
ISYNBOICCSHH2UPG22
Synthetic resin and rubber CCS - Steam Boiler Upgrade
ISYNBOICCSHH2STD22
Synthetic resin and rubber CCS - Steam Boiler New
IFERBOICCSHH2STD22
Fertilizer CCS - Steam Boiler New
IFERBOICCSHH2UPG22
Fertilizer CCS - Steam Boiler Upgrade
IFERBOIHH2STD22
Fertilizer - Steam Boiler New
IFERBOIHH2UPG22
Fertilizer - Steam Boiler Upgrade
INFMBOIHH2STD22
Non Ferrous Metal - Steam Boiler New
INFMBOIHH2UPG22
Non Ferrous Metal - Steam Boiler Upgrade
Steam Boiler
Sector:
Synthetic resin and rubber
Synthetic resin and rubber with CCS
Fertilizer
Fertilizer with CCS
Non ferrous metal
miro


Gaseous H2
Industrial uses
INDHH2
IHRICEM
IHRICON
IHRICOT
IHRIFOR
IHRIIST
IHRIMAN
IHRIMIN
IHRINFM
IHRIPPA
IHRICEMHH225
Cement - Onsite transport Hydrogen New
IHRICONHH225
Construction - Onsite transport Hydrogen New
IHRICOTHH225
Other Chemical - Onsite transport Hydrogen New
IHRIFORHH225
Forestry - Onsite transport Hydrogen New
IHRIISTHH225
Iron & steel - Semi finished products - Onsite transport
IHRIMANHH225
Other manufacturing - Onsite transport Hydrogen New
IHRIMINHH225
Mining - Onsite transport Hydrogen New
IHRINFMHH225
Non ferrous metal - Onsite transport Hydrogen New
IHRIPPAHH225
Pulp and Paper - Onsite transport Hydrogen New
Onsite Transport
Sector:
Cement
Construction
Other chemical
Forestry
Iron and steel
Other manufacturing
Mining
Non ferrous metal
Pulp and paper
INDHH2
INDMETN
INDNGA
INDNH2
INDNH2b
INDNH2c
INDNH2d
INDSYN
IPUCHETCCS
IPUCHET
IPUCHETNGAUPGHH230
Pulp and Paper - Process Heat Lime Kiln Hydrogen Upgrade
IPUCHETCCSNGAUPGHH230
Pulp and Paper - Process Heat Lime Kiln Hydrogen Upgrade CCS
Lime Kiln heat
Sector:
Pulp and paper
Pulp and paper with CCS
miro

