HYDROGEN STRATEGY FOR CANADA

Seizing the Opportunities for Hydrogen

A Call to Action

December, 2020

DISCLAIMER

The Hydrogen Strategy for Canada (the “Strategy”) provides the perspective of numerous stakeholders from across governments, and industry, as well as Indigenous organizations, non-governmental organizations, and academia. While the Government of Canada led the development of the Strategy and consulted broadly with industry, the contents, findings, and recommendations expressed in the Strategy reflects a combined view and may not be unanimously endorsed by all of the participating organizations and their employees.

Aussi disponible en français sous le titre : Stratégie canadienne pour l’hydrogène
Cat. No. M134-65/2020E-PDF (Online) ISBN 978-0-660-36760-6

Foreword to the Hydrogen Strategy for Canada

For more than a century, our nation's brightest minds have been working on the technology to turn the invisible promise of hydrogen into tangible solutions. Canadian ingenuity and innovation has once again brought us to a pivotal moment.

As we rebuild our economy from the impacts of COVID-19 and fight the existential threat of climate change, the development of low-carbon hydrogen is a strategic priority for Canada. The time to act is now.

The Hydrogen Strategy for Canada lays out an ambitious framework for actions that will cement hydrogen as a tool to achieve our goal of net-zero emissions by 2050 and position Canada as a global, industrial leader of clean renewable fuels.

This strategy shows us that by 2050, clean hydrogen can help us achieve our net-zero goal—all while creating jobs, growing our economy, and protecting our environment. This will involve switching from conventional gasoline, diesel, and natural gas to zero-emissions fuel sources, taking advantage of new regulatory environments, and embracing new technologies to give Canadians more choice of zero emission alternatives.

As one of the top 10 hydrogen producers in the world today, we are rich in the feedstocks that produce hydrogen. We are blessed with a strong energy sector, and the geographic assets that will propel Canada to be a major exporter of hydrogen and hydrogen technologies.

Hydrogen might be nature's smallest molecule but its potential is enormous. It provides new markets for our conventional energy resources, and holds the potential to decarbonize many sectors of our economy, including resource extraction, freight, transportation, power generation, manufacturing, and the production of steel and cement.

This Strategy is a call to action. It will spur investments and strategic partnerships across the country and beyond our borders. It will position Canada to seize economic and environmental opportunities that exist coast to coast. Expanding our exports. Creating as many as 350,000 good, green jobs over the next three decades. All while dramatically reducing our greenhouse gas emissions. And putting a net-zero future within our reach.

The importance of Canada's resource industries and our clean technology sectors has been magnified during the pandemic. We must harness our combined will, expertise and financial resources to fully seize the opportunities that hydrogen presents.

This strategy is the product of three years of study and analysis, including extensive engagement sessions, where we heard from more than 1,500 of our country's leading experts and stakeholders. But its release is not the end of a process. This is only the beginning.

Together, we will use this Strategy to guide our actions and investments. By working with provinces and territories, Indigenous partners, and the private-sector and by leveraging our many advantages, we will create the prosperity we all want, protect the planet we all cherish and we will ensure we leave no one behind.

The Honourable Seamus O'Regan
Canada's Minister of Natural Resources

Contributors

For the past three years, the Government of Canada, under the leadership of Natural Resources Canada, has been working with private sector stakeholders, Indigenous organizations, non-Government organizations, and governments at all levels to inform the development of a *Hydrogen Strategy for Canada*. This Strategy contains input from hundreds of companies, organizations and individuals sourced through a variety of different forums, workshops, teleconferences, bilateral discussions, and dialogue through existing working groups. While the Government of Canada led the development of the Strategy and consulted broadly with industry, the contents, findings, and recommendations expressed in the Strategy reflects a combined view and may not be unanimously endorsed by all of the participating organizations and their employees.

The Government has also commissioned a number of key studies on topics such as hydrogen codes and standards, awareness, demand modelling, and GHG emissions reduction potential. These studies along with key international reports, for example from the International Energy Agency and Hydrogen Council, have helped inform the development of the Strategy.

Zen and the Art of Clean Energy Solutions (Zen) is the lead author of this strategy on behalf of the Government of Canada. Zen together with the Institute for Breakthrough Energy + Emission Technologies (IBET) led the aggregated 2050 hydrogen demand modelling work to determine the potential role hydrogen can play in Canada's future energy system. The Strategy summarizes and integrates stakeholder inputs and previous studies, as well as recent modelling and analysis, into a single cohesive document.

The *Hydrogen Strategy for Canada* is a strategic directional document based on best available information at this time. Adjustments will be made as technology, research, codes and standards, the international hydrogen landscape, and policy evolves. Additional research and analysis outlined as recommended actions in this document are planned through the Implementation Strategic Steering Committee, dedicated Working Groups, and Regional Blueprints.

Consultations

Consultations were held with over 1,500 stakeholders from across the value chain to ensure engagement opportunities were as comprehensive as possible. Stakeholder groups include, but are not limited to the private sector, associations and NGOs, academia and research groups, Federal and Provincial Governments, and Indigenous Organizations, communities, and businesses.

Linkages with Industry Working Groups

The Government has also collaborated closely with the Transition Accelerator, the Canadian Hydrogen and Fuel Cell Association (CHFCA), the Canadian Gas Association, and other industry associations which are pursuing actions closely aligned with those identified in the Strategy. Once the strategy is released, Canada will establish a Strategic Steering Committee, with several targeted task teams, to ensure progress toward the recommendations in the strategy is made and measured.

Abbreviations

AHJ	Authority Having Jurisdiction
ASHP	Air Source Heat Pump
ATR	Autothermal Reforming
AZETEC	Alberta Zero-Emissions Truck Electrification Collaboration
BC-LCFS	British Columbia’s Low Carbon Fuel Standard
BECCS	Bio-energy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
BNQ	Bureau de Normalization du Québec
CAD	Canadian Dollars
CCUS	Carbon Capture Utilization, Storage
CEC	California Energy Commission
CFS	Clean Fuel Standard
CHFCA	Canadian Hydrogen and Fuel Cell Association
CHIC	Canadian Hydrogen Installation Code
CI	Carbon Intensity
CMMP	Canadian Minerals and Metals Plan
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSA	Canadian Standards Association
DAC	Direct Air Capture
DOE	Department of Energy (US)
DRI	Direct Reduced Iron
EER	Energy Effectiveness Ratio
FCEB	Fuel Cell Electric Bus
FCEV	Fuel Cell Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GJ	Gigajoule
GW	Gigawatt
H_2	Hydrogen
HD	Heavy-Duty
ICE	Internal Combustion Engine
ICT	Innovative Clean Transit
IEA	International Energy Agency
IMO	International Maritime Organization
IP	Intellectual Property
IRAP	Industrial Research Assistance Program
LD	Light-Duty
LNG	Liquid Natural Gas
MCH	Methylcyclohexane
MJ	Megajoule
NG	Natural Gas
NH_3	Ammonia
NO_x	Nitrogen Oxides
NRC	National Research Council

OEM	Original Equipment Manufacturer
OpEx	Operating Expenditures
PEM	Proton Exchange Membrane
PJ	Petajoules
PSA	Pressure Swing Adsorption
RNG	Renewable Natural Gas
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
SO_x	Sulphur Oxides
SR&ED	Scientific Research and Experimental Development Tax Incentive Program
SDTC	Sustainable Development Technology Canada
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
TWh	Terawatt-hour
VRE	Variable Renewable Energy
WGS	Water Gas Shift
ZEV	Zero-Emission Vehicle

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TIME TO ACT

The world's energy systems are undergoing radical transformation driven by the need to mitigate climate change. Development of an at-scale, clean hydrogen economy is a strategic priority for Canada, needed to diversify our future energy mix, generate economic benefits and achieve net-zero emissions by 2050.

The time to act is now. Governments around the world are releasing and executing hydrogen strategies that are building global momentum. In 2019, Canada seized this momentum by developing and launching a new Hydrogen Initiative under the Clean Energy Ministerial, designed to be the cornerstone for global hydrogen deployment.

Now, one year later, Canada is poised to leverage this momentum, to grow the domestic opportunity for hydrogen, while also benefiting from growth in global demand through export opportunities, guided by this Strategy.

This Strategy seeks to modernize Canada's energy systems by leveraging Canadian expertise – including increased participation from marginalized and underrepresented groups – through building new hydrogen supply and distribution infrastructure and fostering uptake in various end-uses, that will underpin a low-carbon energy ecosystem in the near- and long-term. It will set the foundation to do this over the next five years by:

- Encouraging early deployment HUBs in mature applications, and Canadian demonstrations in emerging applications;
- employing regulations, including the forth-coming Clean Fuel Standard to drive near-term investments; and
- framing new policy and regulatory measures needed to reach net-zero by 2050.

These activities in the short-term will be followed by the growth and diversification of the sector from 2025 to 2030. Thereafter, through rapid expansion until 2050, Canada will start to realize the full benefits of the hydrogen strategy.

Those benefits include:

- positioning Canada to become a world-leading supplier of hydrogen technologies;
- sparking economic recovery while growing domestic low-carbon fuel production to reduce emissions for the longer term, including unique opportunities for Indigenous communities and businesses;
- generating more than 350,000 high-paying jobs nationally; and
- employing hydrogen as a key enabler to reach net-zero emissions by 2050.

The International Energy Agency (IEA) has recommended that governments put clean energy solutions such as hydrogen at the heart of stimulus plans. Green infrastructure investments are key to achieving Canada's post-pandemic economic recovery, clean growth and climate change objectives.

By applying its world-class expertise at home, Canada can showcase hydrogen's real-world applications and benefits and the role hydrogen can play in transforming energy systems. Early deployment HUBs will set Canada on a path for widespread deployment in the mid- and long-term where hydrogen's decarbonization potential can be fully realized.

CONTEXT

Canada has played an important role in the development of the growing global hydrogen economy, starting more than a century ago with innovation in hydrogen production technology and four decades ago as pioneers in fuel cell technology. Canada continues to be an R&D and technology leader in the sector.

Under the Paris Agreement, Canada has committed to reducing GHG emissions by 30% below 2005 levels by 2030. It has also announced a target to achieve net-zero emissions by 2050, joining 72 other nations in this ambitious pledge. In a net-zero future, Canada's economy will be powered by electricity and low carbon fuels – with low carbon fuels expected to provide up to 60% or more of our energy needs. As the lowest carbon fuel, hydrogen is essential to decarbonizing the top third of Canada's most energy intensive and hard-to-abate end-use applications, and there is much work to do to roll out hydrogen at scale domestically.

Canada is not alone in seeing hydrogen as a critical part of the solution to combat climate change and improve air quality, while driving economic growth in a carbon-constrained world. Countries around the world have developed strategies to inform the optimal supply pathways and end-use applications for hydrogen, as well as to define export strategies.

The demand for hydrogen in global energy systems is dramatically increasing, with projections indicating at least a tenfold increase in demand over the next three decades. Studies indicate that hydrogen could provide up to 24%[1] of global energy demand by 2050. The number of countries with polices that support investment in hydrogen technologies is increasing, along with the number of sectors they target. Canada is uniquely positioned to become a large-scale exporter of hydrogen to serve this growing market, but domestic deployments must lead.

For three years, the Government of Canada, under the leadership of NRCan has been working with private sector stakeholders and governments at all levels to inform the development of the *Hydrogen Strategy for Canada.* The release of this strategy comes during unprecedented times. The world has been shaken by COVID-19, and there is daily evidence mounting that climate change poses an ever-increasing risk to the world's economies, habitats, biodiversity, human health, and our future way of life.

Canada has all the ingredients necessary to develop a competitive and sustainable hydrogen economy. The modernization of Canada's energy systems towards a low-carbon economy presents a unique opportunity to leverage Canadians' expertise to build new infrastructure assets to serve as a backbone for a low-carbon energy ecosystem across Canada with hydrogen playing an integral role, delivering up to 30% of Canada's end-use energy by 2050.

This strategy is a call to action. Achieving decarbonization targets requires bold action and radical transformation of Canada's energy system that must begin with the end in mind rather than working incrementally based on old paradigms.

[1] Bloomberg NEF. (2020). *Hydrogen Economy Outlook*. Retrieved from https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

CANADA'S ADVANTAGES

Canada has unique competitive and comparative advantages that position the country to become a world-leading producer, user, and exporter of clean hydrogen, as well as hydrogen technologies and services. A strong hydrogen economy will lead to financial, environmental, and health benefits for Canadians.

- **Rich in feedstocks to produce hydrogen**

  Canada has among the lowest Carbon Intensity (CI) electricity supplies in the world given our hydroelectric generation capacity and status as a Tier-1 nuclear region. Canada also has abundant fossil fuel reserves, world class CO_2 storage geology, potential for growth in variable renewables, large scale biomass supply, and freshwater resources. All of these can be leveraged to produce hydrogen.

- **Leading innovation and industry position**

  Canada is known for its leading hydrogen and fuel cell technology companies and expertise. As of 2017, there were >100 established companies, employing >2,100 people, generating revenues >$200 million. Canada also has significant expertise in carbon capture technology, one of the keys to the production of low CI hydrogen from fossil fuels.

- **Strong energy sector**

  Canada's energy sector accounted for 832,500 direct and indirect jobs as of 2019, with assets valued at $685 billion[1]. This skilled labour force coupled with strategic infrastructure assets position Canada to rapidly pivot to include at- scale hydrogen as an energy currency.

- **Established international collaborations**

  Canadian government, industry and academia are involved in international collaborations related to hydrogen that position Canada as a leader both from an innovation and commercial perspective.

- **Energy export channels to market**

  Canada's proximity to hydrogen import markets including Japan, South Korea, California, the UK, Germany, and all of Europe, along with export assets such as deep water ports, established pipeline networks, and an emerging LNG industry, position Canada to be an exporter of hydrogen as the global economy evolves.

- **Canada's Unique Starting Point**

  Canada is recognized as a global leader in the hydrogen and fuel cell sector, seen as a hub for technical expertise, intellectual property, and leading products and services. Canada is one of the top 10 hydrogen producers in the world today. An estimated three million tonnes are produced per year from natural gas. Canada is home to the largest clean hydrogen production facility in the world to produce hydrogen from natural gas with carbon capture and permanent storage for the resulting CO_2 emissions.

By leveraging these advantages to develop a vibrant and robust clean hydrogen economy, Canadians will benefit from:

- **Economic growth and jobs**

  Canada's hydrogen economy will create new green jobs in R&D, manufacturing, and services supporting increased participation from traditionally marginalized and under-represented groups as part of an inclusive transition. Hydrogen will become a new export currency for both regional energy economies in Western, Central, and Eastern Canada, as well as in the international market. This will allow

[1] NRCan. (2018). *10 Key Facts on Canada's Energy Sector*. Retrieved from https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/10-Key-Facts-on-Canada_s-Energy-Sector-2018-en%20.pdf

Canadian energy companies to move up the value chain as a fuel provider in a zero-emissions future. If Canada fully seizes the opportunity presented by hydrogen, it could lead to more than 350,000 sector jobs and direct revenues of over $50B/year by 2050.

- **Transformative opportunity for Canada's petroleum sector**

  Hydrogen is critical to transforming oil and natural gas industries to net-zero emissions. It provides an opportunity to leverage Canada's diverse talent pool, valuable energy reserves, and infrastructure assets in a way that is carbon-free at the point of use, providing a future pathway to utilize these assets.

- **Energy resilience**

  Hydrogen can act as an energy carrier to enable increased penetration of renewables by providing time shifting and energy storage capabilities. Hydrogen adds optionality in a future net-zero mix, complementing other energy vectors such as direct electrification and biofuels, and serving as a bridge between energy grids in an integrated energy system.

- **Cleaner air**

  Hydrogen does not produce greenhouse gases, black carbon, particulates, SO_x, or ground-level ozone at the point of use. When used in an electrochemical fuel cell, it emits only water and heat. Increased hydrogen adoption leads to cleaner air, with improved health outcomes for Canadians.

- **Meeting decarbonization goals**

  Hydrogen uniquely closes the gap in hard-to-abate, energy intensive applications such as long-range transportation, high-grade heat production, and as a feedstock in industrial processes. Hydrogen has the potential to make significant contributions to Canada's required GHG emission reductions by 2050.

CANADA'S OPPORTUNITY

Clean hydrogen has the potential to deliver up to 30% of Canada's end-use energy by 2050, abating up to 190 Mt-CO_2e of GHG emissions through deployment in transportation, heating, and industrial applications.

With Canada's strong starting position, emissions reductions from an optimistic transformative scenario could contribute up to 45 Mt-CO_2e reduction by 2030. This scenario is more likely to be achieved with strong pricing and regulatory incentives in place at the federal and provincial level to drive hydrogen adoption, supported by immediate and aligned action across government and industry. Canada's recently announced Strengthened Climate Plan, including carbon pricing, the Clean Fuel Standard and the $1.5 billion dollar Low-carbon and Zero-emissions Fuels Fund, is already putting in place foundational federal initiatives that will enable the broad suite of measures contemplated in this Strategy. Benefits realized by hydrogen will accelerate beyond the 2030-timeframe, with potential under the transformative scenario to contribute up to 190 Mt-CO_2e reductions per year, by 2050.

H_2 Opportunity

	2030	2050
% of Delivered Energy	6%	30%
Hydrogen Demand	4 Mt-H_2	20 Mt-H_2
GHG Emissions Abated	up to 45 Mt-CO_2e	up to 190 Mt-CO_2e

Production

Canada's rich feedstock reserves, skilled energy labour force, strategic energy infrastructure assets, and leading position in innovation in hydrogen and fuel cell technologies position Canada to become one of the top three global producers of clean hydrogen.

Canada is one of the top ten global producers of hydrogen today, producing an estimated 3 million tonnes (Mt) annually via steam methane reformation (SMR) of natural gas. While SMR is not considered a clean hydrogen pathway without carbon capture, Canada is well placed to transition to clean pathways going forward. Canada has established production supply chains, primarily in Alberta for fuel upgrading/refining and nitrogen fertilizer production that can be leveraged in the near term. By 2050, Canada could grow production by a factor of seven to meet domestic demand, producing >20 Mt of low CI hydrogen per year, with potential for significant expansion to meet global demand.

Hydrogen can be made from a variety of feedstocks, including water and electricity, fossil fuels, biomass and as a by-product from industrial processes. The CI of the hydrogen pathways can vary significantly, and Canada must be focused on developing cost-effective, low CI pathways in the near and mid term while ultimately transitioning to an increasing percentage of renewable or zero-emission feedstocks over the long term. Canada is working with countries around the world to develop a common methodology to determine and independently certify the CI of hydrogen, which will be necessary to facilitate trade.

Hydrogen production in Canada is expected to be based on a mix of pathways. The aggregate hydrogen demand projected in 2050 highlights the need for Canada to explore all low CI hydrogen production opportunities.

- Electrolytic Hydrogen

  Hydrogen can be produced from water via electrolysis using clean electricity. Canada is the sixth-largest global producer of electricity in the world and has one of the lowest carbon intensity grids due to our vast hydroelectricity generating assets. There are also synergies between hydrogen production, nuclear and renewable electricity. Hydrogen can be produced via electrolysis using off-peak nuclear electricity in the near term, while high-temperature thermal processes or coupling with small modular reactors are viable in the longer term. Hydrogen can also play a role in daily to seasonal storage of variable renewable resources, enabling a higher penetration of intermittent renewables on the grid.