Electricity sector



Fuel sector



Gaseous

H2

CO2

E-fuels

H2FEED

ICO2

SUPELC

BSYNH2CH425
Efuel - Methanation

BSYNJETH225
Efuel - Fischer-Tropsch Jet Fuel

BSYNMETH225
Efuel - Methanol synthesis

SYNH2CH4

SYNH2JET

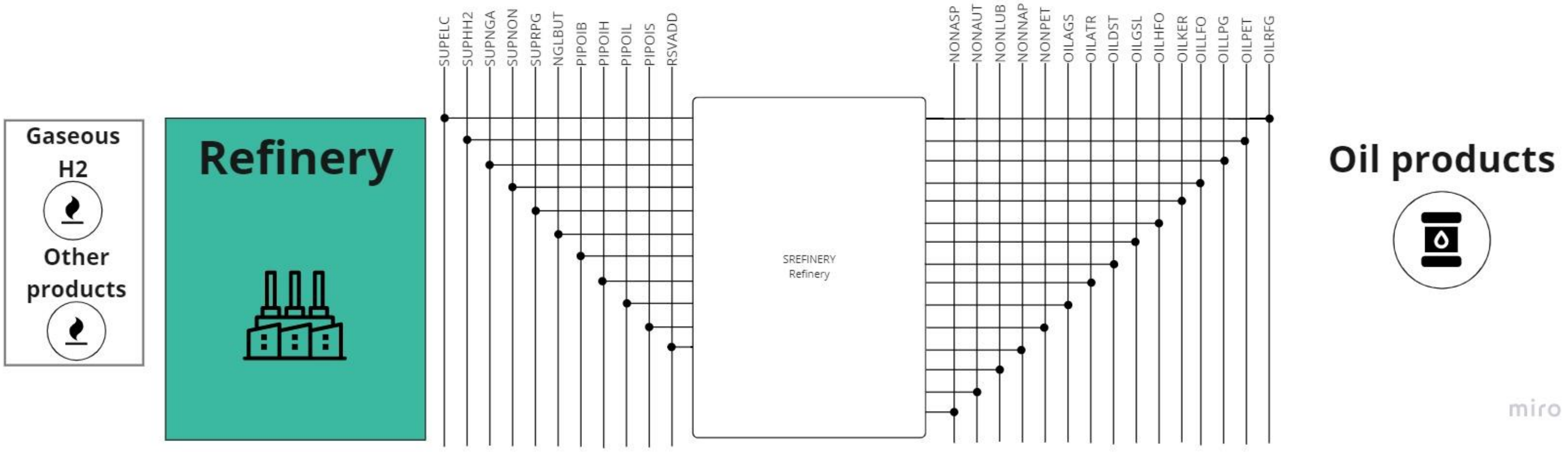
SYNH2MET

Syn Methane

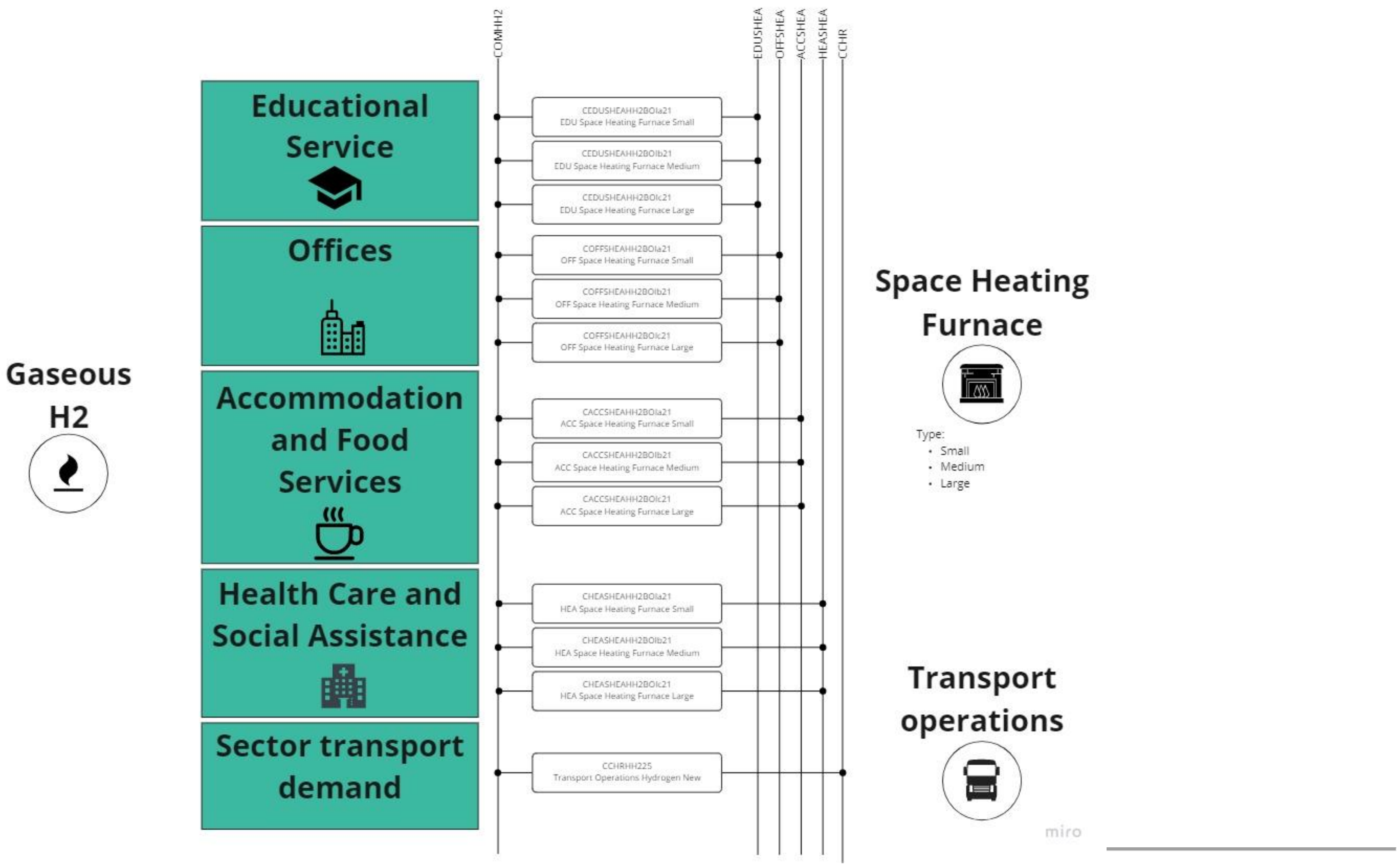
Syn Methanol

Syn Jet Fuel

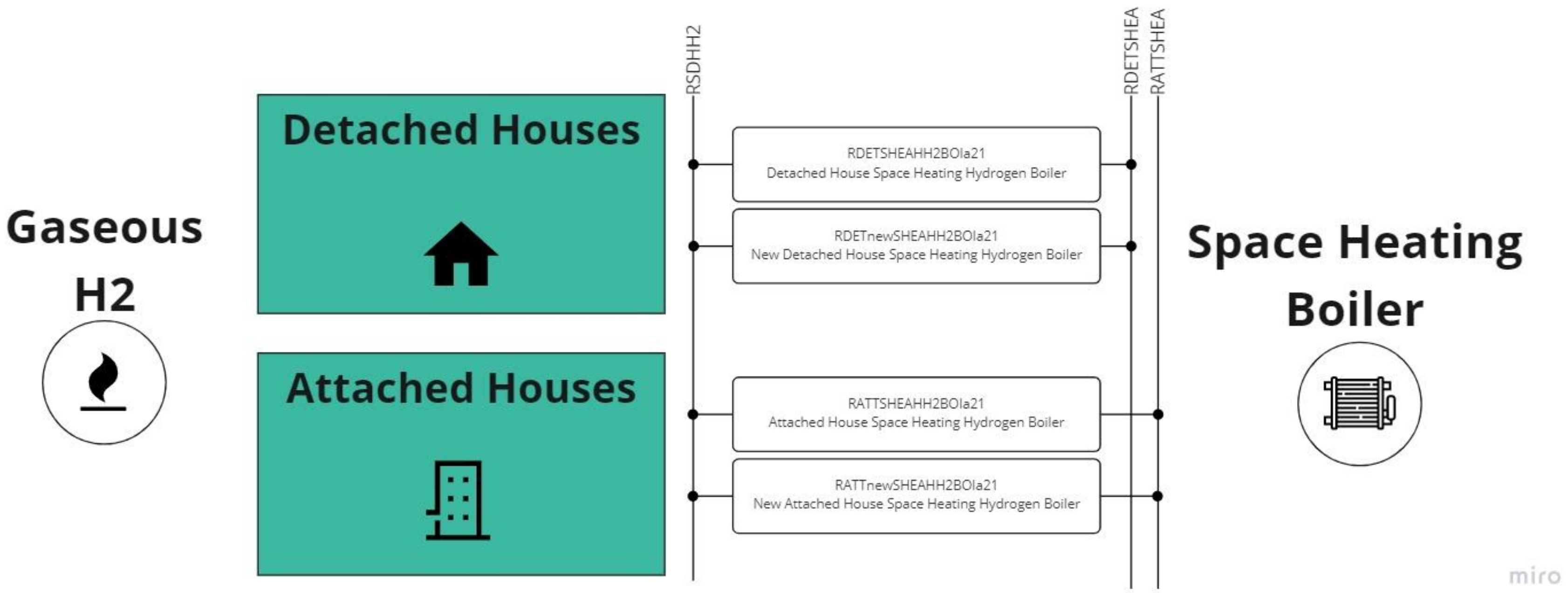
Oil & gas sector



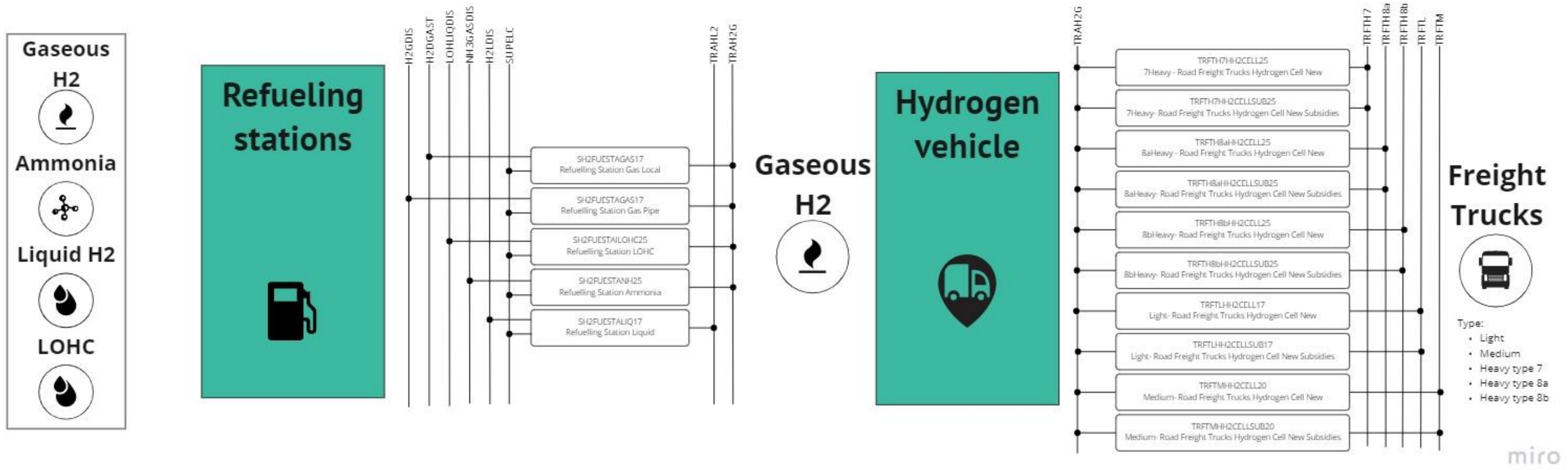
Commercial sector

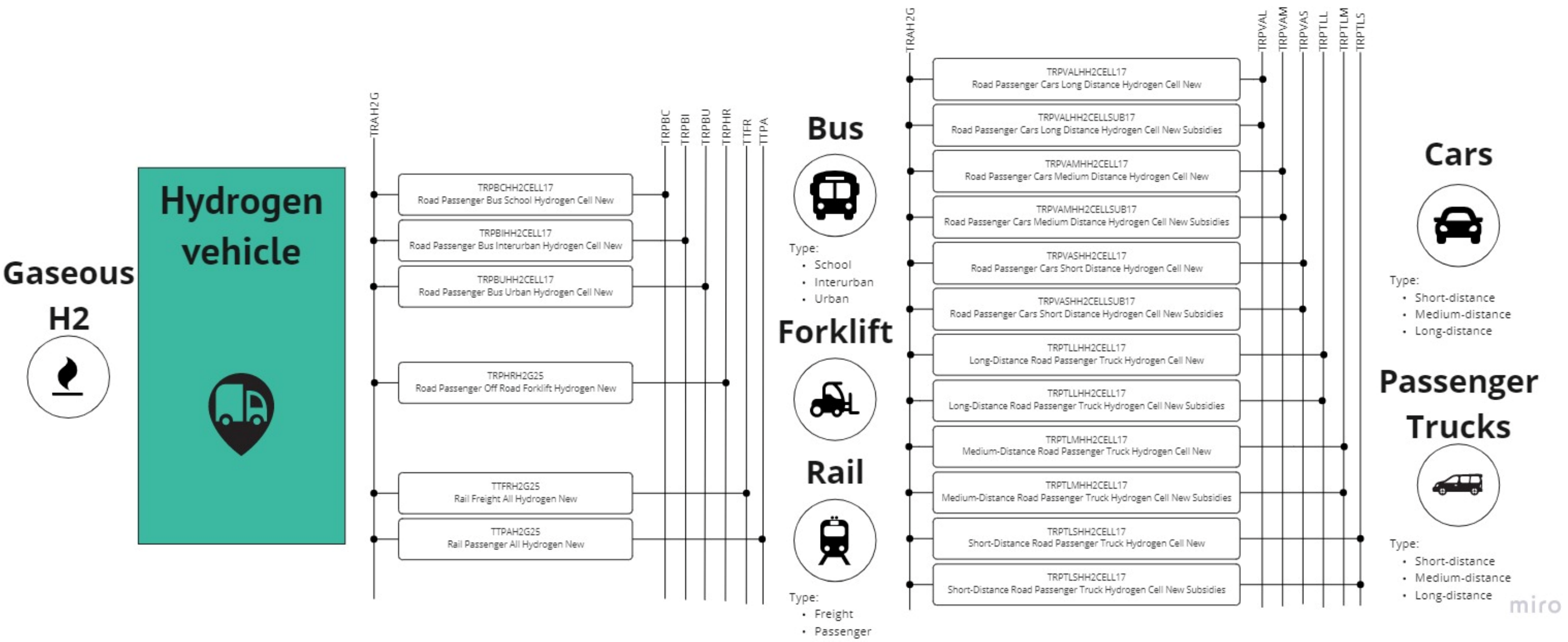


Residential sector



Transport sector




Gaseous H2
Hydrogen vehicle
TRAH2G
TRPBCHH2CELL17
Road Passenger Bus School Hydrogen Cell New
TRPBIHH2CELL17
Road Passenger Bus Interurban Hydrogen Cell New
TRPBUHH2CELL17
Road Passenger Bus Urban Hydrogen Cell New
TRPHRH2G25
Road Passenger Off Road Forklift Hydrogen New
TTFRH2G25
Rail Freight All Hydrogen New
TTPAH2G25
Rail Passenger All Hydrogen New
TRPBC
TRPBI
TRPBU
TRPHR
TTFR
TTPA
Bus
Type:
School
Interurban
Urban
Forklift
Rail
Type:
Freight
Passenger
TRAH2G
TRPVALHH2CELL17
Road Passenger Cars Long Distance Hydrogen Cell New
TRPVALHH2CELLSUB17
Road Passenger Cars Long Distance Hydrogen Cell New Subsidies
TRPVAMHH2CELL17
Road Passenger Cars Medium Distance Hydrogen Cell New
TRPVAMHH2CELLSUB17
Road Passenger Cars Medium Distance Hydrogen Cell New Subsidies
TRPVASHH2CELL17
Road Passenger Cars Short Distance Hydrogen Cell New
TRPVASHH2CELLSUB17
Road Passenger Cars Short Distance Hydrogen Cell New Subsidies
TRPTLLHH2CELL17
Long-Distance Road Passenger Truck Hydrogen Cell New
TRPTLLHH2CELL17
Long-Distance Road Passenger Truck Hydrogen Cell New Subsidies
TRPTLMHH2CELL17
Medium-Distance Road Passenger Truck Hydrogen Cell New
TRPTLMHH2CELL17
Medium-Distance Road Passenger Truck Hydrogen Cell New Subsidies
TRPTLSHH2CELL17
Short-Distance Road Passenger Truck Hydrogen Cell New
TRPTLSHH2CELL17
Short-Distance Road Passenger Truck Hydrogen Cell New Subsidies
TRPVAL
TRPVAM
TRPVAS
TRPTLL
TRPTLM
TRPTLS
Cars
Type:
Short-distance
Medium-distance
Long-distance
Passenger Trucks
Type:
Short-distance
Medium-distance
Long-distance
miro

Annex C – Input Assumptions – Select Technologies

Electricity Generation Technologies

Technology	CAD 2022$	2020	2030	2040	2050
Bioenergy					
Landfill Gas Internal Combustion Engine New	$/kW	2,893	2,437	2,254	2,072
Solid Biomass Dedicated CCS New	$/kW	7,797	7,477	7,023	6,530
Solid Biomass Dedicated New	$/kW	5,618	5,496	5,274	5,019
Solid Biomass Dedicated Retrofit CCS New	$/kW	4,682	4,583	4,543	4,504
Wood Pellet Dedicated New	$/kW	5,618	5,496	5,274	5,019
Geothermal					
Enhanced Geothermal Systems Deep Binary New	$/kW	49,009	46,613	44,334	42,167
Enhanced Geothermal Systems Deep Flash New	$/kW	22,042	20,964	19,939	18,964
Enhanced Geothermal Systems Near-Hydro Binary New	$/kW	49,009	46,613	44,334	42,167
Enhanced Geothermal Systems Near-Hydro Flash New	$/kW	22,042	20,964	19,939	18,964
Hydrothermal Binary Cycle New	$/kW	8,286	7,881	7,495	7,129
Hydrothermal Dual Flash Steam New	$/kW	6,423	6,109	5,810	5,526
Hydro					
Hydro Run-of-River Large New	$/kW	4,528	4,528	4,528	4,528
Hydro Run-of-River Small New	$/kW	7,066	7,066	7,066	7,066
Hydro Conventional Dam Large New *	$/kW	7,054	7,054	7,054	7,054
Hydro Conventional Dam Large New *	$/kW	8,977	8,977	8,977	8,977
Hydro Conventional Dam Large New *	$/kW	10,260	10,260	10,260	10,260
Hydro Conventional Dam Large New *	$/kW	12,825	12,825	12,825	12,825
Hydro Conventional Dam Large New *	$/kW	19,237	19,237	19,237	19,237
Fossil fuel					
Reciprocating Engine Diesel Engine New	$/kW	1,199	1,199	1,199	1,199

Combined Cycle Gas Turbine CCS New	$/kW	5,318	4,996	4,844	4,694
Combined Cycle Gas Turbine New	$/kW	1,329	1,249	1,211	1,173
Gas Turbine Combustion Simple Cycle New	$/kW	1,353	1,249	1,209	1,173
Ultra-supercritical Pulverized Coal CCS 30% New	$/kW	7,613	7,254	6,911	6,525
Ultra-supercritical Pulverized Coal CCS 90% New	$/kW	8,419	8,022	7,643	7,215
Ultra-supercritical Pulverized Coal Retrofit CCS New	$/kW	3,601	3,525	3,495	3,465
Nuclear					
Advanced Reactor New	$/kW	9,096	8,727	8,554	8,383
Small Modular Reactor New	$/kW		8,592	7,687	6,783
Ocean					
Ocean Thermal Energy Conversion Large New	$/kW	25,040	25,040	25,040	25,040
Ocean Thermal Energy Conversion Medium New	$/kW	55,952	55,952	55,952	55,952
Tidal Stream New	$/kW	8,405	5,094	5,094	5,094
Wave Energy Conversion New	$/kW	12,734	7,131	7,131	7,131
Solar					
Photovoltaic 1axis New *	$/kW	1,589	1,274	1,133	1,010
Photovoltaic 1axis New *	$/kW	1,747	1,401	1,246	1,111
Photovoltaic 1axis New *	$/kW	2,097	1,681	1,495	1,333
Photovoltaic 2axis New *	$/kW	2,127	1,706	1,517	1,353
Photovoltaic 2axis New *	$/kW	2,340	1,876	1,668	1,488
Photovoltaic 2axis New *	$/kW	2,808	2,251	2,002	1,785
Decentralized Solar PV Rooftop Commercial New	$/kW	2,399	1,873	1,697	1,499
Decentralized Solar PV Rooftop Residential New	$/kW	3,763	2,111	1,710	1,604
Wind					
Offshore Fix Foundation New	$/kW	4,430	3,197	2,307	1,665
Offshore Floating Structure New	$/kW	6,160	4,030	2,637	1,725
Onshore Turbine Conventional Large New	$/kW	1,801	1,517	1,403	1,290
Onshore Turbine Conventional Medium New	$/kW	2,239	1,836	1,636	1,433
Onshore Turbine Conventional Small New	$/kW	2,294	1,880	1,697	1,710