- Hydrogen from fossil fuels

  Clean hydrogen can be produced from fossil fuels when combined with Carbon Capture Utilization, and Storage (CCUS) or the carbon can alternatively be sequestered in the form of solid carbon. Canada is the world's fourth largest producer of natural gas. Provinces with the highest natural gas and petroleum reserves are Alberta, British Columbia, and Saskatchewan, and the Atlantic Provinces, and these provinces are best suited for hydrogen production from fossil fuels.

- Hydrogen from biomass

  Hydrogen can be derived from the gasification of dry biomass. This is considered to be both renewable and carbon neutral. Most provinces in Canada have access to biomass residues through forest and agriculture sectors.

- Industrial by-product hydrogen

  Hydrogen in Canada currently produced as a by-product of industrial processes including chlor-alkali and sodium chlorate production can be captured, purified, and used directly. Vented hydrogen from large-scale plants can be sufficient to support some near-term needs, but is limited in supply.

The hydrogen supply network in Canada could include both large-scale centralized plants in Canada's natural-gas rich provinces or in regions with high penetration of low-cost renewables, and smaller-scale distributed electrolytic production near demand centers. Delivered hydrogen costs of $1.50-3.50/kg are projected to be achieved as production scale is realized and investment is made in distribution infrastructure.

Industry and Provincial Governments will play an important role in determining which hydrogen production pathways will come to fruition in Canada, and over what timeframes.

End-Use

Domestic deployment of hydrogen is critical to supporting Canada's world-leading hydrogen and fuel cell sector, as well as to meeting climate change objectives. The earlier deployment starts, the sooner scale and user acceptance will be achieved, allowing the realization of longer-term projections on uptake and associated benefits.

Adoption of hydrogen will be focused on energy-intensive applications where it offers advantages over alternative low-carbon options. This includes using hydrogen as a fuel for long-range transportation and power generation, to provide heat for industry and buildings, and as a feedstock for industrial processes.

- **Fuel for Transportation**

Hydrogen can be used directly as a fuel in fuel cell electric vehicles, which have twice the efficiency of combustion engines and zero harmful emissions at the tailpipe. Hydrogen combustion and co-combustion engine technology is also under development as a transitional opportunity.

Fuel cell light-duty passenger vehicles are commercially available today globally, and in limited numbers in Canada. The Government of Canada has set federal targets for zero-emission vehicles (ZEV) to reach 10% of light-duty vehicles sales per year by 2025, 30% by 2030 and 100% by 2040. Canada considers battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and plug-in hybrid electric vehicles (PHEVs) to qualify as ZEVs. BC and Quebec have led provincially with the adoption of consumer purchase incentives for ZEVs and sales regulations. Both of these provinces have started to deploy hydrogen fueling infrastructure and light-duty FCEVs.

Battery electric vehicles are expected to take a significant portion of the market share for light-duty applications in Canada. FCEVs offer choice for consumers desiring longer range and faster fueling times and are well suited to larger passenger vehicle platforms.

Public transit agencies around the world are shifting towards low- and zero-emission vehicles. Fuel cell electric buses (FCEBs) are commercially available today, with more than 2000 FCEBs[1] in service worldwide, and approximately half of those are powered by Canadian technology. Canada has unique potential for a 'made-in-Canada' solution with New Flyer Industries and Ballard Power Systems leading the market with commercial fuel cell electric bus deployments in North America.

The zero-emission bus (ZEB) initiative[2] underway in Canada encourages government to support school boards and municipalities in purchasing 5000 ZEBs over the next five years. Canada can leverage the local supply chain to provide economic value if FCEBs are a portion of the mix. These buses are well suited to longer routes and cold weather climate that Canadian transit agencies service.

Fuel cells are expected to play a significant role in medium- and heavy-duty trucks, rail, and ships that have operations with high power demand, coupled with energy-intensive and long duty cycles. For example, heavy-duty trucks travelling long distances would require many heavy batteries, reducing the load capacity beyond that which would be acceptable to operators. Long charging times could also impact operations negatively. The improved energy density and fast fill characteristics of fuel cell electric trucks will likely make them an optimal choice for certain applications.

[1] Ballard. (2020). *Fuel Cell Electric Buses*. Retrieved from https://www.ballard.com/docs/default-source/web-pdf's/white-paper_fuel-cell-buses-for-france_final-english-web.pdf?sfvrsn=939bc280_0

[2] CUTA. (2019). *New federal government unveils its priorities*. Retrieved from https://cutaactu.ca/en/blog-posts/new-federal-government-unveils-its-priorities

There is a similar value proposition for hydrogen use in mining equipment, including material handling vehicles. Hydrogen presents an opportunity to reduce widespread reliance on diesel for mining vehicles and stationary power equipment. Hydrogen offers the added benefit of reducing harmful exhaust emissions, especially in underground mines. The Canadian Minerals and Metals Plan (CMMP) aims to capitalize on opportunities to strengthen Canada's competitive position within the global mining sector and emphasizes the importance of developing and adopting alternative energy sources, such as hydrogen.

In the near term, as costs and availability of fuel cells challenge uptake, hydrogen-diesel co-combustion in truck applications offers an alternative pathway to create the demand for hydrogen and support infrastructure development.

- **Fuel for Power Generation**

Hydrogen can be used as a fuel for power production through either hydrogen combustion in turbines or electrochemical conversion in stationary fuel cell power plants. Hydrogen provides load management, long-term energy storage, and a path to market that enables the growing use of intermittent renewables.

In the longer term, hydrogen can play a role in greening Canada's electricity grids where there is still a reliance on fossil fuels for power production. Hydrogen can also provide stability for off-grid renewables-based power solutions in remote communities and remote industrial sites such as mines that are today largely dependent on expensive, highly emitting diesel power.

- **Heat for Industry**

As a heating fuel, hydrogen is a cleaner-burning molecule that can be a substitute for the combustion of fossil fuels in applications where high-grade heat is needed and where electric heating is not technically or economically the best solution.

In Canada's oil and gas sector, low CI hydrogen can offer emissions reduction benefits in both upstream extraction (combusted as a heat source) and downstream refining (used as a chemical feedstock). For example, in upstream operations, low CI hydrogen can replace natural gas combusted to produce steam for steam-assisted gravity drainage (SAGD) in-situ bitumen production. Hydrogen can lower the CI of conventional refined petroleum products in this way and could offer a compliance pathway for the federal Clean Fuel Standard.

Other heavy industry in Canada that relies on a large amount of high-grade heat production includes cement and steel manufacturing, the pulp and paper sector, and industrial processes relying on steam production. These sectors can also reduce emissions by converting to blends of hydrogen and natural gas or pure hydrogen for heat production.

- **Heat for Buildings**

Hydrogen can play a role in reducing emissions in heating applications in the built environment. Natural gas (NG) utilities are looking to decarbonize the NG grid by introducing both Renewable Natural Gas (RNG) and hydrogen as alternative low-carbon chemical fuels. Canada's cold climate results in heating accounting for almost 80% of energy use in the home.[1] Since NG is used for both space heating and water heating, hydrogen is gaining increased attention from utilities as a low-carbon option, either as a blend with natural gas or as a replacement fuel. Several jurisdictions in Canada and worldwide are conducting pilot projects to determine the technical feasibility of blending hydrogen into existing natural gas systems. Codes and standards work will be required to support opportunities for the potential blending of hydrogen.

Due to possible technical constraints, beyond blending limits of ~20% by volume, dedicated

[1] NRCan. (2017). *Residential Sector*. Retrieved from https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/handbook_res_00.cfm

hydrogen pipelines start to become an attractive alternative. In a net-zero future where distributed combustion emissions need to be largely eliminated, hydrogen may become the new chemical fuel of choice for heating in Canada, and utilities will play an important leadership role in that transition.

- **Feedstock for Industry**

Hydrogen is used as a feedstock in several industrial processes in Canada today. Most feedstock hydrogen is currently produced via steam methane reforming.

Hydrogen is used as a feedstock for:

- Petroleum refining
- Bitumen upgrading
- Ammonia production
- Methanol production
- Steel production

The greatest use of hydrogen globally today is for refining and upgrading crude oil, where hydrogen-based processes remove impurities like sulphur and process heavy hydrocarbon chains into lighter components. The majority of hydrogen required for refining is produced on-site from either dedicated production facilities or as a by-product. Because of this integration of hydrogen production within refining facilities, production is primarily supplied by natural gas reforming methods. The most significant opportunity to reduce emissions associated with hydrogen in the oil and gas industry is retrofitting existing conversion technology with carbon capture and storage or deploying new clean hydrogen technology that does not produce CO_2.

Availability of low cost, low CI hydrogen can create new industry in Canada. This includes methanol production and liquid synthetic fuel production, an innovative process combining clean hydrogen and carbon captured from the air to produce carbon-neutral, energy-dense liquid fuels that are well suited to applications such as aviation and large marine vessels. Renewable nitrogen fertilizer production also presents an opportunity for a new Canadian industry.

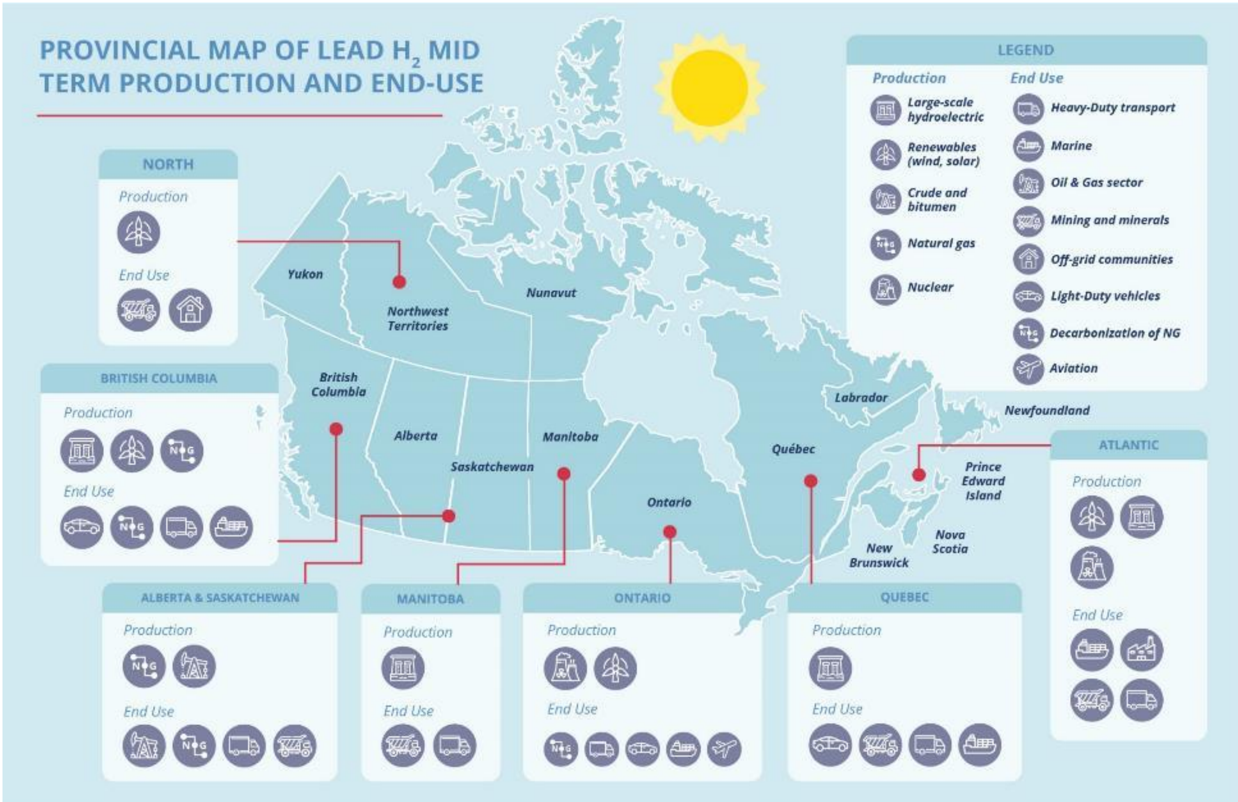
Export

With worldwide demand for hydrogen increasing, the global market is expected to reach more than $2.5T by 2050. There is a significant export opportunity for Canada as energy importers are actively looking to Canada as a potential supplier.

As an energy rich nation with significant clean hydrogen production capacity, established international trade partnerships, and strategic infrastructure assets such as deep water ports and established pipeline networks, Canada is positioned to become top global supplier of clean hydrogen. A 2019 BC study shows an export potential of $15 billion by 2050 from that province alone. Another recent study indicated that hydrogen exports could reach ~$50 billion by 2050[1], doubling the economic potential of the domestic market projected for Canada in that same timeframe. With import countries looking to decarbonize their energy systems, hydrogen could contribute to a significant portion of the energy export market share in the coming decades.

Just as Canada is working to capture the global LNG export market, we can build on this experience to advance a hydrogen strategy with strong early actions and a national plan that builds on Canada's regional strengths. Taken together, we can lead in the emerging hydrogen export market.

[1] The Transition Accelerator. (2020). *Towards Net-Zero Energy Systems in Canada: A Key Role for Hydrogen*. Retrieved from https://transitionaccelerator.ca/wp-content/uploads/2020/09/Net-zero-energy-systems_role-for-hydrogen_200909-Final-print-1.pdf



REMAINING CHALLENGES

Economic and Investment

The factors limiting hydrogen use in some applications today are economic rather than technological, where hydrogen is not yet cost-competitive compared to other conventional fuel options.

While hydrogen can be among the lowest cost alternatives for reducing carbon emissions on a dollar-per-tonne-abated basis, a challenge today is that even with some form of carbon pricing, GHG emissions are not always adequately reflected in the market cost of baseline fuels. Implementation of the federal Clean Fuel Standard will be an important step forward.

The cost of end-use applications that rely on fuel cells is also a barrier to adoption, and R&D and scaled-up manufacturing processes are needed to drive down costs. Development of supporting infrastructure requires significant coordinated investments, which is challenged by uncertain demand creating high risk for investors.

Achieving scale is also critical to economic competitiveness of the industry. While the sector must ultimately be self-sustaining, strong policy and fiscal support are needed in the next 5-10 years to attract and de-risk industry investment.

Technology & Innovation

Canada was an early leader in the hydrogen and fuel cell sector and is recognized worldwide as a region rich with technical expertise, intellectual property, and leading products and services. While some hydrogen and fuel cell technologies are at a level of commercial readiness, support for R&D is needed to reduce costs further, develop solutions in the less mature applications and discover new breakthrough technologies to benefit the sector. Continuing to stay at the forefront of innovation is critical to sustaining Canada's competitive advantages.

Other countries have been rapidly increasing investment to support innovation in the sector, whereas between 2008 and 2016, Canada slowed investment in fundamental research in this sector. While more recently, Canada has again committed to being a global leader in clean tech innovation, this gap in support has resulted in the fact that some Canadian companies developing research centres and/or moving parts of their operations to other countries where there is more support for technology advancement. It is important for Canada to act now to prevent loss of critical intellectual property.

Policy & Regulation

Clean hydrogen projects around the world have primarily been in regions with a combination of supporting policies and regulations. Policies and regulations that encourage the use of hydrogen technologies include low carbon fuel regulations, carbon pricing, vehicle emissions regulations, zero-emission vehicle mandates, creation of emission-free zones, and renewable gas mandates in natural gas networks. Mechanisms to help de-risk investments for end-users to adapt to regulations are also beneficial.

Canada currently lacks a comprehensive and long-term policy and regulatory framework that includes hydrogen. Where policies are in place, they are not consistent across regions resulting in a 'patch-work' approach that slows adoption.

Availability of Hydrogen Infrastructure

Domestic supply of low CI hydrogen is limited in many parts of Canada today, and this is preventing both pilot and commercial rollout. For some applications, there is a need to transport and store hydrogen from the site of production to the end-user. This includes refueling infrastructure for transportation applications.

Over time, as domestic production and demand grow, there will be a need for dedicated infrastructure such as hydrogen pipelines and liquefaction plants. Ensuring that these crucial assets can be built in a coordinated and timely manner will be essential to ensuring low cost, low CI hydrogen can be delivered to both domestic and international markets.

Codes & Standards

The deployment of hydrogen is in the early stages across many jurisdictions and sectors in Canada, and there are gaps in existing codes & standards that need to be addressed to enable adoption. Harmonizing codes and standards across jurisdictions will ensure that best practices are applied across the global hydrogen economy to facilitate the growth of trade and export markets.

Awareness

There is a lack of awareness about the opportunities and safety around hydrogen within the general public, as well as within industry and government. Increased awareness about hydrogen as a viable decarbonization pathway that is safe and provides economic benefits is critical to establishing a vibrant hydrogen sector.

PATH FORWARD

Vision for 2050

If Canada seizes the opportunities for hydrogen, by 2050 the country could realize the following:

- Up to 30% of Canada's energy delivered in the form of hydrogen
- Canada is one of top 3 global clean hydrogen producers, with domestic supply >20 Mt/year
- Established supply base of low carbon intensity hydrogen with delivered prices of \$1.50 - \$3.50/kg
- >Five million FCEVs on the road
- Nationwide hydrogen fueling network
- >50% of energy supplied today by natural gas is supplied by hydrogen through blending in existing pipelines and new dedicated hydrogen pipelines
- New industries enabled by low-cost hydrogen supply network
- ~350,000 hydrogen sector jobs
- >\$50 billion in direct hydrogen sector revenue for the domestic market
- Established and competitive hydrogen export market
- Up to 190 Mt-CO_2e annual GHG reduction

Near Term: Laying the Foundation

The focus of the next five years will be on laying the foundation for the hydrogen economy in Canada. This includes planning for and developing new hydrogen supply and distribution infrastructure to support early deployment HUBs in mature applications while supporting Canadian demonstrations in emerging applications. Regulations such as the Clean Fuel Standard will be fundamental to driving near-term investment in the sector. Introduction of new policy and regulatory measures will also be needed.

Mid Term: Growth and Diversification

Activities to stimulate the sector in the next five years will be followed by growth and diversification of the sector in the 2025 – 2030 timeframe. As the technology matures and the full suite of end-use applications is at or near commercial technology readiness levels, hydrogen use will be focused on applications that provide the best value proposition relative to other zero-emission technologies.

Long Term: Rapid Market Expansion

In the 2030-2050 timeframe, Canada will start to realize the full benefits of a hydrogen economy as the scale of deployments increase and number of new commercial applications grows, supported by Canada's foundational supply and distribution infrastructure.

RECOMMENDATIONS AND IMPLEMENTATION

Recommendations

The release of this strategy is the first step in the next phase of Canada's hydrogen journey. The recommendations will inform the development of concrete actions by all players across the hydrogen ecosystem.

In the implementation phase following the release of the strategy, there will be ongoing engagement with public, private and Indigenous stakeholders to continue the momentum, initiate and track activities related to the recommendations, follow progress, and identify new priority areas as the market evolves. Actions will be coordinated through a Strategic Steering Committee and Working Groups.

The Strategy's recommendations have been developed in consultation with stakeholders and represent actions needed to lay the foundation and maintain momentum for maximizing the benefits of hydrogen in Canada's future energy system mix.

There are 32 recommendations across the eight pillars of the *Hydrogen Strategy for Canada*. Not all of these actions will happen at once - the figure on page XXII outlines how Canada must sequence actions to seize the hydrogen opportunities over time, cementing its essential role in our low-carbon future.

The Strategy's recommendations represent sector-wide themes, highlighted throughout the Strategy. Recommendations have been proposed in eight pillars:

Pillar 1: Strategic Partnerships *- Strategically use existing and new partnerships to collaborate and map out the future of hydrogen in Canada.*

Pillar 2: De-Risking of Investments *- Establish funding programs, long-term policies, and business models to encourage industry and governments to invest in growing the hydrogen economy.*

Pillar 3: Innovation *- Take action to support further R&D, develop research priorities, and foster collaboration between stakeholders to ensure Canada maintains its competitive edge and global leadership in hydrogen and fuel cell technologies.*

Pillar 4: Codes and Standards *- Modernize existing and develop new codes and standards to keep pace with this rapidly changing industry and remove barriers to deployment, domestically and internationally.*

Pillar 5: Enabling Policies and Regulation *- Ensure hydrogen is integrated into clean energy roadmaps and strategies at all levels of government and incentivize its application.*

Pillar 6: Awareness *- Lead at the national level to ensure individuals and communities are aware of hydrogen's safety, uses, and benefits during a time of rapidly developing technologies.*

Pillar 7: Regional Blueprints *- Implement a multi-level, collaborative government effort to facilitate the development of regional hydrogen blueprints to identify specific opportunities and plans for hydrogen production and end use.*

Pillar 8: International Markets *- Work with our international partners to ensure the global push for clean fuels includes hydrogen so Canadian industries thrive at home and abroad.*

Strategic Partnerships

1. *Collaborate across multiple levels of government and with Indigenous groups through Intergovernmental Working Groups to establish priority areas for deployment and to share knowledge, best practices, and lessons learned through early deployments.*
2. *Expand public/private partnerships leveraging Canada's innovative clean technology companies and world-leading hydrogen and fuel cell expertise to accelerate deployment projects across the value-chain.*
3. *Foster cross-sector collaborations within domestic deployment hubs to show the economic and operational benefits of multiple applications operating as part of an integrated ecosystem.*
4. *Leverage international collaborations and pursue synergistic international initiatives to attract direct foreign investment and to accelerate opportunities for Canada in global markets.*

De-Risking Investments

5. *Implement long-term policies that create hydrogen demand certainty and de-risk the private sector investments needed to establish supply and distribution infrastructure.*
6. *Establish multi-year programming as well as a clear and long-term regulatory environment to support early production and end-use projects, including support to assess the feasibility of projects.*
7. *Develop regional deployment HUBs to demonstrate, validate, and implement business cases across the full value chain, from production and distribution to end-use.*
8. *Facilitate co-funding opportunities, leveraging multiple levels of government and the private sector.*

Innovation

9. *Develop strategic fundamental research priorities where Canada can sustainably excel and provide economic value; set technology performance and cost goals.*
10. *Establish dedicated funding for sustained RD&D to ensure Canada retains its leadership position in hydrogen and fuel cell technologies.*
11. *Leverage expertise in academia, government labs, and private sector labs to create regional research hubs and to encourage mission-oriented approaches to research, development, and pilot deployments.*
12. *Foster collaboration between Federal labs, industry, and academia as well as international partners, by supporting consortium-based projects for fundamental research and by coordinating reviews and information sharing.*

Codes and Standards

13. *Update, harmonize and recognize codes and standards (including the Canadian Hydrogen Installation Code) to enable deployments and to facilitate new technology and infrastructure adoption in early markets.*
14. *Establish a codes and standards working group, which includes inter-provincial Authorities Having Jurisdiction representatives, to share lessons learned and identify gaps in codes and standards.*
15. *Develop standards that are performance based versus prescriptive, and ensure hydrogen is not excluded from broader codes, standards, and regulations due to restrictive language.*
16. *Facilitate Canadian leadership and participation on international standard and certification efforts (e.g. development of global carbon intensity metrics, blending levels for hydrogen in natural gas systems), simplifying international trade.*

Enabling Policies and Regulations

17 *Ensure that governments at all levels consider hydrogen's essential role in Canada's energy future as they develop new policies, programs, and regulations.*

18 *Encourage governments to modernize and update existing policies, programs, and regulations to facilitate growth of domestic hydrogen production and end-use.*

19 *Ensure hydrogen is part of integrated clean energy roadmaps at national and provincial/ territorial levels.*

20 *Establish technology-neutral, performance-based standards to define a hydrogen carbon-intensity threshold. Establish tiered, time-based requirement for renewable hydrogen content in government supported projects.*

Awareness

21 *Support community engagement and outreach where deployment HUBs are established.*

22 *Establish awareness and outreach campaigns to educate government, industry, the public, and other important influencers about hydrogen safety, uses, and benefits.*

23 *Develop a suite of tools and resources for early hydrogen markets to help end-users quantitatively evaluate hydrogen as an option for their operations. Host the tools and resources through a central, government-run website.*

24 *Support collaborations between industry and academia to develop hydrogen-specific curriculums to build awareness, interest, skills development, and training to develop the next generation talent pool and prepare the labour force for new opportunities.*

Regional Blueprints

25 *Facilitate the development of regional hydrogen blueprints, as a multi-level government collaborative effort, to identify specific opportunities and plans for hydrogen production and end-use. Ensure federal participation to capture synergies with the Hydrogen Strategy for Canada.*

26 *Identify opportunities for the establishment of regional HUBs, comprised of projects along the entire value-chain.*

27 *Include utilities, major industry from adjacent sectors, and cleantech companies in development and implementation of blueprints.*

28 *Identify areas for alignment and replication with other provinces/regions to facilitate and accelerate overall adoption.*

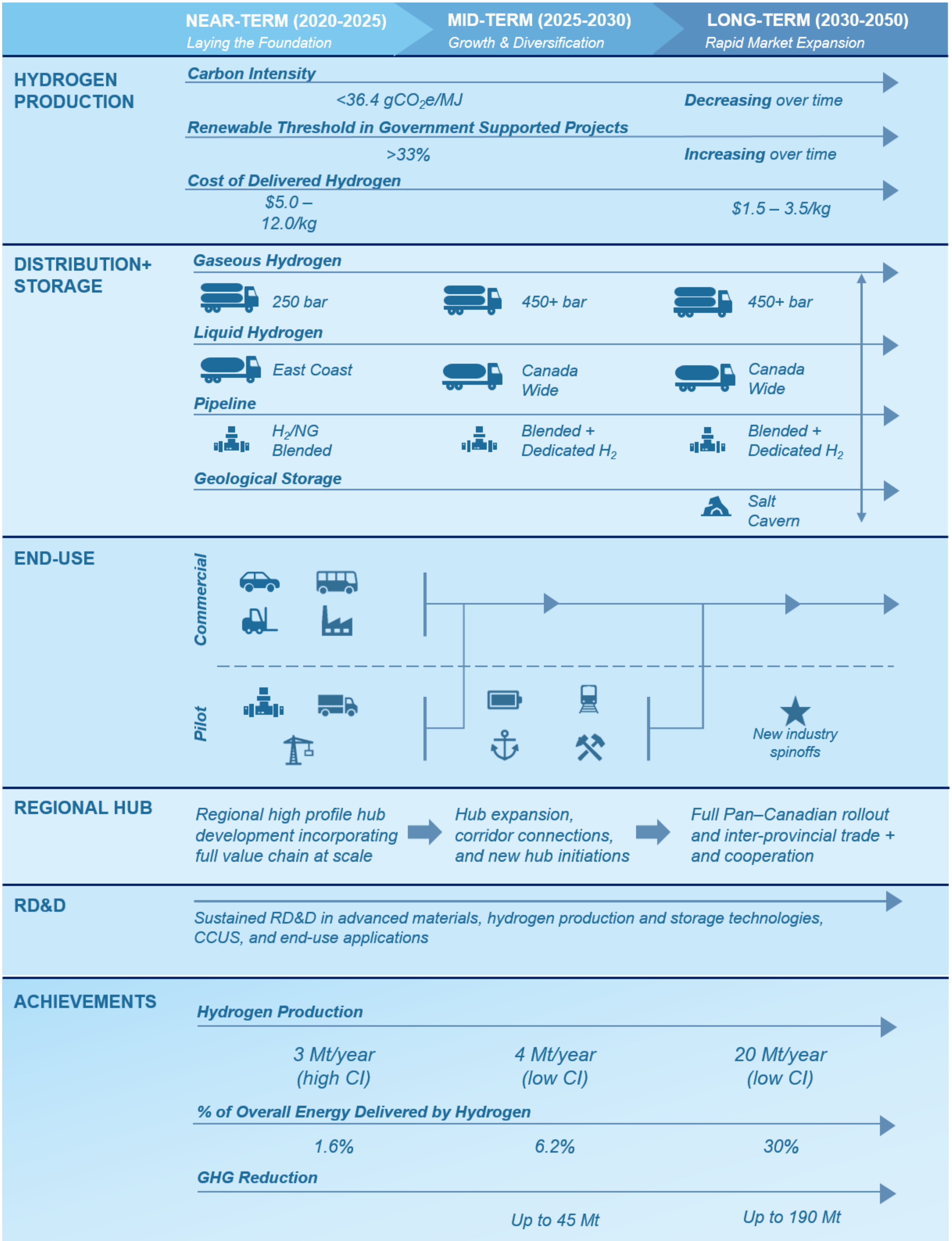
International Markets

29 *Develop a strong Canadian brand, positioning Canada to be a global supplier of choice for low carbon hydrogen, and the technologies to use it.*

30 *Invest in infrastructure to connect Canadian supply to international markets, such as liquefaction assets for energy dense hydrogen transport and hydrogen pipelines from western Canada to the US.*

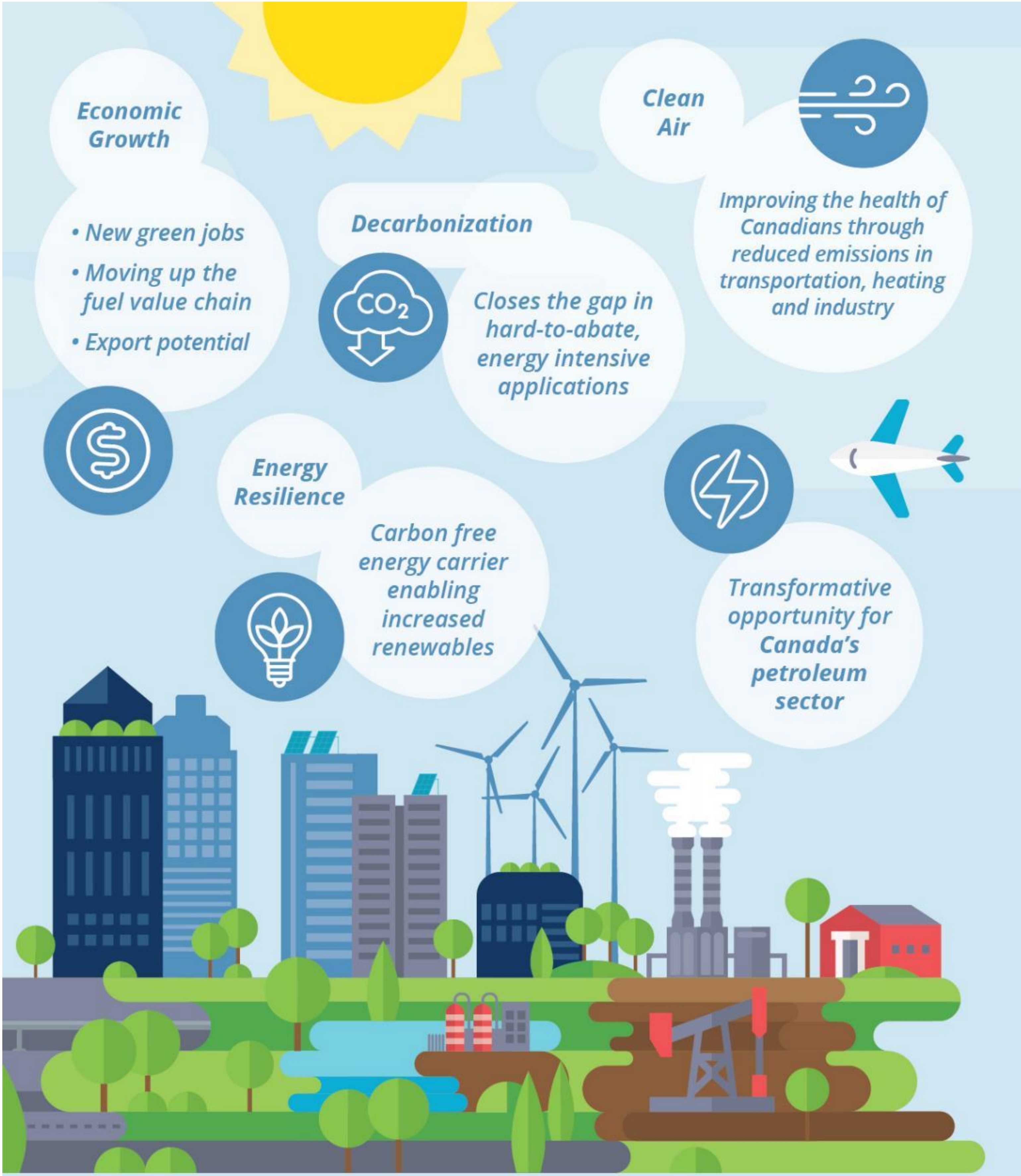
31 *Establish domestic flagship projects that highlight Canada's expertise, attract investments into the domestic market, and that can be replicated internationally.*

32 *Leverage existing international fora (e.g. Clean Energy Ministerial Hydrogen Initiative, G20, IEA) to showcase Canada's leadership, and advance new market opportunities.*



NEAR-TERM (2020-2025)
Laying the Foundation
MID-TERM (2025-2030)
Growth & Diversification
LONG-TERM (2030-2050)
Rapid Market Expansion
HYDROGEN PRODUCTION
Carbon Intensity
<36.4 gCO_2e/MJ
Decreasing over time
Renewable Threshold in Government Supported Projects
>33%
Increasing over time
Cost of Delivered Hydrogen
$5.0 – 12.0/kg
$1.5 – 3.5/kg
DISTRIBUTION+ STORAGE
Gaseous Hydrogen
250 bar
450+ bar
450+ bar
Liquid Hydrogen
East Coast
Canada Wide
Canada Wide
Pipeline
H_2/NG Blended
Blended + Dedicated H_2
Blended + Dedicated H_2
Geological Storage
Salt Cavern
END-USE
Commercial
Pilot
New industry spinoffs
REGIONAL HUB
Regional high profile hub development incorporating full value chain at scale
Hub expansion, corridor connections, and new hub initiations
Full Pan–Canadian rollout and inter-provincial trade + and cooperation
RD&D
Sustained RD&D in advanced materials, hydrogen production and storage technologies, CCUS, and end-use applications
ACHIEVEMENTS
Hydrogen Production
3 Mt/year (high CI)
4 Mt/year (low CI)
20 Mt/year (low CI)
% of Overall Energy Delivered by Hydrogen
1.6%
6.2%
30%
GHG Reduction
Up to 45 Mt
Up to 190 Mt


WHY HYDROGEN IN CANADA?
Rich in Feedstocks
Low carbon intensity grid, abundant fossil fuel reserves, fresh water
Established International Collaborations
Strong Energy Sector
Head Start: One of top 10 H_2 producers in world
Leading Innovation & Industry Position
>100 H_2 and Fuel Cell companies
Skilled labour force, strategic infrastructure assets
Energy export channels to market
Unique Competitive and Comparative Advantages



...Creating Benefits for Canadians

1. Why Hydrogen in Canada?

Canada has all the ingredients necessary to develop a competitive and sustainable hydrogen economy, from rich feedstocks to produce hydrogen and world-leading innovation, to a strong energy industry and vast international relationships. This places Canada in a unique and advantageous starting position on the road to establishing a clean hydrogen economy. If Canada fully capitalizes on its advantages, by 2050 Canadians can benefit from more than $50B in domestic revenues, the conventional oil and gas sector can be transformed, a vibrant export market can be established, and the use of hydrogen can reduce emission by up to 190Mt-CO_2e while improving air quality across the country.

CANADA'S ADVANTAGES

Rich in Feedstocks

Canada has one of the lowest carbon intensity (CI) electricity supply systems in the world, abundant fossil fuel reserves, world-class CO_2 storage geology, large scale biomass supply, and freshwater resources, all of which can be leveraged to produce hydrogen.

Canada is the sixth-largest global producer of electricity, generating 652 TWh of electricity in 2017.[1] Sixty-seven percent of Canada's electricity comes from renewable resources and 82% from non-GHG emitting sources. Canada is the world's third-largest producer of hydroelectricity, making up 60% of today's total generation capacity.[2] Canada also has significant potential to expand the deployment of variable renewables such as wind and solar. Electricity from wind energy is one of the fastest-growing sources of electricity in the world and Canada. Wind accounts for 4% of electricity generation in Canada today, and both wind and solar photovoltaic deployments are growing. Canada is a Tier-1 nuclear supplier, and 14.6% of nationwide electricity generation comes from Canada's nineteen operating power reactors at four nuclear-generating stations in Canada. Canada is exploring the potential to expand nuclear capacity through small modular reactors that can provide non-GHG emitting power in remote communities, building on Canadian innovation in this sector.

Canada has the third-largest oil reserves in the world as well as one of the largest proven natural gas reserves, and at current rates of consumption can meet the country's needs for 300 years, with enough

[1] NRCan. (2020). *Electricity facts*. Retrieved from https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/energy-facts/electricity-facts/20068

[2] IEA (2020). Key World Energy Statistics 2020. Retrieved from https://www.iea.org/reports/key-world-energy-statistics-2020

remaining for export[1]. Canada is home to one-fifth of the world's large-scale carbon capture utilization and storage (CCUS) projects in operation, and a number of leading CCUS innovators that can be leveraged to support emissions reductions in multiple sectors - including low carbon intensity hydrogen production. Canada has a large supply of renewable forest biomass, as well as access to forest industry by-products and residues. B.C., Ontario, Alberta, Quebec, and New Brunswick are the provinces with the largest biomass capacity and generation. Finally, Canada has 7% of the world's fresh water. Water is an important feedstock in the production of hydrogen using electrolysis powered by clean electricity.

Leading Innovation, Intellectual Property, and Industry Position

As a result of early leadership in RD&D and clean tech development Canada is known for its leading hydrogen and fuel cell technology companies and expertise. As of 2017, there were more than 100 established hydrogen and fuel cell companies spanning the full value chain, employing more than 2100 people in direct jobs within Canada, and generating revenues in excess of $200 million. The sector spends upwards of $90 million in revenue per year to keep Canadian companies at the forefront of innovation.[2] There are new and established hydrogen and fuel cell companies as well as large energy companies and utilities developing and deploying hydrogen solutions in most provinces within Canada. British Columbia, Ontario, and Quebec host the largest clusters of companies in the sector.