Storage					
Centralized Battery Lead-acid Peak	$/kW	6,617	5,211	4,880	4,797
Centralized Battery Lithium-ion Peak	$/kW	3,960	1,656	1,152	1,008
Centralized Battery Sodium-sulphur Peak	$/kW	8,465	5,341	3,930	3,325
Centralized Battery Utility-Scale lithium-ion Peak	$/kW	1,924	1,214	1,063	911
Centralized Battery Vanadium redox-flow Peak	$/kW	6,344	3,366	2,460	2,201
Centralized Compressed Air Seasonal	$/kW	2,776	2,776	2,803	2,831
Centralized Flywheel Peak	$/kW	4,310	2,719	2,001	1,693
Centralized Pumped Hydro Peak	$/kW	4,683	4,683	4,730	4,777
Centralized Pumped Hydro Seasonal **		not currently economical			
Decentralized Battery Commercial Peak	$/kW	1,793	1,132	990	849
Decentralized Battery Residential Peak	$/kW	880	556	486	417
Decentralized Thermal Apartments AirCircuit Residential RoomUnit Peak	$/kW	3,254	3,061	2,880	2,710
Decentralized Thermal Attached Houses AirCircuit Residential HomeUnit Peak	$/kW	761	716	673	634
Decentralized Thermal Attached Houses AirCircuit Residential RoomUnit Peak	$/kW	3,254	3,061	2,880	2,710
Decentralized Thermal Detached Houses AirCircuit Residential HomeUnit Peak	$/kW	761	716	673	634
Decentralized Thermal Detached Houses AirCircuit Residential RoomUnit Peak	$/kW	3,254	3,061	2,880	2,710

* Supply curve steps; Canadian average (vary across provinces in the model)

** Technology is not yet commercially viable, re CANMET feedback

Hydrogen and Ammonia Production, Conversion and Transport

CEN - Centralized
DCN - Decentralized

LOHC -Liquid Organic Hydrogen Carrier	**CAD 2022$**	**scenario**	**2020**	**2030**	**2040**	**2050**
Hydrogen Biomass Gasification CEN CCS Woody Small	$/kW	Supportive		3,711	3,447	3,281
Hydrogen Biomass Gasification CEN CCS Woody Small	$/kW	Challenging		5,551	5,551	5,551
Hydrogen Biomass Gasification CEN CCS Woody Small	$/kW	Neutral	5,810	5,301	4,925	4,688
Hydrogen Biomass Gasification CEN CCS Woody Large	$/kW	Supportive		1,615	1,504	1,435
Hydrogen Biomass Gasification CEN CCS Woody Large	$/kW	Challenging		2,430	2,430	2,430
Hydrogen Biomass Gasification CEN CCS Woody Large	$/kW	Neutral	2,802	2,548	2,377	2,260
Hydrogen Biomass Gasification CEN Woody	$/kW	Supportive		1,453	1,417	1,417
Hydrogen Biomass Gasification CEN Woody	$/kW	Challenging		1,472	1,472	1,472
Hydrogen Biomass Gasification CEN Woody	$/kW	Neutral	1,490	1,453	1,417	1,417
Hydrogen Electrolysis Alkaline CEN Small	$/kW	Supportive		555	446	391
Hydrogen Electrolysis Alkaline CEN Small	$/kW	Challenging		1,031	1,031	1,031
Hydrogen Electrolysis Alkaline CEN Small	$/kW	Neutral	1,269	793	637	558
Hydrogen Electrolysis Alkaline CEN Medium	$/kW	Supportive		485	390	341
Hydrogen Electrolysis Alkaline CEN Medium	$/kW	Challenging		900	900	900
Hydrogen Electrolysis Alkaline CEN Medium	$/kW	Neutral	1,108	693	556	488
Hydrogen Electrolysis Alkaline CEN Large	$/kW	Supportive		439	352	309
Hydrogen Electrolysis Alkaline CEN Large	$/kW	Challenging		815	815	815
Hydrogen Electrolysis Alkaline CEN Large	$/kW	Neutral	1,003	627	503	441
Hydrogen Electrolysis Polymer electrolyte membrane CEN Small	$/kW	Supportive		777	624	547
Hydrogen Electrolysis Polymer electrolyte membrane CEN Small	$/kW	Challenging		1,428	1,428	1,428
Hydrogen Electrolysis Polymer electrolyte membrane CEN Small	$/kW	Neutral	1,745	1,110	892	782
Hydrogen Electrolysis Polymer electrolyte membrane CEN Medium	$/kW	Supportive		539	433	379

Hydrogen Electrolysis Polymer electrolyte membrane CEN Medium	$/kW	Challenging		990	990	990
Hydrogen Electrolysis Polymer electrolyte membrane CEN Medium	$/kW	Neutral	1,210	770	618	542
Hydrogen Electrolysis Polymer electrolyte membrane CEN Large	$/kW	Supportive		466	375	328
Hydrogen Electrolysis Polymer electrolyte membrane CEN Large	$/kW	Challenging		857	857	857
Hydrogen Electrolysis Polymer electrolyte membrane CEN Large	$/kW	Neutral	1,047	666	535	469
Hydrogen Electrolysis Solid oxide electrolyzer cell CEN Standard	$/kW	Supportive		1,343	1,079	945
Hydrogen Electrolysis Solid oxide electrolyzer cell CEN Standard	$/kW	Challenging		2,362	2,362	2,362
Hydrogen Electrolysis Solid oxide electrolyzer cell CEN Standard	$/kW	Neutral	3,153	1,919	1,541	1,351
Hydrogen Biomass Gasification CEN CCS Waste	$/kW	Supportive		2,574	2,353	2,186
Hydrogen Biomass Gasification CEN CCS Waste	$/kW	Challenging		3,899	3,899	3,899
Hydrogen Biomass Gasification CEN CCS Waste	$/kW	Neutral	4,361	3,887	3,544	3,301
Hydrogen Natural gas Autothermal Reforming CEN CCS Medium	$/kW	Supportive		1,696	1,463	1,289
Hydrogen Natural gas Autothermal Reforming CEN CCS Medium	$/kW	Challenging		1,936	1,936	1,936
Hydrogen Natural gas Autothermal Reforming CEN CCS Medium	$/kW	Neutral	2,038	1,834	1,581	1,393
Hydrogen Natural gas Autothermal Reforming CEN CCS Large	$/kW	Supportive		1,309	1,129	994
Hydrogen Natural gas Autothermal Reforming CEN CCS Large	$/kW	Challenging		1,494	1,494	1,494
Hydrogen Natural gas Autothermal Reforming CEN CCS Large	$/kW	Neutral	1,572	1,415	1,220	1,075
Hydrogen Natural gas Autothermal Reforming Gas heating CEN CCS Medium	$/kW	Supportive		1,256	1,083	954
Hydrogen Natural gas Autothermal Reforming Gas heating CEN CCS Medium	$/kW	Challenging		1,433	1,433	1,433
Hydrogen Natural gas Autothermal Reforming Gas heating CEN CCS Medium	$/kW	Neutral	1,632	1,469	1,267	1,116
Hydrogen Natural gas Autothermal Reforming Gas heating CEN CCS Large	$/kW	Supportive		999	861	759
Hydrogen Natural gas Autothermal Reforming Gas heating CEN CCS Large	$/kW	Challenging		1,140	1,140	1,140
Hydrogen Natural gas Autothermal Reforming Gas heating CEN CCS Large	$/kW	Neutral	1,259	1,134	977	861
Hydrogen Natural gas Steam methane reforming CEN CCS Small	$/kW	Supportive		1,524	1,342	1,182
Hydrogen Natural gas Steam methane reforming CEN CCS Small	$/kW	Challenging		1,727	1,727	1,727
Hydrogen Natural gas Steam methane reforming CEN CCS Small	$/kW	Neutral	2,300	2,026	1,785	1,572
Hydrogen Natural gas Steam methane reforming CEN CCS Medium	$/kW	Supportive		1,167	1,028	906