Increasing global demand for hydrogen has led to export market opportunities for Canadian companies. For example, more than half of fuel cell buses deployed around the world contain Canadian fuel cell powertrain technology.[3] Canadian companies are well positioned to supply technology, products and services in support of hydrogen production, distribution, storage, and fueling infrastructure, and end-use applications such as trains, heavy-duty vehicles, material handling equipment, marine and aviation propulsion systems, and back-up and stationary power solutions. Canadian technologies in areas related to electrolyzer products and advanced storage materials and engineered solutions also play a significant role in renewable energy systems across the world, integrating with wind and solar technologies. A Canadian supply chain has emerged that provides parts, components, testing equipment, and engineering and financial services to global hydrogen and fuel cell technology developers. Strategic partnerships between industry, academia, and federal labs have been instrumental in developing new intellectual property (IP) and training the next generation of talent for the sector.

Since 2012, Canadian funding to hydrogen clean tech and innovation has dropped, allowing other countries to catch up. Reinvesting in RD&D will enable Canada to capitalize on our head start and maximize Canadian technology penetration in emerging global markets. However, technology development alone will not secure Canada's place in global markets. Following the release of the Hydrogen Strategy, it will be critical to continue to engage on an industrial strategy to further quantify the opportunity and set Canada on a clear path to secure our place in the Global hydrogen economy.

To grow clean hydrogen production in Canada, renewed support for CCUS is also required. Canada's early leadership in this technology space is slipping, as competing countries are strengthening policy incentives and funding to drive RD&D and commercial deployment. Canada needs to take similar action to level the playing field with the US and other countries, and entice our world-renowned technology developers to deploy their expertise at home in support of domestic reductions as well as abroad to capitalize on the growing multi-billion-dollar global market for CCUS climate solutions.

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[1] CAPP. (2018). *Canada's Energy Mix*. Retrieved from https://www.capp.ca/energy/canadas-energy-mix/

[2] CHFCA. (2018). *Canadian Hydrogen and Fuel Cell Sector Profile*. Retrieved from http://www.chfca.ca/wp-content/uploads/2019/10/CHFC-Sector-Profile-2018-Final-Report.pdf

[3] Ballard. (2020). *Fuel Cell Electric Buses*. Retrieved from https://www.ballard.com/docs/default-source/web-pdf's/white-paper_fuel-cell-buses-for-france_final-english-web.pdf?sfvrsn=939bc280_0

Strong Energy Sector

Canada's energy sector is critical to supporting the restart and recovery of the Canadian economy as it emerges from the COVID-19 pandemic. It accounted for 832,500 direct and indirect jobs as of 2019 , with assets of valued at $685 billion as of 2019.[1]It was also , and the energy sector was responsible for directly and indirectly contributing 10.2 percent % to Canada's nominal GDP in that same timeframe.

A key component of this is the hard hit oil and gas industry, which is facing exceptional challenges due to fall in oil prices and a collapse in global oil demand because of the pandemic. Despite this, the petroleum sector remains an engine of recovery, employing 576,000 Canadians, including 11,000 Indigenous people, working in 4,500 companies across Canada.

Further reinforcing the energy sector's strength and resilience is that existing and developing energy infrastructure assets can be repurposed for clean hydrogen. For example, Canada's extensive network of natural gas transmission and distribution pipelines could act as large-scale energy storage and distribution networks for hydrogen, carrying either a blend of hydrogen and natural gas or pure hydrogen over the long term.

Storage assets such as depleted wells, saline aquifers and salt caverns can be an important enabler for wide-spread deployment by serving as permanent CO_2 storage, and potentially for storing hydrogen at scale. In addition, Canada already produces abundant hydrogen from natural gas in the oil and gas sector used for upgrading and refining petroleum products, and these hydrogen generation assets can be leveraged and combined with new assets to produce abundant low CI hydrogen.

Canadian talent in the energy sector is extensive and spans all levels of the value chain in a wide range of areas relevant to hydrogen for at-scale production. From strategic R&D in the chemicals industry, to manufacturing of components and products ranging from materials to complete turnkey solutions, to construction and service and maintenance expertise, Canada's energy labour force is well positioned to pivot to bring hydrogen into the energy fold.

Established International Collaborations

Canada has several bilateral and multi-lateral agreements in place, which formalize and strengthen collaboration with countries and regions around the world, including Germany, the EU, Portugal, and Japan. Over the last three decades, Canada has been a founding member of several international initiatives across the value chain and continues to leverage these strategic partnerships to advance global collaboration on hydrogen.

- Canada was a founding member of the IEA Hydrogen and Advanced Fuel Cell initiatives, which evolved into the current Technology Collaboration Programs (TCPs) - designed to coordinate private and public researchers to accelerate R&D, demonstrations and advance innovation on a global basis.
- Canada is a founding member and key partner in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). Member countries have committed to commercializing fuel cell and hydrogen technologies to address awareness and essential codes and standards.

- Most recently, Canada led the development and launch of a Hydrogen Initiative under the auspices of the Clean Energy Ministerial (CEM). Canada co-leads this Initiative, comprised of more than 20 member countries, with the objective to be the cornerstone of global hydrogen collaboration and to incorporate hydrogen's essential role in the global energy transformation in discussions of energy Ministers from around the world.

Canadian industry has also initiated international collaborations to accelerate and leverage R&D efforts and share learnings related to business case and practical deployment considerations. For example, the Canadian Hydrogen and Fuel Cell Association (CHFCA) and Australian Hydrogen Council (AHC) recently signed an MOU to strengthen collaboration between Canada and Australia in the commercial deployment of hydrogen and fuel cell technologies, including in mining and transportation applications.

Several of Canada's most important energy partners, including Japan, South Korea, China, and the US have released national strategies or announced significant investments into their hydrogen economies (see Figure 10). This recent interest is driven by multiple factors and forces but some of the most important include:

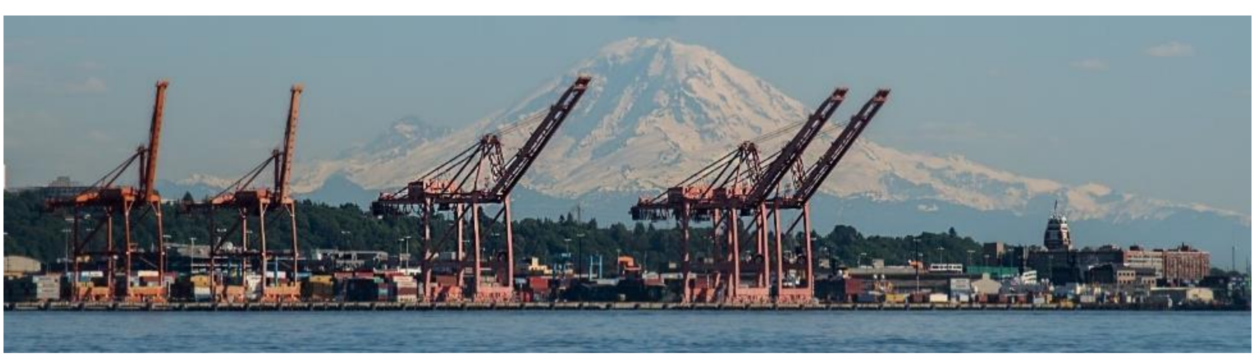
- The movement toward decarbonization across all sectors;
- The increasing penetration of variable renewable energy sources;
- The uncertainty of future investments in the oil and gas sector; and
- The rapidly falling costs of hydrogen production technologies.

Unlike previous rounds of excitement around hydrogen, today's interest is driven by the realization that hydrogen will be an essential tool to address climate change. While there are still many challenges to overcome, the message is clear: hydrogen will have a critical role in a carbon neutral future and most of the world's largest economies are already developing the strategies and investments required to make this a reality.

Energy Export Channels to Market

With over $100 billion in exports[1] as of 2017, Canada has established trade relationships for existing energy commodities such as natural gas, crude, refined petroleum products, and electricity that can be leveraged to offer a new low-carbon fuel to the market.

In addition, Canada's proximity to hydrogen import markets including Japan, South Korea, California, and Europe, along with export assets such as deep-water ports, a developing Liquefied Natural Gas (LNG) industry, and established pipeline networks as well as natural gas and oil transportation companies, position Canada to be an exporter of hydrogen as the global economy evolves.



[1] CER. (2017). *Market Snapshot: Energy's Share of Canadian Exports Growing Again*. Retrieved from https://www.cer-rec.gc.ca/nrg/ntgrtd/mrkt/snpsht/2017/09-03nrgshrcndnxprts-eng.html

OUR UNIQUE STARTING POINT

Canada has played an important role in the advancement of hydrogen production technology and storage and distribution equipment and has been a pioneer in fuel cell technology for more than 40 years. Canadian 'hydrogen firsts' include the first patent for electrolysis technology in 1915, and the first major breakthrough in proton exchange membrane (PEM) fuel cell power density in the early 1990s to prove the technology as viable for transportation applications.

Canada has a head start in deploying both production and end-use applications. For example, Canada deployed the first industrial-scale production of hydrogen in the 1920s, the first fuel cell bus demonstration in the 1990s, and the first fuel cell forklift and light-duty fuel cell electric vehicle in the early 2000s.

Today, Canada is one of the top 10 hydrogen producers in the world today, with an estimated 3 million tonnes of hydrogen produced per year. Most hydrogen in Canada is produced by the chemical industry and the oil and gas sector from fossil fuels. Geographically, most hydrogen is produced in Western Canada, followed by Central Canada and Atlantic Canada. With the anticipation of Canada's federal low carbon fuel standard, existing users of hydrogen, including refinery operations, are exploring alternative pathways for hydrogen production. Alternative production pathways include electrolysis or steam methane reforming (SMR) of natural gas coupled with CCUS, to use cleaner hydrogen as a feedstock and compliance pathway to reduce carbon intensity of conventional fuels.

Industrial gas companies operate in both Ontario and Quebec, with hydrogen production and liquefaction assets. Air Liquide's addition of a 20 MW proton exchange membrane (PEM) electrolyzer at its plant in Bécancour, Quebec which it describes as the largest in North America, increases the facility's production capacity by 50%. Over and above this, there are a number of other new hydrogen production projects in development across Canada.

Canada continues to be an R&D and technology leader in the sector. For example, Canadian heavy-duty fuel cell engine technology powers more than half of worldwide fuel cell electric buses in revenue service in a range of international markets and climates. In 2018, Canadian technology was used in the first hydrogen powered commuter train. Novel hydrogen production techniques are being pioneered across the country, positioning Canada as a global leader in next-generation clean hydrogen generation. Canada's expertise and technologies are exported and used in countries around the world, demonstrating the opportunity for growth and deployment on an international scale.

Despite this success, there are currently few large-scale domestic hydrogen projects. This impacts Canada's global competitiveness in several ways. First, Canadian companies are not able to point to relevant examples of local deployments when promoting their technologies abroad. Second, Canadian talent is being drawn to other jurisdictions where there are more opportunities to develop hands-on experience. Finally, industrial clusters supporting hydrogen technology development, deployments and supply chains are unable to build or retain a critical mass of activity.

While domestic deployments are limited, the sector is not starting from zero. There are activities related to low CI hydrogen production and use happening across Canada, as shown in Figure 2. There are strategic hydrogen production and liquefaction assets in Eastern Canada, and end-use applications range from deployments of light-duty FCEVs and hydrogen retail fueling infrastructure, to pilot projects to explore blending of hydrogen into natural gas networks to decarbonize natural gas. There are also many projects in development and regional studies being conducted to explore hydrogen opportunities. This infographic does not include production and use of grey hydrogen in the oil and gas and nitrogen fertilizer production sectors. These industries represent an opportunity for conversion to low CI supply, providing important anchor tenants as production capacity of low CI hydrogen in Canada is expanded.

Current global momentum on hydrogen presents a significant opportunity for Canada if it is able to continue to be a leader in technology development supported by new local deployments. Without local projects and active investment, other countries will erode this first mover advantage and Canada's technology is at risk of becoming outdated. Now is the time to act and invest in Canada's hydrogen future.

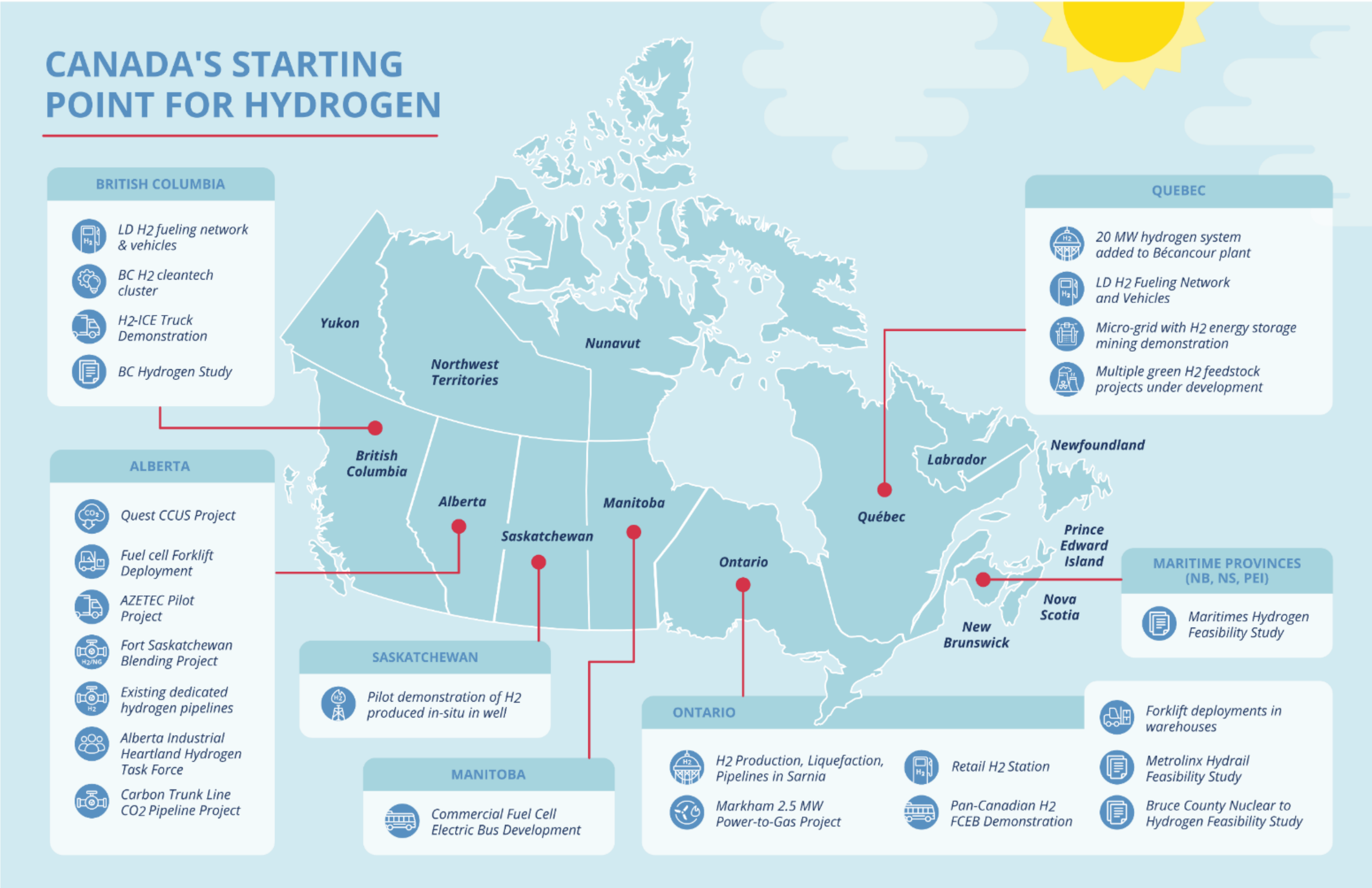


Figure 2 – Canada's Starting Point for Low-CI Hydrogen Production and Use

HYDROGEN AT SCALE DELIVERS REAL BENEFITS FOR CANADIANS

Economic Growth

Canada's hydrogen economy will create new jobs in R&D, manufacturing, and services. Hydrogen will also become a new export currency for both regional energy economies in Western, Central, and Eastern Canada, and in the international market. This will allow Canadian energy companies to move up the value chain as an end-use fuel provider in a zero-emission future. Canadian companies already export goods and services related to hydrogen and fuel cell technologies, as well as in adjacent complementary sectors like CCUS, throughout the world. Growth of domestic deployments will serve as important reference projects to help these Canadian businesses continue to thrive and grow.

If Canada seizes the hydrogen opportunity, the domestic market for direct hydrogen and related product sales could be worth more than $50 billion per year by 2050, with additional opportunity related to indirect revenues and export offering the potential to approximately double the value of the sector. It is estimated that more than 350,000 Canadians could be working in the hydrogen sector by 2050, providing an opportunity to pivot some of the >800,000 workers in traditional energy sector jobs as well as create new jobs. This also provides the potential to create more equitable and inclusive workforces, by mobilizing participation from underrepresented groups including but not limited to women, youth, and people with disabilities. Hydrogen production and use also provides opportunities for Indigenous communities and organizations to lever their existing resources to open new market opportunities.

Transformative Opportunity for Canada's Petroleum Sector

Hydrogen is critical to achieving a net-zero transformation for oil and natural gas industries. It provides an opportunity to leverage valuable energy and infrastructure assets, including fossil fuel reserves and natural gas pipelines, in a way that is carbon-free at the point of use, providing a pathway to maximize these valuable assets in a 2050 carbon neutral future. The petroleum sector is an important part of Canada's energy sector and contributor to the Canadian economy, especially in Alberta. The recent decline in oil prices has had a large impact on Canada's oil and gas industry, which in turn creates ripple effects in other industries. Advancing a hydrogen economy will reduce the carbon intensity of conventional fuels and provide opportunities to diversify the sector.

In a net-zero energy system of the future, distributed combustion of fossil fuels like natural gas will be limited, meaning that gas utilities must transform their current suite of products and services, if they are to remain competitive. Renewable natural gas and landfill gas can displace natural gas, but supply is limited. Hydrogen produced at scale can be the long-term answer for Canada's natural gas utilities to stay competitive in a carbon constrained future.

The role of hydrogen in Canada's petroleum sector will shift over time. Initially low CI hydrogen offers a compliance pathway to reduce carbon intensity of conventional fuels. In parallel as the demand for hydrogen as a transportation fuel grows through increasing deployments of fuel cell vehicles, the sector will determine how best to participate in the value chain. Liquid synthetic fuels combining non-emitting hydrogen with CO_2 recovered through direct air capture may also play a role as a feedstock for GHG neutral, energy-dense liquid fuels for end-use applications like industrial processes as well as large marine vessels and aircraft still utilizing internal combustion engines.

Energy Resilience

Hydrogen is a versatile energy carrier that can be created from a number of different pathways, and this diversity of feedstock creates resilience in Canada's energy system. Hydrogen can help regions reliant on energy imports to become more energy independent. Hydrogen can also be the energy vector to tie disparate energy systems together into a more optimized and resilient, integrated energy system.

Hydrogen does not compete with direct electrification, but rather can help enable increased penetration of renewables by providing time shifting and energy storage capabilities. While the primary source of renewable energy in Canada is hydroelectricity which comes with inherent energy storage capability, wind power capacity has been growing steadily in the last 10 years. Electricity from wind energy is one of the fastest growing sources of electricity in the world and in Canada, now making up 4% of the national electricity generation with Ontario and Quebec leading in capacity.

As seen in countries like Germany, hydrogen can be the best option for utility scale energy storage as electricity grids reach greater penetrations of variable renewables as a ratio of the overall mix. Prince Edward Island by way of example, with 98% of local electricity generation coming from wind, currently relies on importing dispatchable grid power from New Brunswick. Hydrogen could be a solution to provide dispatchable power to increase energy independence and could also be used directly for heating in the winter as a hybrid system to offset seasonal spikes in electric heating demand. The flexibility of hydrogen as an energy carrier provides customizable options for each region in Canada.

Cleaner Air

When hydrogen is used in an electrochemical fuel cell, it emits nothing but water, completely eliminating particulate emissions, SO_x, NO_x, and ground-level ozone. When combusted, it is cleaner burning than other chemical fuels. Increased hydrogen adoption leads to cleaner air, and cleaner air means improved health outcomes for Canadians.

Although substantial efforts have been made to improve air quality in Canada over the last few decades, indicators suggest that outdoor air pollution continues to be an important public health issue in Canada[1]. Approximately 2% of deaths, excluding deaths from injuries, can be attributed to ozone exposure and 0.8% to fine particulate exposure, and the proportion of deaths that can be attributed to ozone shows an increasing trend. Global deployment of hydrogen in zero-emission fuel cell vehicles is focused both on meeting health-based air quality standards and greenhouse gas emission reduction goals. It is anticipated that more cities will impose further restrictions and bans on PM2.5-emitting diesel trucks to improve air quality for their citizens through initiatives such as the C40 Cities program.[2]

[1] Environment and Climate Change Canada. (2018). *Air health trends.* Retrieved from https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/air-health-trends.html

[2] C40 Cities Climate Leadership Group, Inc. (2020). *About* C40. Retrieved from https://www.c40.org/about

Meeting Decarbonization Goals

Hydrogen's ability to contribute to decarbonization of energy systems is the biggest driver for adoption.

Under the Paris Agreement, Canada committed to reducing GHG emissions by 30% below 2005 levels by 2030, setting a 2030 target of 511 Mt. The Government of Canada has also announced a target to achieve net-zero emissions by 2050. The magnitude of the challenge is 729 Mt-CO_2e reduction over the next 30 years based on 2018 emissions levels. In reality that challenge is far greater, as increasing population and economic growth will be competing forces in the efforts to decarbonize.

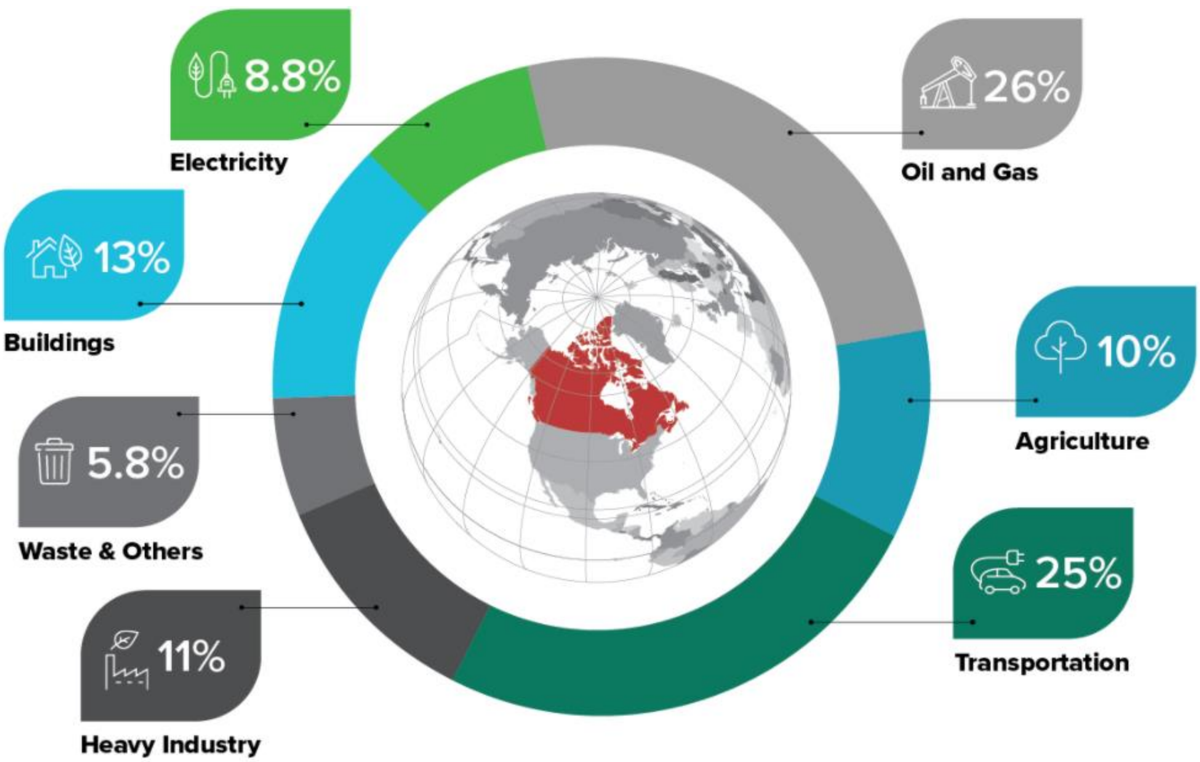


Figure 3 – Canada's 2017 GHG Emission Inventory[1]

Distributed combustion of carbon-based fuels is a significant contributor to Canada's GHG emissions in oil and gas, transportation, buildings, electricity, and heavy industry sectors.

Many levers will be needed to achieve Canada's net-zero emissions target by 2050. Low CI hydrogen shows the potential to contribute to the 2050 GHG reduction challenge, addressing the toughest third of applications where other options like direct electrification may not be technically or economically favourable. Applications such as long-range transportation, high-grade heat for industry and buildings, and for use as a feedstock in industrial process are best served by low carbon intensity hydrogen.

[1] Government of Canada. (2017). *Canada's actions to reduce emissions*. Retrieved from https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/reduce-emissions.html

2. What is Hydrogen?

Hydrogen's decarbonization potential is garnering significant global interest as a critical element in net-zero energy systems. However to fully understand the economic and environmental opportunities that hydrogen presents, it is important to understand some hydrogen fundamentals. Hydrogen is a versatile, carbon-free energy carrier that can be produced from a variety of feedstocks that are abundant across Canada. Hydrogen can be converted to electricity through a fuel-cell in electric vehicles and power generation equipment, combusted to produce heat, or used as a feedstock in a range of chemical and industrial processes.

HYDROGEN FUNDAMENTALS

Hydrogen is the first element on the periodic table as it is the simplest and lightest element on earth – approximately fourteen times lighter than air. Hydrogen is the most abundant element in the universe, accounting for about 75% of all mass. In its natural and gaseous state, hydrogen is invisible, odorless, tasteless, and non-toxic, making it difficult to detect. Like electricity, hydrogen is an energy carrier that transports useable energy created elsewhere to another location. Hydrogen has the highest energy per mass of any fuel; the energy in 1 kg of hydrogen is the same as approximately 2.8 kg of gasoline. However, hydrogen has a low volumetric energy density and as a result cost-effective distribution and storage is a challenge.

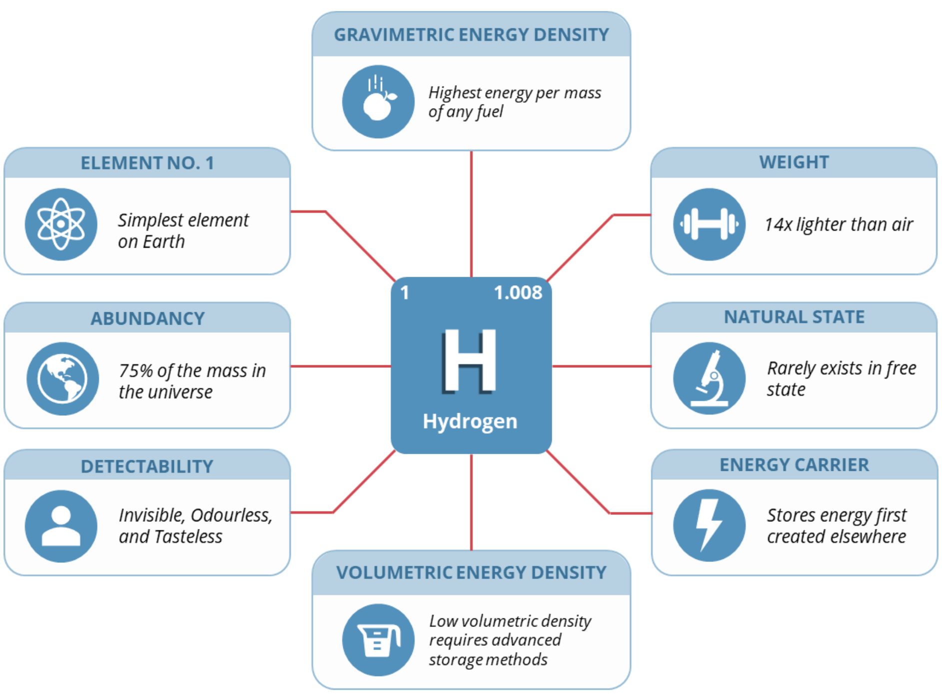


Figure 4 – What is Hydrogen?

Its ability to produce electricity with limited by-products makes hydrogen a desirable alternative fuel. The chemical reaction between hydrogen and oxygen produces electricity, heat, and water, with no pollutants or carbon emissions released at the point of use. Hydrogen is also a clean burning fuel when combusted. Despite the abundance of hydrogen in the universe, it is rarely found in its natural state on earth and is commonly found bonded in other sources such as water (H_2O) and methane (CH_4). Electrolysis and steam methane reforming are common practices used to extract hydrogen from water and methane, respectively.

Benefits

Hydrogen is a versatile and unique energy carrier that enables economic and environmental benefits and can play a significant role in decarbonization of energy systems. As a compressed gas or liquid, hydrogen is a multifaceted energy carrier. It has the highest energy per mass of any fuel allowing it to transfer large amounts of energy from its point of production to end-use application. Hydrogen can be produced from clean energy sources and is carbon and pollutant-free at its point of use when used in a fuel cell.

Hydrogen is suitable for energy-intense applications where electrification is challenging or limited, and where applications currently relying on low-cost natural gas are more suited to energy-dense chemical fuels. Similarities between natural gas and hydrogen include their safety considerations, ability to be transported over long distances via pipeline or road, and versatility as energy carriers, making hydrogen an excellent alternative to natural gas in a range of applications.

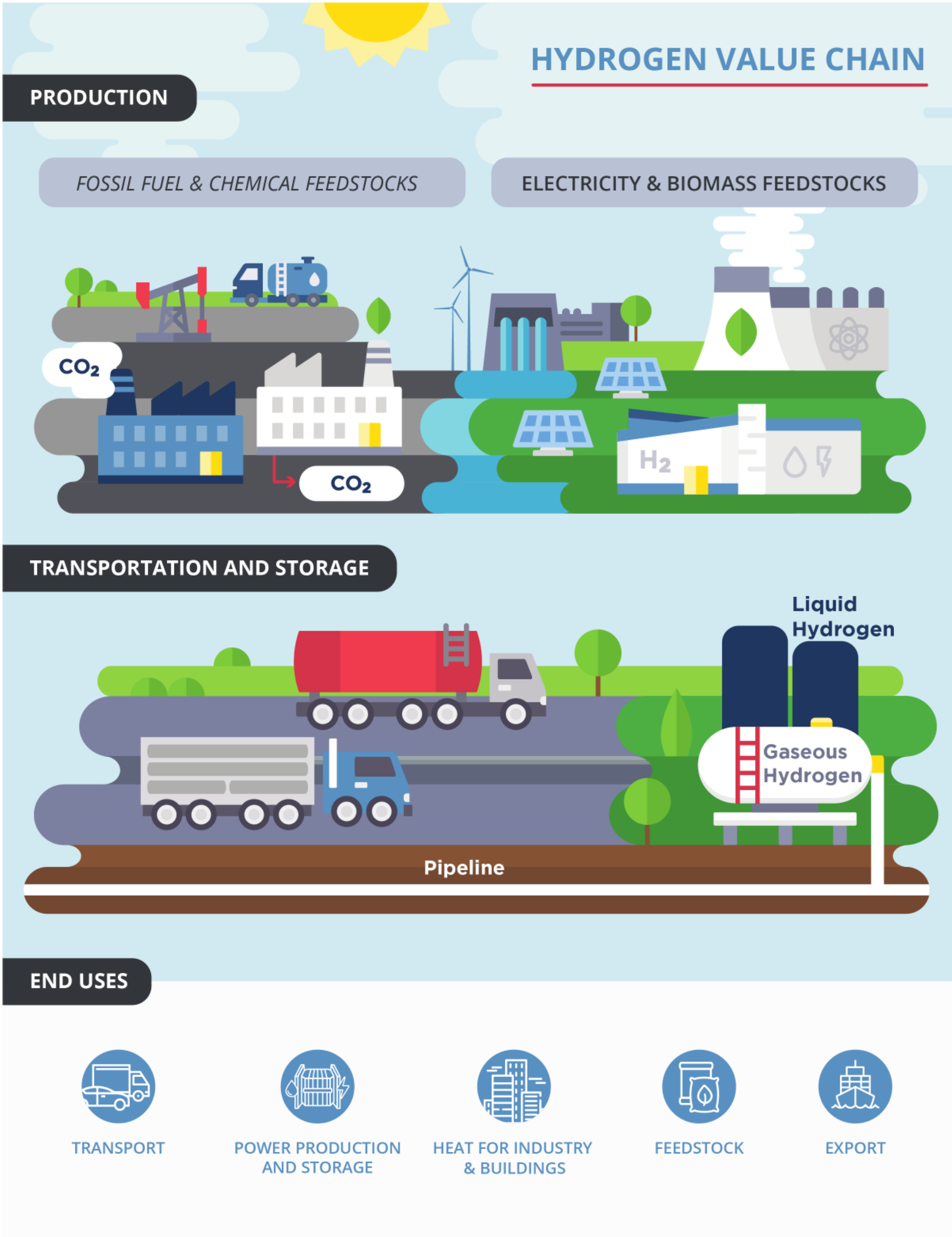
Figure 5 – Key Benefits of Using Hydrogen

Hydrogen use as a fuel for FCEVs is quickly becoming an attractive zero-emission alternative for transportation, especially heavy-duty vehicles and transit buses that require energy dense fuels. Hydrogen can also be used as a fuel for power generation which allows for load management, and energy storage. This enables the growth of the variable renewable power sector.

Hydrogen can be burned directly or as a blend with natural gas to reduce carbon emissions in providing building heat and high-grade heat for industry.

Hydrogen is commonly used as a feedstock for industrial processes such as petroleum refining, bitumen upgrading, ammonia production, methanol production, and steel production.

For more information regarding hydrogen's end-uses, refer to *Hydrogen End-Use Opportunities*.


HYDROGEN VALUE CHAIN
PRODUCTION
FOSSIL FUEL & CHEMICAL FEEDSTOCKS
ELECTRICITY & BIOMASS FEEDSTOCKS
CO2
CO2
H2
TRANSPORTATION AND STORAGE
Liquid Hydrogen
Gaseous Hydrogen
Pipeline
END USES
TRANSPORT
POWER PRODUCTION AND STORAGE
HEAT FOR INDUSTRY & BUILDINGS
FEEDSTOCK
EXPORT

GLOBAL MOMENTUM FOR CLEAN HYDROGEN

Current Global Hydrogen Production by Energy Source

Figure 7 shows the global production of hydrogen by energy source in 2018. The total global production of hydrogen in 2018 was 144 Mt, in which 67% of production was deliberate, and 33% was produced as a by-product to industrial processes.[1]

Most of the hydrogen produced today is made from fossil fuels. In 2018, 48% of total hydrogen produced worldwide was derived from natural gas. Hydrogen production from coal, which is mostly due to its popularity as an energy source in China, accounted for 18% of production. Electricity and oil each contributed 0.48%, and the balance was produced as a by-product of another industrial process such as sodium chlorate and chlor-alkali production.

Current Global Hydrogen Demand

Global demand for hydrogen in 2018, displayed in Figure 8, was 115 Mt-H_2.

Applications utilizing pure hydrogen accounted for 60% (69 Mt-H_2) of all demand. Pure hydrogen for oil refining and ammonia production were the most common end-uses, accounting for 33% and 27% of total demand, respectively. The remainder of pure hydrogen use in 2018 included transport, chemicals, metals, electronics, and glass making industries.

Demand for mixed hydrogen covered the remaining 40% (46 Mt-H_2) of the market with other end-uses such as heat generation from steelworks arising gases and by-product gas from steam crackers accounting for 23% of total demand. Other uses of mixed hydrogen included production of methanol and direct reduced iron steel (DRI).

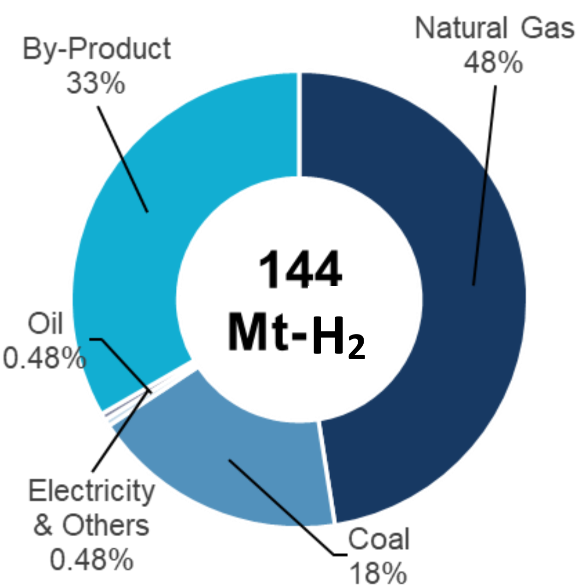
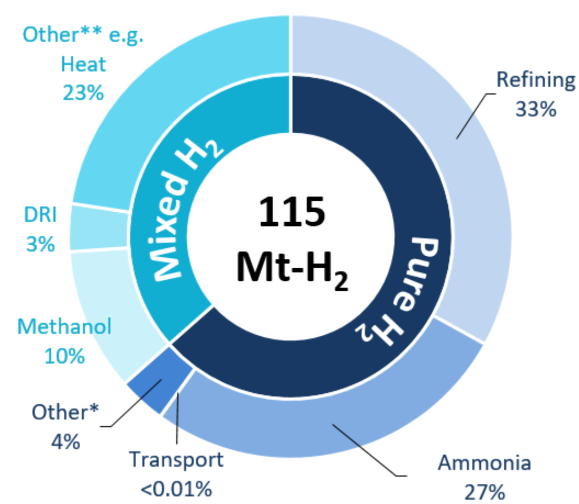


Figure 7 – Global Hydrogen Production by Energy Source (2018)[1]



* Chemicals, metals, electronics, and glass making industries

** Generation of heat from steel works arising gases and by-product gas from steam crackers

Figure 8 – Global Hydrogen Demand by End-Use (2018)[1]

[1] IEA. (2019). *The Future of Hydrogen*. Retrieved from https://www.capenergies.fr/wp-content/uploads/2019/07/the_future_of_hydrogen.pdf

Interest in hydrogen in the global energy transformation is growing rapidly with projections indicating at least a tenfold increase in demand in the coming decades. Since 2010, global demand for hydrogen has grown by a moderate 28%. However, studies indicate that hydrogen, backed by the right incentives, investments, and policies, could provide between 18% and 24% of global energy demand by 2050[1], with some countries being much higher. The five largest consumers of hydrogen are expected to be China, the EU, Japan, South Korea and California, based on their existing strategies and targets.