Hydrogen Natural gas Steam methane reforming CEN CCS Medium	$/kW	Challenging		1,323	1,323	1,323
Hydrogen Natural gas Steam methane reforming CEN CCS Medium	$/kW	Neutral	1,762	1,552	1,367	1,205
Hydrogen Natural gas Steam methane reforming CEN CCS Large	$/kW	Supportive		965	850	749
Hydrogen Natural gas Steam methane reforming CEN CCS Large	$/kW	Challenging		1,094	1,094	1,094
Hydrogen Natural gas Steam methane reforming CEN CCS Large	$/kW	Neutral	1,457	1,284	1,131	996
Hydrogen Natural gas Steam methane reforming CEN CCS less Small	$/kW	Neutral	1,840	1,621	1,428	1,258
Hydrogen Natural gas Steam methane reforming CEN CCS less Medium	$/kW	Neutral	1,410	1,242	1,094	964
Hydrogen Natural gas Steam methane reforming CEN CCS less Large	$/kW	Neutral	1,166	1,027	905	797
Hydrogen Natural gas Steam methane reforming CEN Standard	$/kW	Neutral	660	660	660	660
Hydrogen By product DCN Standard PlantA	$/kW	Neutral	536	536	536	536
Hydrogen By product DCN Standard PlantB	$/kW	Neutral	429	429	429	429
Hydrogen Electrolysis Polymer electrolyte membrane DCN	$/kW	Supportive		1,108	877	877
Hydrogen Electrolysis Polymer electrolyte membrane DCN	$/kW	Challenging		1,747	1,747	1,747
Hydrogen Electrolysis Polymer electrolyte membrane DCN	$/kW	Neutral	1,911	1,582	1,253	1,253
Hydrogen Natural gas Steam methane reforming DCN Standard	$/kW	Neutral	1,256	1,133	1,010	1,010
Hydrogen Refuelling Station Compressed Gas Local	$/GJ	Supportive		41	41	41
Hydrogen Refuelling Station Compressed Gas Local	$/GJ	Challenging		51	51	51
Hydrogen Refuelling Station Compressed Gas Local	$/GJ	Neutral	51	51	51	51
Hydrogen Refuelling Station Compressed Gas Pipeline	$/GJ	Supportive		41	41	41
Hydrogen Refuelling Station Compressed Gas Pipeline	$/GJ	Challenging		51	51	51
Hydrogen Refuelling Station Compressed Gas Pipeline	$/GJ	Neutral	51	51	51	51
Hydrogen Refuelling Station Liquid	$/GJ	Supportive		41	41	41
Hydrogen Refuelling Station Liquid	$/GJ	Challenging		51	51	51
Hydrogen Refuelling Station Liquid	$/GJ	Neutral	51	51	51	51
Hydrogen Refuelling Station LOHC	$/GJ	Supportive		388	388	388
Hydrogen Refuelling Station LOHC	$/GJ	Challenging		484	484	484
Hydrogen Refuelling Station LOHC	$/GJ	Neutral	484	484	484	484
Hydrogen Refuelling Station Ammonia]	$/GJ	Supportive		283	283	283
Hydrogen Refuelling Station Ammonia]	$/GJ	Challenging		354	354	354

Hydrogen Refuelling Station Ammonia]	$/GJ	Neutral	354	354	354	354
Hydrogen to liquid organic hydrogen carrier	$/GJ	Supportive		2	2	2
Hydrogen to liquid organic hydrogen carrier	$/GJ	Challenging		2	2	2
Hydrogen to liquid organic hydrogen carrier	$/GJ	Neutral	2	2	2	2
Hydrogen liquefaction Standard	$/GJ	Supportive		53	53	53
Hydrogen liquefaction Standard	$/GJ	Challenging		66	66	66
Hydrogen liquefaction Standard	$/GJ	Neutral	66	66	66	66
Hydrogen distribution Pipeline Transmission Small New	$/GJ	Supportive		10	10	10
Hydrogen distribution Pipeline Transmission Small New	$/GJ	Challenging		12	12	12
Hydrogen distribution Pipeline Transmission Small New	$/GJ	Neutral	12	12	12	12
Hydrogen distribution Pipeline Transmission Medium New	$/GJ	Supportive		29	29	29
Hydrogen distribution Pipeline Transmission Medium New	$/GJ	Challenging		36	36	36
Hydrogen distribution Pipeline Transmission Medium New	$/GJ	Neutral	36	36	36	36
Hydrogen distribution Pipeline Transmission Large New	$/GJ	Supportive		24	24	24
Hydrogen distribution Pipeline Transmission Large New	$/GJ	Challenging		30	30	30
Hydrogen distribution Pipeline Transmission Large New	$/GJ	Neutral	30	30	30	30
Hydrogen distribution Pipeline Transmission Retrofit Small New	$/GJ	**Regional**		7	7	7
Hydrogen distribution Pipeline Transmission Retrofit Small New	$/GJ	**GasTransRetrofit**		7	7	7
Hydrogen distribution Pipeline Transmission Retrofit Small New	$/GJ	Neutral				
Hydrogen distribution Pipeline Transmission Retrofit Medium New	$/GJ	**Regional**		21	21	21
Hydrogen distribution Pipeline Transmission Retrofit Medium New	$/GJ	**GasTransRetrofit**		21	21	21
Hydrogen distribution Pipeline Transmission Retrofit Medium New	$/GJ	Neutral				
Hydrogen distribution Pipeline Transmission Retrofit Large New	$/GJ	**Regional**		18	18	18
Hydrogen distribution Pipeline Transmission Retrofit Large New	$/GJ	**GasTransRetrofit**		18	18	18
Hydrogen distribution Pipeline Transmission Retrofit Large New	$/GJ	Neutral				
Hydrogen distribution Ship Liquid	$/GJ	Supportive		5	5	5
Hydrogen distribution Ship Liquid	$/GJ	Challenging		6	6	6
Hydrogen distribution Ship Liquid	$/GJ	Neutral	6	6	6	6
Hydrogen Storage Salt Cavern	$/GJ	Supportive		350	350	350
Hydrogen Storage Salt Cavern	$/GJ	Challenging		437	437	437