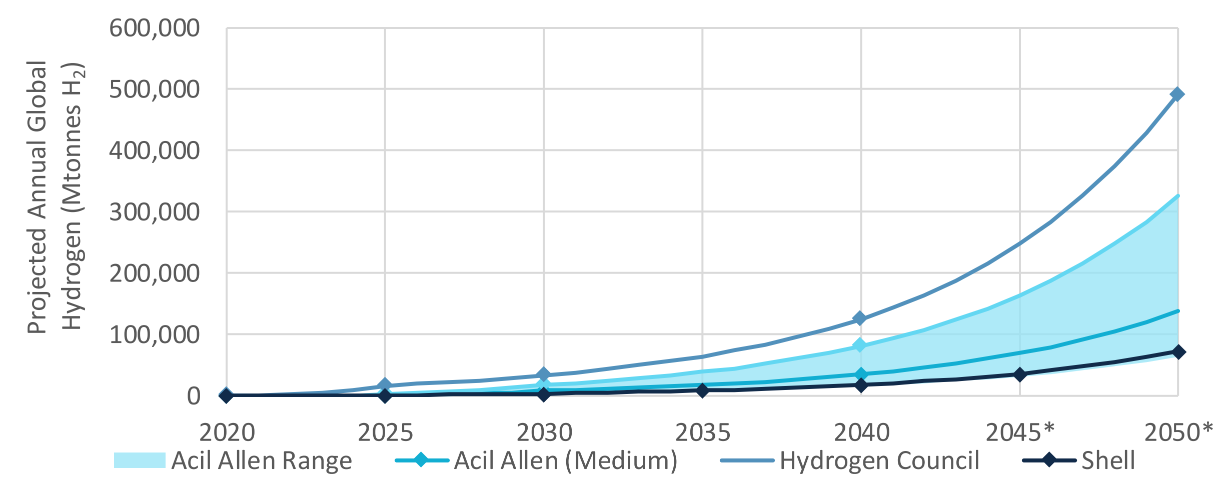


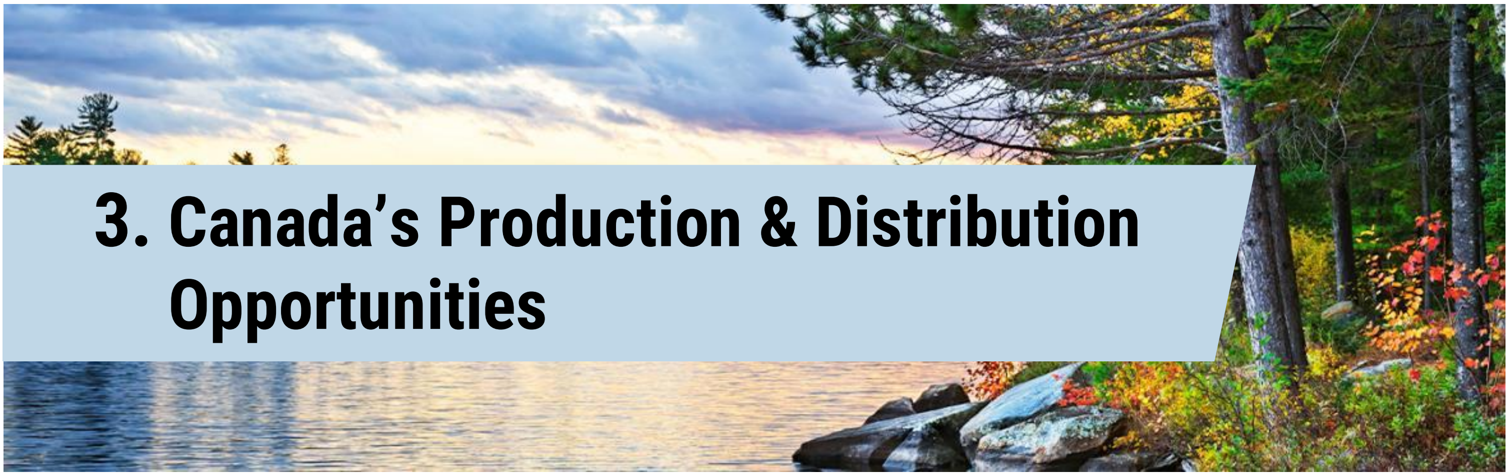
Figure 9 – Ranges of Estimates for Annual Global Hydrogen Demand

Countries around the world are developing strategies and roadmaps to inform their unique paths toward a hydrogen economy. These country- and region-specific strategies seek to make optimal use of supply pathways and end-use applications for hydrogen to power their clean economies and to position themselves in the international market. The number of countries with polices that directly support investment in hydrogen technologies is increasing, along with the number of sectors they target. Figure 10 shows announcements of national or regional strategies, major project plans, and other major plans or investments in the last two years. According to the Hydrogen Council, as of January 2020, 18 governments, whose economies account for more than 70 per cent of global GDP, have developed hydrogen national strategies.[2]

[1] IEA. (2019). *The Future of Hydrogen*. https://www.capenergies.fr/wpcontent/uploads/2019/07/the_future_of_hydrogen.pdf

[2] Hydrogen Council. (2020). *Path to hydrogen competitiveness: A Cost perspective*. Retrieved from https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

Figure 10 – International Momentum on Hydrogen



3. Canada's Production & Distribution Opportunities

Canada is well positioned to become a top global producer of clean hydrogen. Specifically, hydrogen can be made from a variety of Canadian feedstocks, including water and clean electricity, fossil fuels, biomass and as a by-product from industrial processes. The scale of projected domestic and global hydrogen demand will require Canada to maximize use of all low carbon intensity pathways across the country. This will give all regions the opportunity to benefit from their unique mix of production, based on local resources and economic factors and Canada's extensive natural gas pipeline network, combined with new storage and distribution assets, can be leveraged to move hydrogen from production to end-use locations.

PRODUCTION PATHWAYS

Hydrogen is a chemical energy carrier that can be made from a variety of feedstocks, including water and electricity, fossil fuels including natural gas and crude oil, biomass, and as a by-product from industrial processes. Canada has a distinct advantage as a hydrogen producer owing to its significant low-cost hydrocarbon resources and abundant clean electricity supply from sources including hydroelectricity, nuclear, wind and solar. The various ways hydrogen is produced, from input feedstocks to output bulk gas, are known as its production pathways. All energy carriers, including fossil fuel and electricity, experience conversion losses when they are produced, distributed, and used. These losses accumulate along the production pathway and affect the overall efficiency of the energy carrier. In the same way, the carbon intensity of the various processes in the production pathway add up to the overall carbon intensity, typically expressed in grams-CO_2e/MJ. In evaluating hydrogen production pathways, together and relative to other energy carriers, the conversion efficiency, carbon intensity, feedstock availability, cost, and storage and distribution impacts must all be considered.

Hydrogen molecules do not generally exist on their own in a free state in nature but are found in many abundant compounds. Hydrogen must be produced from feedstocks using energy inputs. When investigating viable local hydrogen pathways, the availability of both feedstocks and energy sources should be considered. Hydrogen also has the advantage of being carbon free at the point of use, making it ideal for both distributed and centralized consumption. When combusted, hydrogen does not produce greenhouse gases, particulates, SO_x, or ground-level ozone, although there can be NO_x emissions. When used in an electrochemical fuel cell, it emits nothing but water. However, production of hydrogen can lead to greenhouse gas emissions and the production pathway defines the carbon intensity. Given that a big driver for the use of hydrogen in Canada is the GHG reductions it can offer, it is important for Canada to focus future hydrogen production on economic low carbon intensity pathways.

Canada is a major hydrogen producer today with an estimated 3 million tonnes produced annually primarily via steam methane reforming of natural gas for industrial uses including fuel refining and nitrogen fertilizer production, ranking in the top ten of global hydrogen producers. While steam-methane reforming alone is not considered a low carbon intensity hydrogen pathway, Canada is well placed to transition to clean pathways going forward.

Colours are often used to represent the different hydrogen production pathways. For reference, common colour definitions are provided in Table 1. While this terminology is widely used, definitions and delineations are not standardized and can lead to ambiguity. In this section, the various production pathways will instead be described in terms of their input feedstocks and estimated carbon intensities.

Canada has among the lowest CI electricity supplies in the world given our hydroelectric generation capacity and status as a Tier-1 nuclear region, abundant fossil fuel reserves, world class CO_2 storage geology, potential for growth in variable renewables, large scale biomass supply, and freshwater resources, all of which can be leveraged to produce hydrogen.

Table 1 – Common Hydrogen Feedstock and Production Pathways Being Researched and Deployed

Production Process		Feedstock & energy source	Pros and Cons	Examples
GREY	Produced by steam methane reformation **without** carbon capture and sequestration (CCS)	**Feedstock:** natural gas, gasified coal	**Pros:** lowest cost, abundant **Cons:** highest carbon intensity	Canada produces approximately 3 million tonnes of grey hydrogen per year primarily for industrial use.
BLUE	Produced from fossil fuels by steam methane reformation, pyrolysis or other processes **with** carbon capture and sequestration (CCS).	**Feedstock:** natural gas, coal, crude bitumen	**Pros:** low-cost, abundant, low CI, pyrolysis offers scale and siting flexibility **Cons:** SMR pathway siting is constrained by CCUS, feedstock is not renewable	Alberta's Quest project
GREEN	Produced from water by electrolysis using renewable electricity such as hydroelectricity, wind or solar.	**Feedstock:** Water **Energy source:** Renewable electricity	**Pros:** lowest carbon intensity, scalable **Cons:** highest cost, opportunity cost - competes with electrification demand	Air Liquide's 20 MW electrolyzer plant in Becancour, Projects developing in BC to support hydrogen fueling network.
NUCLEAR	Produced from water by electrolysis or high temperatures from nuclear energy	**Feedstock:** Water **Energy source:** Uranium / nuclear electricity	**Pros:** low carbon intensity **Cons:** limited availability and siting constraints	Feasibility study planned in Bruce County.

An overview of mature Canadian production pathways is shown in Figure 11. Additional emerging technologies are under development and also show promise.

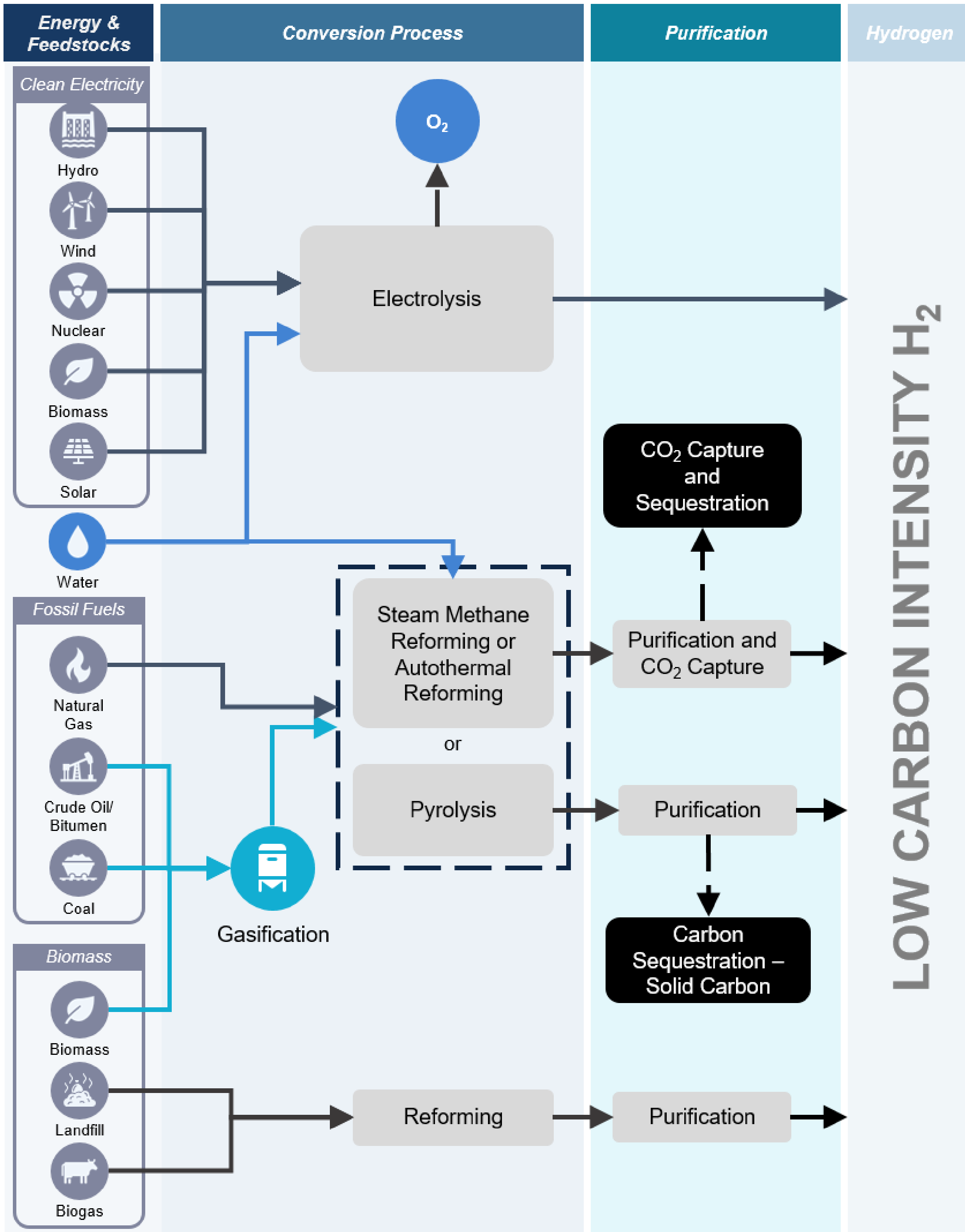


Figure 11 – Hydrogen Production Pathways in Canada

Hydrogen Production from Water & Electricity

Canada is well positioned as a producer of hydrogen from electricity given that 67% of Canada's electricity supply comes from renewable sources and 82% from non-GHG emitting sources[1]. Canada is also the world's third largest producer of hydroelectricity. These large, predictable, and low-carbon sources of electricity are favourable for the large-scale production of hydrogen using electrolysis.

Electrolysis is the process by which electricity is used to split water into hydrogen and oxygen. In this process, water is split into hydrogen and oxygen using an electric current and an electrolyte or membrane. About 9 L of freshwater is required for every 1 kg of H_2 and 8kg of O_2 produced. The resulting hydrogen is very pure and can be used directly in transportation and other end-uses without further processing. The oxygen, while often vented, can also be used in medical or industrial applications.

The main electrolyzer technologies are alkaline, Proton Exchange Membrane (PEM) and Solid Oxide Electrolysis Cells (SOEC). Alkaline is an older technology that has been in use for over a century. It operates best with a constant load, has low capital costs and can scale to larger than 150 MW. PEM electrolyzers rely on the same membrane technology as PEM fuel cells. They can be operated at a range of loads and can respond dynamically making them advantageous for electrical utilities looking for flexible demand to pair with variable renewables. The final technology, SOEC, is still being commercialized and operates at high temperature. There is potential to combine these electrolyzers with output heat from nuclear power plants, and geothermal and solar thermal systems.

Renewables & Hydro

Canada is the world's third largest producer of hydroelectricity. The provinces with the greatest portion of hydroelectric power production are:

- Manitoba: 96.8% hydroelectric generation
- Quebec: 95% hydroelectric generation
- Newfoundland and Labrador: 93.7 % hydroelectric generation
- Yukon: 92% hydroelectric generation
- British Columbia: 90% hydroelectric generation

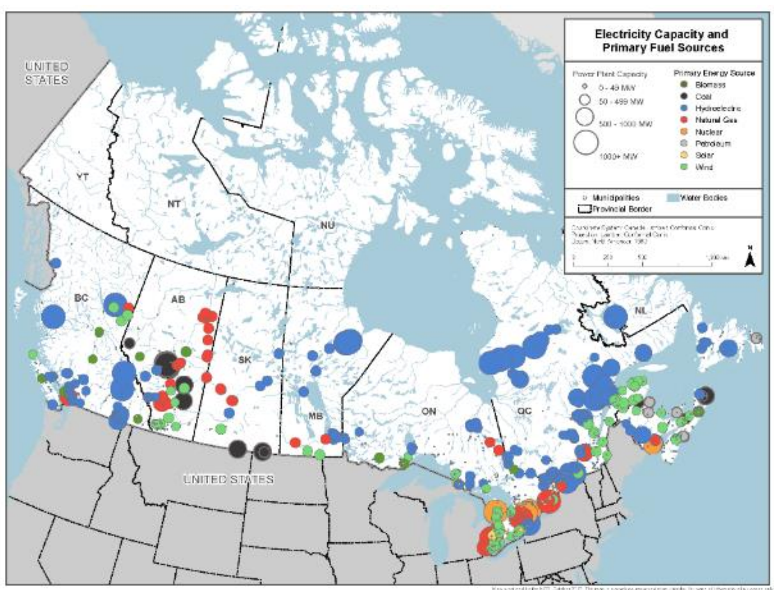


Figure 12 – Electricity Capacity and Primary Fuel Sources per Province in Canada

[1] NRCan. (2020). *Electricity facts*. Retrieved from https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/energy-facts/electricity-facts/20068

In these provinces, the electric utility providers could play an important role in the hydrogen value chain. Electrolyzer farms co-located at generation facilities can provide grid regulation services, and the hydrogen produced can provide an alternative high-value revenue stream for the utilities. Decentralized production via electrolysis can also be co-located close to demand centers. Electrolyzers are inherently scalable, and many equipment manufacturers have developed containerized solutions that are easy to site.

Independent Power Producers, for example operating run of river, wind, or solar power generating assets, can also play an important role in the value chain, particularly in provinces where power purchase agreements are up for renegotiation.

As increasing wind and solar are brought into Canada's energy mix, they offer the potential to expand the production of low carbon hydrogen and reduce costs for variable supply. Hydrogen can in turn improve the economics of variable renewables by providing large-scale energy storage that optimizes the utilization of these power generation assets. For example, Ontario curtailed in the order of 6-8 TWh of renewable electricity in 2016 that resulted in significant lost revenue, that could instead have been used to produce hydrogen.[2] Canada ranks 9th in the world for both wind and solar installations. Generation from wind farms and solar photovoltaic panels grew from a negligible amount in 2005 to approximately 5% of total electricity generation in 2018, with Canada's wind power capacity at 13.0 GW and solar power capacity at 2.9 GW. The majority of the wind facilities in Canada are located in Ontario, Quebec, and Alberta, while Ontario is home to over 98% of Canada's solar installations.

Nuclear

Nuclear reactors produce electricity as well as process heat that can be used in the production of low CI hydrogen. Large reactors are suitable for large-scale centralized hydrogen production, while small modular reactors will be more suitable for distributed hydrogen production. Hydrogen can be made via electrolysis using inexpensive off-peak electricity from existing nuclear power plants. There are efforts underway to study the economics of nuclear hydrogen production in Ontario at the Bruce Nuclear Generating Station. Opportunity for nuclear hydrogen production today is in Ontario, where three of the four nuclear generation stations are located, and in New Brunswick.

Small modular reactors are under development in Canada and around the world. Some small modular reactor designs can produce high temperature process heat, which enhances the overall efficiency of hydrogen production (see below). Commercial deployment of advanced reactors and small modular reactors is not expected to be a near-term opportunity but offers a longer-term opportunity for production of hydrogen.

High Temperature Nuclear and Electrolysis

There are several hydrogen production pathways that utilize the high temperature heat produced by nuclear reactors. One method is to use the steam produced by nuclear reactors as the reactant in the steam methane reformation process described above. This would eliminate the need to use natural gas to create steam and would simplify and lower the cost of carbon capture.

Using steam in the place of liquid water in an electrolyzer can also reduce the electricity input requirements as steam is easier to separate than water. SOEC electrolyzers, which operate at elevated

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[1] CER. (2017). Retrieved from https://www.cer-rec.gc.ca/nrg/ntgrtd/mrkt/nrgsstmprfls/mg/cnd-mp-lctrct-eng.pdf

[2] Environmental Energy Commission. (2018). *2018 Energy Conservation Progress Report, Volume One*. Retrieved from http://docs.assets.eco.on.ca/reports/energy/2018/Making-Connections-07.pdf

temperatures, could take advantage of the steam produced by nuclear reactors to improve the efficiency of hydrogen production and make use of heat that would otherwise go to waste.

As new nuclear reactor designs are commercialized, including small modular reactors, high temperature fission reactors, and eventually fusion reactors, the output water temperature will continue to increase. Thermochemical water splitting uses heat from 500-2000°C and reusable chemical reactants such as cerium oxide and copper chloride to generate hydrogen. Because the process is a closed system, the chemicals are reusable. High temperature nuclear hydrogen production could be a valuable cogeneration process for Canada's next generation nuclear sites, improving the overall system efficiency.

Hydrogen Production from Fossil Fuels with CCUS

Canada has vast fossil fuel resources in the form of natural gas, crude oil, and bitumen. When combined with Carbon Capture, Utilization, Storage (CCUS), these resources can be converted into low CI hydrogen. This pathway has the advantage of being the lowest cost production method of large-scale, clean hydrogen based on today's technologies and commodity costs, and with Canada's fossil fuel reserves and CO_2 storage capacity can meet large-scale demand for many decades. This section summarizes the main commercial hydrogen production pathways from fossil fuels in Canada and their associated options for CCUS.

There is significant growth potential in CCUS and hydrogen production in Canada, which could have a major impact on emissions reductions. Based on recent analysis by the Transition Accelerator, there is an upper bound potential for eight times the current domestic production of hydrogen from natural gas in a 2050 net-zero energy system in Canada. The CCUS requirement for this magnitude of hydrogen production would be approximately 203 Mt CO2 per year. Given Canada's current CCUS operational projects capture and store about 4 Mt of CO2 per year, this would represent a significant increase in CCUS activity. These opportunities have also been identified in Alberta's Natural Gas Vision and Strategy goal of large-scale blue hydrogen production with CCUS deployment across the province by 2030.

TRANSITION PATHWAY FOR CANADA' OIL & GAS SECTOR

Canada has the potential to produce vast amounts of hydrogen from natural gas coupled with CCUS. Provinces with the highest natural gas production are Alberta and BC, followed by Saskatchewan, and these are the provinces most suited to this hydrogen production pathway.

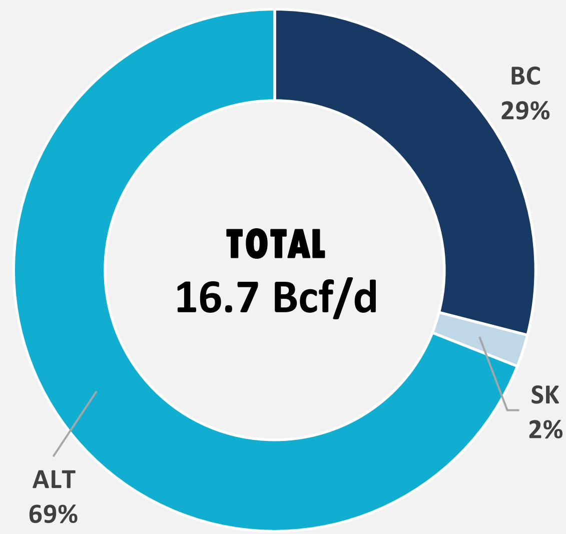


Figure 13 – Canada's 2018 Marketable Natural Gas Production by Province

In Alberta, a new Task Force has been announced to advance the hydrogen economy in Alberta's Industrial Heartland to seize this transformative opportunity. The Task Force will bringing together production, distribution and supply industries in the area to de-risk investments, with a particular focus on heavy-duty transport. This type of multi-facetted deployment, covering actions across the value-chain is an example of an early HUB for deployment.

Natural Gas

Canada is the world's fourth largest producer and sixth largest exporter of natural gas. Canadian marketable resources of natural gas can sustain current production levels for up to 300 years. However, when burned or utilized directly as methane, GHG emissions are released. If the methane is instead converted into hydrogen and combined with CCUS, the carbon intensity of the resulting fuel can be reduced by approximately 90%. Hydrogen production from natural gas offers a unique opportunity to leverage Canada's vast gas reserves to produce a low carbon intensity energy carrier while other production technologies are being scaled.

The carbon, when captured in the form of CO_2, can be used for enhanced oil recovery or as an industrial feedstock, provided the emissions do not go back into the atmosphere. It can also be stored underground provided the right sub-surface geology exists. The production of hydrogen from natural gas via steam methane reforming with CCUS will be constrained by the availability and accessibility of carbon storage geology. Alberta, BC and Saskatchewan have both large natural gas reserves and CO_2 storage potential making them favourable for this production pathway. In the production of hydrogen from natural gas via the pyrolysis pathway, the carbon is captured in the form of solid carbon and this enables distributed production close to demand without geological constraints.

There are three main commercially available methods to convert natural gas into hydrogen and carbon by-products: 1) Steam Methane Reforming (SMR) which uses high temperature water as an oxidant and a source of hydrogen, 2) Autothermal Reforming which use both water and air oxidants, and 3) Pyrolysis which relies on methane splitting into hydrogen and solid carbon using high heat.

In SMR, natural gas is used both as feedstock and as fuel to generate steam. In the first reaction, the methane is combined with steam (H_2O + Heat) to produce a synthetic gas consisting of CO_2, CO and H_2. The synthetic gas is then separated using a Water Gas Shift (WGS) reactor and Pressure Swing Adsorption (PSA). Adding carbon capture at various places in the process adds costs and reduces overall efficiency, but improves environmental performance. Capturing CO_2 from both the WGS and the PSA can reduce emissions by about 60%, while also capturing the flue gas CO_2 can achieve 90% total carbon capture at an additional cost of 45%[1]. SMR is the most widely used technology for hydrogen production in Canada and is expected to continue to be one of the primary pathways going forward, with the addition of CCUS to achieve lower carbon intensities.

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

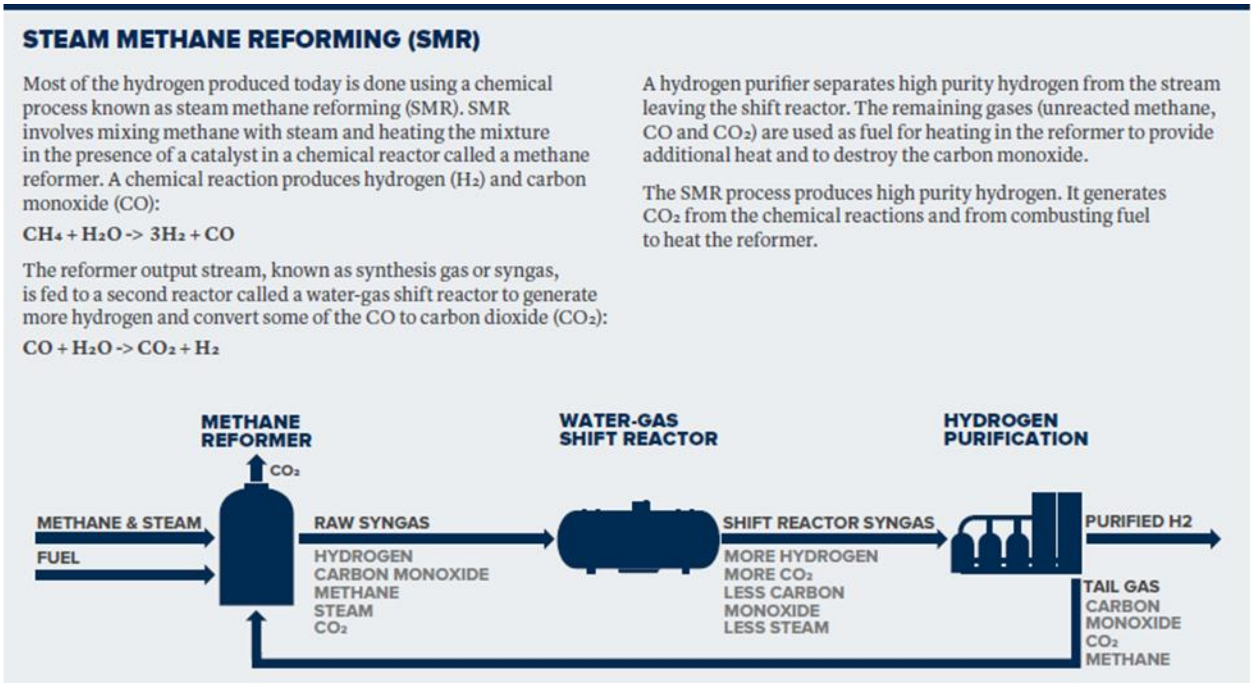


Figure 14 – Steam Methane Reforming (SMR) Process and Description[1]

Autothermal Reforming (ATR) is another technology that uses the heat produced in the reformer itself to achieve higher CO_2 recovery rates. All the CO_2 from the process is produced within the reformer so there is no additional flue gas from heat generation requiring decarbonization. This lowers the cost of CO_2 capture as the resulting gases are more concentrated. ATR is widely used in the ammonia and methanol industries and pilot ATR+CCUS plants are being planned in the UK and EU[2].

Pyrolysis is a developing hydrogen production technology which uses high temperature heat to split the methane molecule into its constituent elements. The result is a very pure form of hydrogen gas and solid carbon. The two main pyrolysis technologies are thermal and plasma pyrolysis. In thermal pyrolysis, heat from natural gas is used to break up the methane molecule. Some of the feedstock methane is not reacted and this is recaptured for use as the process fuel. This reduces the conversion efficiency and increases the CO_2 emissions. Plasma pyrolysis is a specific type of pyrolysis which uses an electric arc to generate a high temperature plasma. While there are significant heat losses, the overall system efficiency can be better than using the electricity to power an electrolyzer[3]. There are many other ways to provide heat to the pyrolysis system and systems based on microwave and photo catalysts are also being developed. The solid carbon is chemically stable and can be used in a variety of industrial materials such as rubber, plastics and in printers. Pyrolysis technology has been deployed commercially but remains limited primarily as a source of commercial solid carbon (thermal black). It is now being developed as an economic alternative to SMR for hydrogen production. Pyrolysis has the potential to produce distributed hydrogen at the point of use, using natural gas as a feedstock and leveraging existing distribution pipeline networks. Because the carbon is sequestered as a solid carbon, production does not need to be co-located where CO_2 can be sequestered.

[1] Global CCS Institution. (2019). *Global Status of CCS*.

[2] IEA. (2019). *The Future of Hydrogen*. Retrieved from https://www.capenergies.fr/wp-content/uploads/2019/07/the_future_of_hydrogen.pdf

[3] Ibid

Crude Oil, Bitumen, and Coal

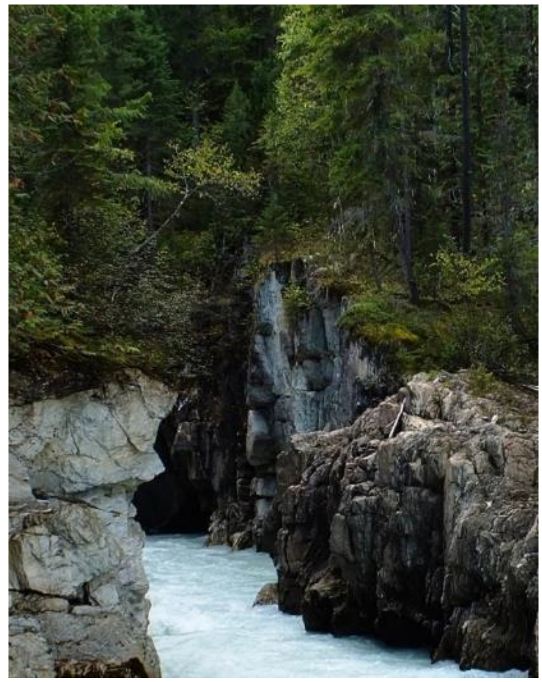
In addition to Canada's natural gas reserves, there are also substantial resources in the form of crude oil and bitumen in the regions of Northern Alberta and Saskatchewan, and coal in Alberta and British Columbia. Gasification of crude oil, bitumen, or coal uses a process similar to gasification of biomass. The feedstocks are reacted with steam and/or oxygen at a high temperature producing a synthetic gas mixture that can be further separated into CO_2 and H_2. This process can take place in an industrial plant once the feedstock has been extracted, in which case CCUS would need to be employed to capture the resulting CO_2. In-situ gasification is an emerging technology currently being developed in Alberta and Saskatchewan for crude oil and bitumen feedstocks. In this process, the gasification takes place deep underground, such as in an existing oil field, and the hydrogen is filtered using a selective membrane. This has the advantage of leaving the CO_2 already underground and sequestered, saving cost and reducing complexity. The selection of reservoirs with appropriate geological properties to hold the CO_2 underground in a stable state is an important consideration for this technology.

Carbon Capture, Utilization, & Storage

To achieve Canada's net-zero by 2050 target, all hydrogen production will need to be carbon-neutral - which includes electrolytic hydrogen from non-GHG emitting electricity, or hydrogen produced from fossil fuels coupled with CCUS – or it will need to be offset, for example through direct air capture of CO_2. At present, fossil fuel derived hydrogen with CCUS is more cost-competitive than electrolytic hydrogen in Canada[1], particularly due to our abundance of low-cost natural gas.

[1] IEA, Energy Technology Perspectives, 2020

Canada has decades of experience in CCUS with leadership in technology innovation; an abundance of suitable geology for permanent CO_2 storage, notably in the Western Canadian Sedimentary Basin[1]; transferable expertise from the oil and gas sector; and growing markets and emerging pathways for CO_2 utilization. Canada is also home to one-fifth of the world's large-scale projects in operation, which has been enabled by the existing policy environment and a strong history of advancing the technology through public-private partnerships. However, challenges remain in terms of high technology costs for some applications, technical and commercial risks, required infrastructure investment, and competitiveness with other countries like the US, UK and Norway with stronger policy incentives in place. Canada's early CCUS leadership has included work to advance hydrogen production with CCUS. Projects include the Shell Quest Project, and the Sturgeon Refinery linked to the Alberta Carbon Trunk Line.



NRCan is considering opportunities for a CCUS sector that will leverage Canada's natural advantages and capabilities to support emissions reductions in industrial sectors (e.g. oil and gas, cement, iron & steel, chemicals, power), enable low carbon hydrogen, other CO_2 based fuels and products, and negative emissions solutions like direct air capture (DAC) and bioenergy with CCS (BECCS).

There is significant growth potential in CCUS alongside clean hydrogen production in Canada, which could have a major impact on emissions reductions. Based on recent analysis by the Transition Accelerator – a pan-Canadian, non-profit organization working on emissions reductions solutions for business and society – there is an upper bound potential for eight times the current domestic production of clean hydrogen from natural gas in a 2050 net-zero energy system in Canada. The carbon capture and storage requirement for this magnitude of clean hydrogen production would be approximately 203 Mt CO2 per year. Given Canada's current CCUS operational projects capture and store about 4 Mt of CO2 per year, this would represent a very significant increase in CCUS activity. These opportunities have been identified in includes Alberta's Natural Gas Vision and Strategy goal of large-scale blue hydrogen production with CCUS deployment across the province by 2030.

Capture & Compression

Capturing CO_2 at the point of conversion of fossil fuels into hydrogen is much easier than capturing it once released into the atmosphere. The concentration of CO_2 in the source gas process stream is a significant driver of cost and energy requirements of capturing CO_2, and these capture and compression costs dominate the overall costs of CCUS[2]. Large, high-concentration CO_2 emissions such as those from ethanol, natural gas processing, and hydrogen production typically have the lowest CO_2 capture costs[3]. Adding

NRCan. (2013). *North American Carbon Storage Atlas*. Retrieved from https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/files/pdf/11-1454_eng_acc.pdf

[2] National Petroleum Council. (2019). *Meeting the Dual Challenge - A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage*. Vol II. Chapter 2. Report available online at https://dualchallenge.npc.org

[3] National Petroleum Council. (2019). *Meeting the Dual Challenge - A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage*. Vol II. Chapter 2. Report available online at https://dualchallenge.npc.org

CCUS to SMR plants leads, on average, to cost increases of about 50% for CapEx and requires 10% extra fuel. It also leads on average to a doubling of OpEx as a result of CO_2 transport and storage costs[1].

The Shell Quest Project located in the Scotford Upgrader is a high profile SMR+CCUS project currently operating in Alberta capturing ~1.2Mt-CO_2/year. The captured carbon is dehydrated, compressed, and transported via pipeline ~65 km to a saline aquifer north of Redwater, AB, and injected more than two kilometres underground. In the five years since its start up, Quest has captured and safely stored five million tonnes of CO_2 at a lower cost than anticipated. According to Shell, the cost to operate Quest is about 35% lower than what was forecast in 2015, due to an excellent storage reservoir with significant capacity for CO_2 injection, and strong capture reliability. In addition, if Quest were to be built today, it would cost about 30% less as a result of capital efficiency improvements.[2] Other CCUS projects globally, such as the Northern Lights CCS project in Norway, have incorporated lessons from Quest – which has been sharing knowledge and lessons learned over the last five years to encourage more widespread implementation of CCUS.

CO_2 Transportation & Low-carbon Industrial Hubs

Compressed CO_2 can be transported by ship, pipeline and road. Pipelines are the most economical way of transporting CO_2 in large quantities onshore. The Alberta Carbon Trunk Line (ACTL) pipeline is a major CCUS project in operation and has the capacity to carry ~14.6Mt-CO_2/year along a 240km pipeline. It is supplied by two CO_2 sources, one of which is a byproduct of hydrogen produced via the gasification of heavy oil bottoms at the Sturgeon Refinery. The ACTL has 85% available capacity to facilitate CCUS uptake at additional hydrogen production and other high-emitting facilities in Alberta's Industrial Heartland.

As hydrogen production from fossil fuels scales up, more CO_2 pipelines more will be required to scale up CCUS deployment. Development of low-carbon industrial hubs are trending as a way to advance CCUS opportunities to spur innovation, enable new business models, and encourage development of cost-effective CCUS technologies at scale. Industrial hubs link emitting facilities with CO_2 storage or utilization projects, providing the benefit of shared CO_2 infrastructure, economies of scale, and decreased commercial risk across multiple stakeholders. CCUS hubs are best suited for regions where CO2 storage or utilization opportunities are near clusters of high emitting facilities.