Hydrogen Storage Salt Cavern	$/GJ	Neutral	437	437	437	437
Hydrogen Storage Salt Cavern Before transmission	$/GJ	Supportive		350	350	350
Hydrogen Storage Salt Cavern Before transmission	$/GJ	Challenging		437	437	437
Hydrogen Storage Salt Cavern Before transmission	$/GJ	Neutral	437	437	437	437
Hydrogen Storage Salt Cavern ELC	$/GJ	Supportive		350	350	350
Hydrogen Storage Salt Cavern ELC	$/GJ	Challenging		437	437	437
Hydrogen Storage Salt Cavern ELC	$/GJ	Neutral	437	437	437	437
Hydrogen Storage Storage Pipe	$/GJ	Supportive		8,162	8,162	8,162
Hydrogen Storage Storage Pipe	$/GJ	Challenging		10,203	10,203	10,203
Hydrogen Storage Storage Pipe	$/GJ	Neutral	10,203	10,203	10,203	10,203
Hydrogen Storage Storage Pipe Before transmission	$/GJ	Supportive		8,162	8,162	8,162
Hydrogen Storage Storage Pipe Before transmission	$/GJ	Challenging		10,203	10,203	10,203
Hydrogen Storage Storage Pipe Before transmission	$/GJ	Neutral	10,203	10,203	10,203	10,203
Hydrogen Storage Storage Pipe	$/GJ	Supportive		8,162	8,162	8,162
Hydrogen Storage Storage Pipe	$/GJ	Challenging		10,203	10,203	10,203
Hydrogen Storage Storage Pipe	$/GJ	Neutral	10,203	10,203	10,203	10,203
Hydrogen Storage Storage Pipe ELC	$/GJ	Supportive		8,162	8,162	8,162
Hydrogen Storage Storage Pipe ELC	$/GJ	Challenging		10,203	10,203	10,203
Hydrogen Storage Storage Pipe ELC	$/GJ	Neutral	10,203	10,203	10,203	10,203
Hydrogen Storage Storage Tank ELC	$/GJ	Supportive		894	894	894
Hydrogen Storage Storage Tank ELC	$/GJ	Challenging		1,117	1,117	1,117
Hydrogen Storage Storage Tank ELC	$/GJ	Neutral	1,117	1,117	1,117	1,117
Hydrogen Storage Storage Tank	$/GJ	Supportive		894	894	894
Hydrogen Storage Storage Tank	$/GJ	Challenging		1,117	1,117	1,117
Hydrogen Storage Storage Tank	$/GJ	Neutral	1,117	1,117	1,117	1,117
Hydrogen Storage Storage Tank	$/GJ	Supportive		894	894	894
Hydrogen Storage Storage Tank	$/GJ	Challenging		1,117	1,117	1,117
Hydrogen Storage Storage Tank	$/GJ	Neutral	1,117	1,117	1,117	1,117
Hydrogen distribution Truck Compressed Gas	$/GJ	Supportive		30	30	30
Hydrogen distribution Truck Compressed Gas	$/GJ	Challenging		37	37	37

Hydrogen distribution Truck Compressed Gas	$/GJ	Neutral	37	37	37	37
Hydrogen distribution Truck Liquid	$/GJ	Supportive		7	7	7
Hydrogen distribution Truck Liquid	$/GJ	Challenging		9	9	9
Hydrogen distribution Truck Liquid	$/GJ	Neutral	9	9	9	9
Hydrogen Fuel Cell CEN Small New	$/kW	Supportive	12,070	10,439	10,439	10,439
Hydrogen Fuel Cell CEN Small New	$/kW	Challenging	13,049	13,049	13,049	13,049
Hydrogen Fuel Cell CEN Small New	$/kW	Neutral	13,049	13,049	13,049	13,049
Hydrogen Fuel Cell CEN Medium New	$/kW	Supportive	2,523	2,182	2,182	2,182
Hydrogen Fuel Cell CEN Medium New	$/kW	Challenging	2,728	2,728	2,728	2,728
Hydrogen Fuel Cell CEN Medium New	$/kW	Neutral	2,728	2,728	2,728	2,728
Hydrogen Fuel Cell CEN Large New	$/kW	Supportive	1,483	1,283	1,283	1,283
Hydrogen Fuel Cell CEN Large New	$/kW	Challenging	1,603	1,603	1,603	1,603
Hydrogen Fuel Cell CEN Large New	$/kW	Neutral	1,603	1,603	1,603	1,603
NH3.Ammonia.Biomass.Gasificasion.CEN.CCS.	$/kW	Supportive		4,167	4,167	4,167
NH3.Ammonia.Biomass.Gasificasion.CEN.CCS.	$/kW	Challenging		5,953	5,953	5,953
NH3.Ammonia.Biomass.Gasificasion.CEN.CCS.	$/kW	Neutral	5,953	5,953	5,953	5,953
NH3 Ammonia Biomass Gasificasion CEN Standard	$/kW	Supportive		3,225	3,225	3,225
NH3 Ammonia Biomass Gasificasion CEN Standard	$/kW	Challenging		4,608	4,608	4,608
NH3 Ammonia Biomass Gasificasion CEN Standard	$/kW	Neutral	4,608	4,608	4,608	4,608
NH3 Ammonia Electrolysis Polymer electrolyte membrane CEN Standard	$/kW	Supportive		1,268	1,197	1,127
NH3 Ammonia Electrolysis Polymer electrolyte membrane CEN Standard	$/kW	Challenging		1,898	1,898	1,898
NH3 Ammonia Electrolysis Polymer electrolyte membrane CEN Standard	$/kW	Neutral	1,985	1,811	1,711	1,610
NH3 Ammonia Natural gas CEN CCS	$/kW	Supportive		2,135	2,055	1,974
NH3 Ammonia Natural gas CEN CCS	$/kW	Challenging		2,722	2,722	2,722
NH3 Ammonia Natural gas CEN CCS	$/kW	Neutral	2,775	2,669	2,569	2,468
NH3 Ammonia Natural gas CEN Standard	$/kW	Supportive		1,917	1,917	1,917
NH3 Ammonia Natural gas CEN Standard	$/kW	Challenging		1,917	1,917	1,917
NH3 Ammonia Natural gas CEN Standard	$/kW	Neutral	1,917	1,917	1,917	1,917

Hydrogen Consuming Technologies

process	CAD 2022$	scenario	2020	2030	2040	2050
Building						
Space heating Hydrogen Furnace Small New	$/kW	Supportive	950	822	822	822
Space heating Hydrogen Furnace Small New	$/kW	Challenging	1,027	1,027	1,027	1,027
Space heating Hydrogen Furnace Small New	$/kW	Neutral	1,027	1,027	1,027	1,027
Space heating Hydrogen Furnace Medium New	$/kW	Supportive	933	807	807	807
Space heating Hydrogen Furnace Medium New	$/kW	Challenging	1,008	1,008	1,008	1,008
Space heating Hydrogen Furnace Medium New	$/kW	Neutral	1,008	1,008	1,008	1,008
Space heating Hydrogen Furnace Large New	$/kW	Supportive	924	799	799	799
Space heating Hydrogen Furnace Large New	$/kW	Challenging	999	999	999	999
Space heating Hydrogen Furnace Large New	$/kW	Neutral	999	999	999	999
Residential New Space heating Hydrogen Boiler New	$/kW	Supportive	4,663	4,033	4,033	4,033
Residential New Space heating Hydrogen Boiler New	$/kW	Challenging	5,041	5,041	5,041	5,041
Residential New Space heating Hydrogen Boiler New	$/kW	Neutral	5,041	5,041	5,041	5,041
Industries						
Chemical Steam Boiler Hydrogen Bi-fuel CCS New	$/kW	Supportive	587	516	516	516
Chemical Steam Boiler Hydrogen Bi-fuel CCS New	$/kW	Challenging	644	644	644	644
Chemical Steam Boiler Hydrogen Bi-fuel CCS New	$/kW	Neutral	644	644	644	644
Chemical Steam Boiler Hydrogen Standard CCS New	$/kW	Supportive	337	296	296	296
Chemical Steam Boiler Hydrogen Standard CCS New	$/kW	Challenging	370	370	370	370
Chemical Steam Boiler Hydrogen Standard CCS New	$/kW	Neutral	370	370	370	370
Chemical Steam Boiler Hydrogen Bi-fuel New	$/kW	Supportive	294	258	258	258
Chemical Steam Boiler Hydrogen Bi-fuel New	$/kW	Challenging	322	322	322	322
Chemical Steam Boiler Hydrogen Bi-fuel New	$/kW	Neutral	322	322	322	322
Chemical Steam Boiler Hydrogen Standard New	$/kW	Supportive	169	148	148	148
Chemical Steam Boiler Hydrogen Standard New	$/kW	Challenging	185	185	185	185
Chemical Steam Boiler Hydrogen Standard New	$/kw	Neutral	185	185	185	185

Pulp and paper Steam boiler Hydrogen Bi-fuel CCS New	$/kw	Supportive	638	561	561	561
Pulp and paper Steam boiler Hydrogen Bi-fuel CCS New	$/kw	Challenging	701	701	701	701
Pulp and paper Steam boiler Hydrogen Bi-fuel CCS New	$/kw	Neutral	701	701	701	701
Pulp and paper Steam boiler Hydrogen CCS New	$/kw	Supportive	389	341	341	341
Pulp and paper Steam boiler Hydrogen CCS New	$/kw	Challenging	427	427	427	427
Pulp and paper Steam boiler Hydrogen CCS New	$/kw	Neutral	427	427	427	427
Pulp and paper Steam boiler Hydrogen Bi-fuel New	$/kw	Supportive	319	280	280	280
Pulp and paper Steam boiler Hydrogen Bi-fuel New	$/kw	Challenging	350	350	350	350
Pulp and paper Steam boiler Hydrogen Bi-fuel New	$/kw	Neutral	350	350	350	350
Pulp and paper Steam boiler Hydrogen New	$/kw	Supportive	194	171	171	171
Pulp and paper Steam boiler Hydrogen New	$/kw	Challenging	213	213	213	213
Pulp and paper Steam boiler Hydrogen New	$/kw	Neutral	213	213	213	213
Other manufacturing Steam boiler Bi-fuel Hydrogen New	$/kw	Supportive	312	274	274	274
Other manufacturing Steam boiler Bi-fuel Hydrogen New	$/kw	Challenging	343	343	343	343
Other manufacturing Steam boiler Bi-fuel Hydrogen New	$/kw	Neutral	343	343	343	343
Other manufacturing Steam boiler Hydrogen New	$/kw	Supportive	187	164	164	164
Other manufacturing Steam boiler Hydrogen New	$/kw	Challenging	206	206	206	206
Other manufacturing Steam boiler Hydrogen New	$/kw	Neutral	206	206	206	206
Iron and Steel Iron Direct reduction from hydrogen New	$/t	Supportive		470	442	432
Iron and Steel Iron Direct reduction from hydrogen New	$/t	Challenging		617	617	617
Iron and Steel Iron Direct reduction from hydrogen New	$/t	Neutral		540	540	540
Transport						
Road Freight Trucks Class7 Heavy Hydrogen CELL New	Unit	Supportive		172,308	176,110	184,717
Road Freight Trucks Class7 Heavy Hydrogen CELL New	Unit	Challenging		283,892	283,892	283,892
Road Freight Trucks Class7 Heavy Hydrogen CELL New	Unit	Neutral	394,486	215,385	220,137	230,897
Road Freight Trucks Class8a Heavy Hydrogen CELL New	Unit	Supportive		271,831	235,374	230,009
Road Freight Trucks Class8a Heavy Hydrogen CELL New	Unit	Challenging		442,945	442,945	442,945

Road Freight Trucks Class8a Heavy Hydrogen CELL New	Unit	Neutral	503,701	339,789	294,218	287,512
Road Freight Trucks Class8bHeavy Hydrogen CELL New	Unit	Supportive		271,831	235,374	230,009
Road Freight Trucks Class8bHeavy Hydrogen CELL New	Unit	Challenging		442,945	442,945	442,945
Road Freight Trucks Class8bHeavy Hydrogen CELL New	Unit	Neutral	503,701	339,789	294,218	287,512
Road Freight Trucks Light Hydrogen CELL New	Unit	Supportive		65,623	59,609	55,917
Road Freight Trucks Light Hydrogen CELL New	Unit	Challenging		132,991	132,991	132,991
Road Freight Trucks Light Hydrogen CELL New	Unit	Neutral	156,171	82,028	74,512	69,896
Road Freight Trucks Medium Hydrogen CELL New	Unit	Supportive		112,539	100,510	95,668
Road Freight Trucks Medium Hydrogen CELL New	Unit	Challenging		209,370	209,370	209,370
Road Freight Trucks Medium Hydrogen CELL New	Unit	Neutral	242,221	140,674	125,638	119,585
Road Passenger Buses School Hydrogen CELL New	Unit	Supportive		133,223	128,716	124,209
Road Passenger Buses School Hydrogen CELL New	Unit	Challenging		232,107	232,107	232,107
Road Passenger Buses School Hydrogen CELL New	Unit	Neutral	260,212	166,528	160,895	155,261
Road Passenger Buses Interurban Hydrogen CELL New	Unit	Supportive		172,308	176,110	184,717
Road Passenger Buses Interurban Hydrogen CELL New	Unit	Challenging		283,892	283,892	283,892
Road Passenger Buses Interurban Hydrogen CELL New	Unit	Neutral	394,486	215,385	220,137	230,897
Road Passenger Buses Urban Hydrogen CELL New	Unit	Supportive		846,066	846,066	846,066
Road Passenger Buses Urban Hydrogen CELL New	Unit	Challenging		1,057,583	1,057,583	1,057,583
Road Passenger Buses Urban Hydrogen CELL New	Unit	Neutral	1,057,583	1,057,583	1,057,583	1,057,583
Road Passenger Trucks Light Long Distance Hydrogen CELL New	Unit	Supportive		84,288	73,811	67,079
Road Passenger Trucks Light Long Distance Hydrogen CELL New	Unit	Challenging		112,936	112,936	112,936
Road Passenger Trucks Light Long Distance Hydrogen CELL New	Unit	Neutral	92,063	79,020	69,198	62,886
Road Passenger Trucks Light Medium Distance Hydrogen CELL New	Unit	Supportive		84,288	73,811	67,079
Road Passenger Trucks Light Medium Distance Hydrogen CELL New	Unit	Challenging		112,936	112,936	112,936

Road Passenger Trucks Light Medium Distance Hydrogen CELL New	Unit	Neutral	92,063	79,020	69,198	62,886
Road Passenger Trucks Light Short Distance Hydrogen CELL New	Unit	Supportive		84,288	73,811	67,079
Road Passenger Trucks Light Short Distance Hydrogen CELL New	Unit	Challenging		112,936	112,936	112,936
Road Passenger Trucks Light Short Distance Hydrogen CELL New	Unit	Neutral	92,063	79,020	69,198	62,886
Road Passenger Cars Long Distance Hydrogen CELL New	Unit	Supportive		75,684	67,216	67,216
Road Passenger Cars Long Distance Hydrogen CELL New	Unit	Challenging		106,495	106,495	106,495
Road Passenger Cars Long Distance Hydrogen CELL New	Unit	Neutral	86,523	70,953	63,015	63,015
Road Passenger Cars Medium Distance Hydrogen CELL New	Unit	Supportive		75,684	67,216	67,216
Road Passenger Cars Medium Distance Hydrogen CELL New	Unit	Challenging		106,495	106,495	106,495
Road Passenger Cars Medium Distance Hydrogen CELL New	Unit	Neutral	86,523	70,953	63,015	63,015
Road Passenger Cars Short Distance Hydrogen CELL New	Unit	Supportive		75,684	67,216	67,216
Road Passenger Cars Short Distance Hydrogen CELL New	Unit	Challenging		106,495	106,495	106,495
Road Passenger Cars Short Distance Hydrogen CELL New	Unit	Neutral	86,523	70,953	63,015	63,015

Annex D - ESMIA's approach VS recommendation from CESD Audit

Purpose: Report how ESMIA Consultants' (ESMIA) contract with Natural Resources Canada to provide *Updated Modelling of Hydrogen's Potential* across multiple sectors of the Canadian economy (Contract No: 3000752048) contributes to addressing the recommendations in the Report of the Commissioner of the Environment and Sustainable Development to the Parliament of Canada *Hydrogen's Potential to Reduce Greenhouse Gas Emissions*

Recommendation	ECCC/NRCan Response	Contribution from *Updated Modelling of Hydrogen's Potential* (Contract No: 3000752048)
3.34 Natural Resources Canada should perform a comprehensive bottom-up modelling for the use of hydrogen. This modelling should account for the following: • emission reduction efficiencies by sector (cost of emission reductions per megatonne of carbon dioxide equivalent) • substitutional fuels (for example, biofuel, electrification, credit systems) • feasible deployment of technologies and supporting infrastructure	Agreed. Natural Resources Canada agrees that it is important to model the potential role for hydrogen use across all sectors of the economy, including resulting emission reductions potential and cost. The modelling undertaken for the Hydrogen Strategy for Canada focused on the nearest term, most likely and economically viable end-uses—such as heavy-duty transportation, natural gas blending, cement and steel manufacturing, and low-carbon fuel production. This sector by- sector analysis of hydrogen end-uses included aspects of technology readiness levels, economic competitiveness, adoption potential, and other factors, including supporting infrastructure. This analysis	ESMIA is providing comprehensive energy system modelling for NRCan for updates to be included in the Hydrogen Strategy Biennial report. ESMIA's model (NATEM) is a bottom-up model with over 5,000 technologies represented by their cost and performance characteristics. Within the model, each technology has a detailed quantitative representation including capital and operating costs for given capacity, energy use per product or service, technology readiness, construction times, and other factors.

	will be updated as new deployment activities occur and new technologies enter the market. Results of the energy use modelling can then be used by Environment and Climate Change Canada to inform their modelling of potential emissions reductions, while also contributing to Environment and Climate Change Canada's efforts to address the recommendation identified in paragraph 3.65. We acknowledge that the modelling undertaken did not include a specific cost per tonne, given the focus was on hydrogen’s full potential for use across the economy, as opposed to focusing on the cost and impacts of a specific measure or combination of specific measures. Because costs per tonne are dependent on a number of variables, including production technologies (and feedstocks), distribution, type of investment, and specific end-use, the Government analyzes cost per tonne on a measure-by-measure basis when considering possible new regulatory, fiscal, or program measures, as opposed to economy-wide modelling.	ESMIA’s use of NATEM for this project maximizes emission reduction efficiencies (when measured in costs per tonne) over the long-term energy system, subject to technology and resource feasibility. This setup will also maximize emission reduction efficiencies by sector. The model solves by finding the set of technologies that meets the economic and environmental goals at the least social cost. For this project, ESMIA is using future GHG emissions as a goal. NATEM covers energy types that could be used as substitutions or competition to hydrogen, including options for fossil fuels (unabated and abated), biofuels, electricity and domestic mitigations options that could provide credits. NATEM does not model international options for generating climate mitigation credits. NATEM covers the full energy system from resource extraction to energy use by consumers. The model will ensure that the infrastructure is developed within the solution to transport the energy to technologies. ESMIA assesses the model results for feasibility by comparing outcomes with literature reviews and reviews by experts in the field. When the model outcomes do not align for physical reasons, ESMIA will carefully consider applying limits on technology deployment. For example, ESMIA includes construction times for large industrial plants that account for necessary physical needs.

3.35 Based on the updated modelling, Natural Resources Canada, in partnership with interested stakeholders, should publish a hydrogen market development roadmap to track progress and outcomes of the deployment of the hydrogen in Canada.	Given the evolving nature of the hydrogen market, additional analysis will continue through the 16 thematic working groups that have been established to support the implementation of the Hydrogen Strategy for Canada. This analysis is focused on all aspects of the hydrogen value chain—from production to distribution and multiple end-use. Natural Resources Canada is also working on the development of the reporting framework for the biennial progress report, which will track progress on the recommendations outlined in the Hydrogen Strategy for Canada, as well as data and market analysis related to the expected growth in Canada and globally. The biennial report will be a single compendium of information and results on all hydrogen-related activities undertaken across the country, including activities directly receiving federal or provincial/territorial support, as well as those undertaken strictly through the private sector. It will include key metrics and data related to hydrogen production, end-uses, investments, jobs, and exports.	Not applicable for modelling contract
3.50 To improve consistency across departments, Environment and Climate Change Canada and other federal departments should adopt a standard framework to estimate emission impacts of proposed policies, clean technologies, and fuels.	It is agreed that consistent and reliable emission estimates of proposed policies are necessary to inform decision making. The recently established Integrated Climate Lens Centre of Expertise, located at Environment and Climate Change Canada, has a mandate to ensure that major government decisions, namely through budget and Cabinet processes, consider climate mitigation and adaptation in a rigorous, consistent and, where possible, measureable manner.	Not applicable for modelling contract
3.64 In order to increase transparency of its emission projections, Environment and Climate Change Canada should develop and publish results for	This recommendation aligns with current Environment and Climate Change Canada practice. Environment and Climate Change Canada's greenhouse gas emission projections	Not directly applicable for this project but note that ESMIA has reviewed and uses the outcomes of the ECCC modelling of the “with additional measures”

scenarios • that include a detailed list of measures and assumptions considered • that show a clear distinction between (1) scenarios based on existing policies and measures and (2) exploratory scenarios that include proposed or aspirational policies and measures	are published in accordance with international standards that require a clear distinction between existing and planned initiatives.	scenarios. For example, ESMIA uses ECCC modelling for setting preliminary GHG constraints in our modelling.
3.65 In order to better inform decision making, Environment and Climate Change Canada, in coordination with Natural Resources Canada, should improve its pathways modelling by using reasonable, cost-effective, and technically feasible assumptions.	For purposes of modelling greenhouse gas projections in the context of Canada's climate plan, Environment and Climate Change Canada publishes both a "Reference" case and a "With Additional Measures" case. Both use reasonable, cost-effective and technically feasible assumptions. These assumptions are informed by the policy and program development work led by other government departments, including Natural Resources Canada, and include other considerations such as uncertainty in assumptions about future costs and technical parameters, particularly for rapidly evolving or emergent technologies. The assumptions are also informed by reviewing the latest academic literature.	ESMIA take great pride in our extensive database of technology representations based on public, peer-reviewed references. For this project ESMIA has taken extra steps to ensure confidence in our input assumptions by sharing a spreadsheet with technology input assumptions for over 290 individual technologies with over 70 technical experts. We have received and responded to feedback on this information. We are holding at least two workshops with peers on the assumptions and preliminary results. There were over 50 attendees to the first workshop. The experts that received the technology assumptions and attended the workshop include staff from ECCC, CER, and NRCan,
3.73 To improve quality, transparency, and trust in climate change modelling, Environment and Climate Change Canada should develop a formal review framework where its modelling would be subject to • enhanced peer review • formal consultations with stakeholders • formal periodic quality assurance control • public scrutiny	Environment and Climate Change Canada agrees with the importance of ensuring the ongoing suitability of the models themselves and shares the objective of maximizing the transparency of the inputs to those models.	This recommendation is not directly applicable to the ESMIA work for Natural Resources Canada. However, we have included informal peer review of the modelling input assumptions and scenario approach.

Annex E – Summary of Engagement

ESMIA worked closely with NRCan and ECCC colleagues throughout the project so help ensure that this modelling contributes to the updated Hydrogen Strategy Progress report and to future Government of Canada policy decisions. In particular ESMIA had small group meetings with:

ECCC

- Lifecycle Analysis team (December 22, 2022)
- Modelling teams (January 23, 2023)
- Technology experts and modelling team (February 1, 2023 and March 8, 2023)

NRCan

- CanmetENERGY (November 3, 2022 and January 6, 2023) and phone calls
- Technical authority (multiple meetings and phones calls)

Canada Energy Regulator

- Modelling team (January 1, 2023)

Workshops

ESMIA provided three workshops to vet assumptions and discuss preliminary results

- ESMIA worked with NRCan to define the set of experts to participate in review of this work. ESMIA reached out to experts in the following areas (with number of people invited to participate)
    - Federal government (40)
    - Provincial government (32)
    - Academic and Non-government Organizations (11)
    - Private sector (41)
    -
- Some people declined to participate leaving 110 people invited in total to the three workshops
    - Workshop attendees received list of hydrogen technologies with assumed costs and asked to provide feedback. ESMIA updated the technology assumptions based on feedback (see Annex C for assumptions used in the final analysis)

Three workshops were held, same content for each workshop, but multiple sessions to reach out to wide range

Workshop date	Focus	# of attendees
February 7, 2023	Main workshop – project definition, model description, modelling results (2 hours)	53
February 9, 2023	Additional workshop for those unavailable on February 9, at request of Transition Accelerator director (2 hours)	20
February 22, 2023	Workshop for private sector experts (1 hour)	18

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