[1] IEA. (2019). *The Future of Hydrogen*. Retrieved from https://www.capenergies.fr/wp-content/uploads/2019/07/the_future_of_hydrogen.pdf

[2] Shell. (2020). *Quest CCS Facility Captures And Stores Five Million Tonnes Of CO2 Ahead Of Fifth Anniversary.* Retrieved from https://www.shell.ca/en_ca/media/news-and-media-releases/news-releases-2020/quest-ccs-facility-captures-and-stores-five-million-tonnes.html

Utilization & Storage

The last stage of CCUS is its long-term storage and sequestration underground or its use in industrial and commercial processes. CO_2 can be stored in porous sedimentary formations including depleted gas, crude oil, and bitumen reservoirs, deep saline aquifers, salt caverns and in coal seams. The long-term suitability of these options depends on their accessibility, the overlying cap rock formations and other factors. Canada is rich in geology that is suitable for CO_2 storage, including sedimentary basins, saline formations and oil and gas formations in proximity to a significant portion of emitting industries.[1] The Western Sedimentary Basin is a geological formation that covers Northern BC, Alberta, and parts of Saskatchewan and contains many potential sites for storage. Deep saline aquifers are the most secure and most widely available storage locations in Canada.

Overall, CO_2 storage is safe, permanent, and well-demonstrated in Canada, with decades of monitoring that proves that injected CO_2 remains within reservoirs. It is important to note that CO_2 storage and use, particularly for enhanced oil recovery, has been in commercial operation since 1972 with hundreds of millions of tonnes of CO_2 successfully sequestered all over the world. As an example of advanced protocols, California Air Resources Board (CARB) under the low carbon fuel standard (LCFS) rules allows negative emission CO_2 anywhere in the world to be sequestered and receive LCFS credits for the CO_2. As part of that they have a monitoring and verification protocol for ensuring that the CO_2 stays sequestered and anyone claiming the credit must comply with that protocol.

A number of new technologies and products are emerging that utilize CO_2 either as feedstock or offer long term sequestration potential, for example in the form of useful products like concrete, liquid synthetic fuels, and consumable beverages. A number of Canadian companies are leading in this space, offering complementary technology expertise that can ultimately also benefit the hydrogen sector.

[1] Dooley, J.J., R.T. Dahowski, C.L. Davidson, S. Bachu. N. Gupta and J. Gale. 2004. A CO2-storage Supply Curve for North America and its Implications for the Deployment of Carbon Dioxide Capture and Storage Systems, p7, http://uregina.ca/ghgt7/PDF/papers/peer/282.pdf.

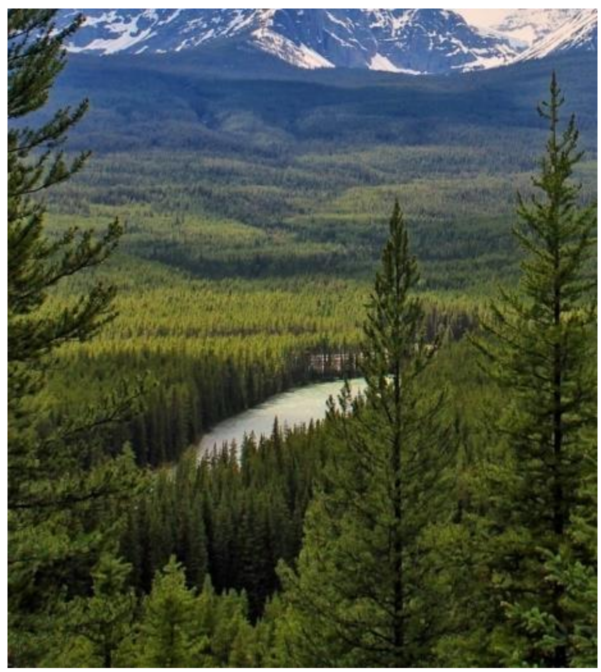
Hydrogen Production from Biomass

Biomass gasification is considered both renewable and carbon-neutral and is a viable hydrogen production pathway in Canada. Plants consume CO_2 as they grow, so the release of CO_2 through this type of process is net carbon-neutral over its life cycle. Any renewable organic resources comprised of mostly carbon, hydrogen and oxygen can be used a biomass feedstock. Biomass gasification technology extracts hydrogen by gasifying and then reforming forest or agricultural residues or other dry organic wastes. Hydrogen production using bio-energy with carbon capture and storage (BECCS) presents an opportunity not only to decrease emissions on hydrogen production, but in other sectors as well, thanks to the carbon negativity of the process.

Forestry and Agricultural Biomass Gasification

Biomass gasification is a stable technology that uses high temperature steam (generally >700°C) and oxygen from the air to break down biomass into hydrogen and other products without combustion. Biomass gasification is generally undertaken in two stages, 1) An initial gasification stage, and 2) a water-gas shift reaction in which carbon monoxide (CO) is converted to carbon dioxide (CO_2), generating additional H_2. PSA is then used to purify the hydrogen and remove the CO_2.

The economies of scale associated with biomass gasification are substantial, so producing hydrogen in this way requires a centralized production model. Forest and agricultural biomass are in demand in Canada for producing liquid biofuels, renewable natural gas and co-processing in petroleum refineries. While technically viable, biomass gasification requires a large, dependable supply of locally-/regionally-sourced feedstocks to be a major production pathway. Incorporating existing forest product facilities into the hydrogen infrastructure network could capitalize on their position as an aggregator of biomass and serve to improve overall efficiency of resource use. There is also the potential to develop ‘biohubs’ to help with regional supply challenges. Arguments can be made for investing in biomass collection, storage and processing to support hydrogen production and should be explored further in regional hydrogen plans.



Landfill/Sewage/Agricultural Gas Reformation

Methane gas (CH_4) resulting from the breakdown of organic matter in landfills, sewage treatment plants and agricultural waste sites is another potential source of hydrogen from biomass. Similar to the natural gas SMR or ATR processes, the methane from these sources is collected, reacted with steam, and the hydrogen is separated out. The CO_2 from this feedstock originates from the atmosphere; therefore, the only additional emissions created from the process come from the heat require to generate the steam. Like solid biomass feedstocks, these gaseous waste streams are regionally specific, and are in limited supply. Given the increasing demand for renewable natural gas (RNG) as an alternative fuel, it is likely that these feedstocks will be used directly in methane form rather than be converted to hydrogen.

Other Hydrogen Production Pathways

Industrial By-Product Capture

Many industrial plants produce hydrogen as a by-product. In some cases, by-product hydrogen is captured and used as a feedstock in chemical production, and in others it is simply vented to the atmosphere. A 2019 *British Columbia Hydrogen Study*[1] found that, approximately 18.5 tonnes of relatively pure hydrogen is currently vented to the atmosphere every day in BC. This represents an important near-term hydrogen source for this province and an opportunity to create a new market for industrial plants to sell by-product hydrogen. This production method requires minimal cleanup and represents a low-cost, low carbon intensity hydrogen supply estimated at $0.88/kg prior to distribution and storage, based on the heating value of the fuel. Supply of by-product hydrogen in the near-term is low-cost relative to dedicated new production, and these chemical plants that currently vent hydrogen could become focal points around which near-term deployment HUBs are based.

The supply of this source of hydrogen in Canada that is not already utilized or sold is estimated at about 70,000 tonnes per year[2], or 190 tonnes per day. Canada's chlor-alkali and sodium chlorate plants tend to be located where electricity costs are lowest, including BC, Manitoba, Saskatchewan, and Quebec.

CANADA'S REGIONAL HYDROGEN PRODUCTION RESOURCES

The production pathways adopted in each region of Canada will depend on the availability of feedstocks, energy inputs, and in some cases suitable sites for CCUS. Each region/province will need to carefully consider their entire energy system before investing in any particular production pathway. Overall, the production pathway that makes the most sense for each region will minimize costs and carbon intensity while maximizing the use of local feedstocks and energy sources.

Industry and Provincial Governments will play a key role in determining which hydrogen production pathways will come to fruition over what timeframes in Canada, with government playing the role of establishing policy, for example setting CI limits, and industry determining the most economical pathways that fit within the limits. Overall, a balanced, regional approach to developing Canada's hydrogen supply from a mix of fossil fuel-derived and clean electricity-derived sources is anticipated to evolve. This diversification of fuel sources would best enable production volumes to support the development of domestic and export markets. Figure 15 shows the most likely potential pathways for each province/region based on their existing electrical grid and access to feedstocks.

[1] Source: ZEN and the Art of Clean Energy Solutions

[2] Source: Ekona Power, private market study

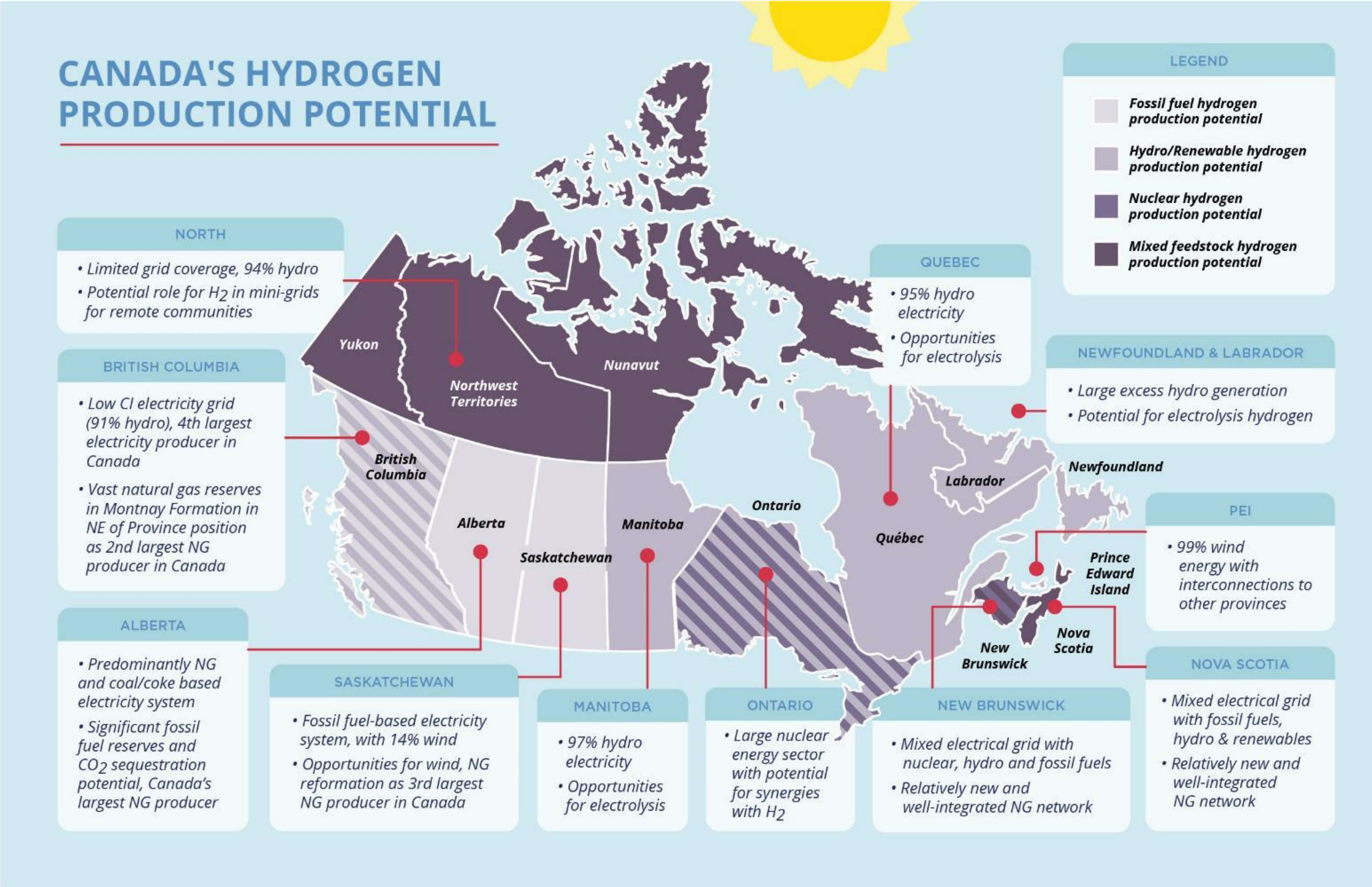


Figure 15 – Provincial Map of Potential Hydrogen Production Pathways

PRODUCTION PATHWAYS' COST & CARBON INTENSITY

The production cost of hydrogen for various pathways is influenced by technical and economic factors, including feedstock costs (e.g. natural gas, electricity), capital costs and ongoing operating costs. According to the IEA, fuel and feedstocks are the largest component of production costs and account for between 45% to 75% depending on where in the world the hydrogen is being produced[1]. Canada has one of the overall lowest cost of production in the world for both SMR+CCUS and hydroelectric electrolysis according to a 2018 report from the Asia Pacific Research Centre[2]. This cost advantage provides an opportunity for Canada to begin producing low-cost, low-CI hydrogen almost immediately. Currently, low CI hydrogen production at scale in Canada is lowest cost when using fossil fuel feedstocks compared to electrolysis pathways. While Canada has competitive electricity prices relative to international markets, costs need to be in the range of <$40/MWh to produce hydrogen at target price points. Industrial tariffs with high peak demand charges and tariff structures that do not recognize decarbonizing benefits can be a barrier to electrolysis pathways.

As demand grows, economies of scale and technical advances will further lower the cost of hydrogen production in Canada, and this will provide time for more renewables to be added to the grid for even lower carbon intensity production. Figure 16 compares projected bulk hydrogen production costs (not including distribution costs) by different pathways projected over time from a range of international and Canadian studies. By 2030, the cost of SMR+CCUS hydrogen is expected to be in the range of ~$1.00 - $2.00/kg-$H_2$ when produced at scale (>100 tons per day - TPD) in Canada based on studies out of Alberta and British Columbia, while the cost of electrolysis from dedicated renewables shows potential to be in the $3.20/kg-$H_2$ range in that timeframe.

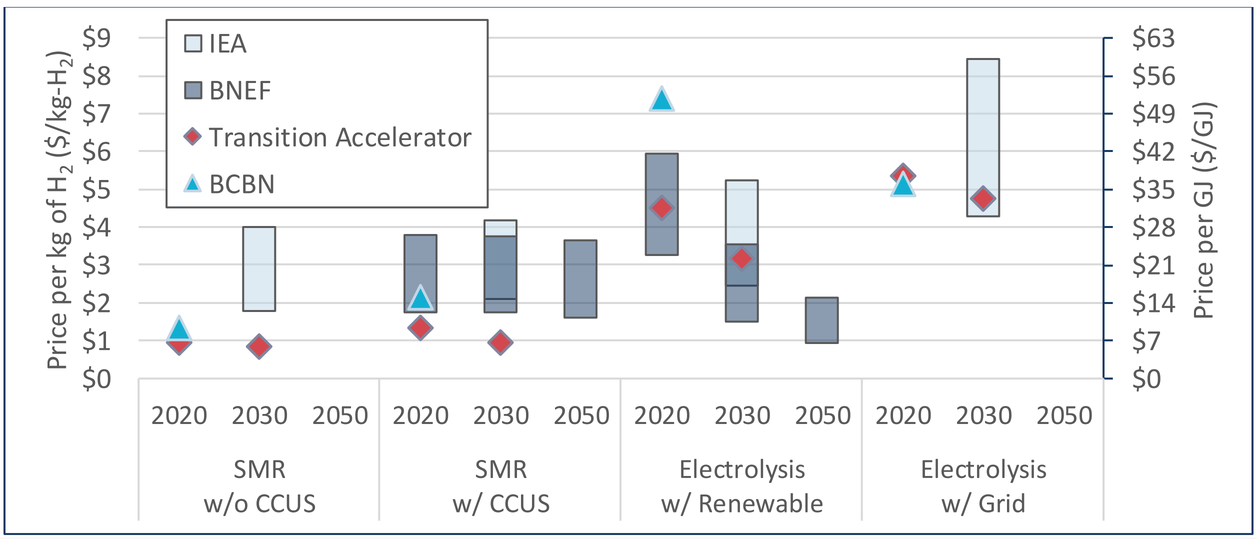


Figure 16 – Comparison of Hydrogen Production Pathway Costs 2020, 2030, and 2050[1,2,3,4]

BloombergNEF predicts the global levelized cost of hydrogen from large renewable energy powered projects will be cost competitive with low carbon hydrogen from natural gas via SMR w/CCUS by 2030. Their study shows that by 2050, renewable hydrogen could be produced for less than a dollar per kilogram[4]. This may not be directly applicable to Canada, but the general trend of renewable hydrogen

[1] IEA. 2019. The Future of Hydrogen: Seizing Today's Opportunities.

[2] Asia Pacific Energy Research Centre, "Perspectives on Hydrogen in the APEC Region.pdf," Jun. 2018 [Online]. Available: https://aperc.ieej.or.jp/file/2018/9/12/Perspectives+on+Hydrogen+in+the+APEC+Region.pdf

[3] BCBN BC Hydrogen Study, Zen and the Art of Clean Energy Solutions Inc., 2019

[4] BloombergNEF: Hydrogen Economy Outlook, March 20, 2020,

costs coming down over time is valid and warrants further study regionally in Canada. However, this renewable hydrogen would be variable and not at the scale required on its own for large continuous petajoule energy applications. The situation in Canada may favour fossil fuel-based hydrogen over electrolytic hydrogen due to our inexpensive and plentiful natural gas and access to CCUS. However, it should be noted that scale and transportation costs are important factors that have a big impact on delivered cost of hydrogen, particularly as the market is developing. Hydrogen produced vis SMR + CCUS requires significant scale to be economical, which requires high capital investments and relatively long buildout timing. Electrolyzers are modular and easily scaled and can be situated close to end-use applications. It is therefore expected that both will play an important role.

The Carbon Intensity (CI) of hydrogen production is a method for comparing the end-to-end lifecycle GHG emissions of hydrogen as it moves from primary energy source/feedstock to delivered energy commodity. End-use can also sometimes be considered in the lifecycle analysis, but for simplicity this is separated from production pathway emissions herein. In the case of hydrogen made from natural gas via SMR + CCUS, this includes the upstream emissions required to recover the gas, and the emissions released during the SMR or ATR process (minus any CCUS). Upstream emissions vary regionally in Canada, and there are national and provincial efforts underway to lower emissions through actions such as reducing fugitive methane emissions and electrifying upstream equipment.

For hydrogen produced through electrolysis, the CI can be almost zero if produced from emission-free sources of electricity such as hydroelectricity, wind, solar, and nuclear. Hydrogen produced with electricity from a grid with mixed sources will have a CI relative to the mix of sources. For example, a grid fed from nuclear and renewables will have a much lower CI than one fed mainly from coal power plants. It is important to note that hydrogen produced through electrolysis is not necessarily cleaner than hydrogen produced through SMR, and as regions throughout Canada develop hydrogen supply, the CI measure is critical for comparing different production pathways and sources. Hydrogen can in fact help to lower the CI of electricity grids in regions with mixed generation sources that include generation from fossil fuels; this is discussed further in the end-use opportunities section. Figure 17 compares hydrogen pathway CI based on Canadian and international sources.

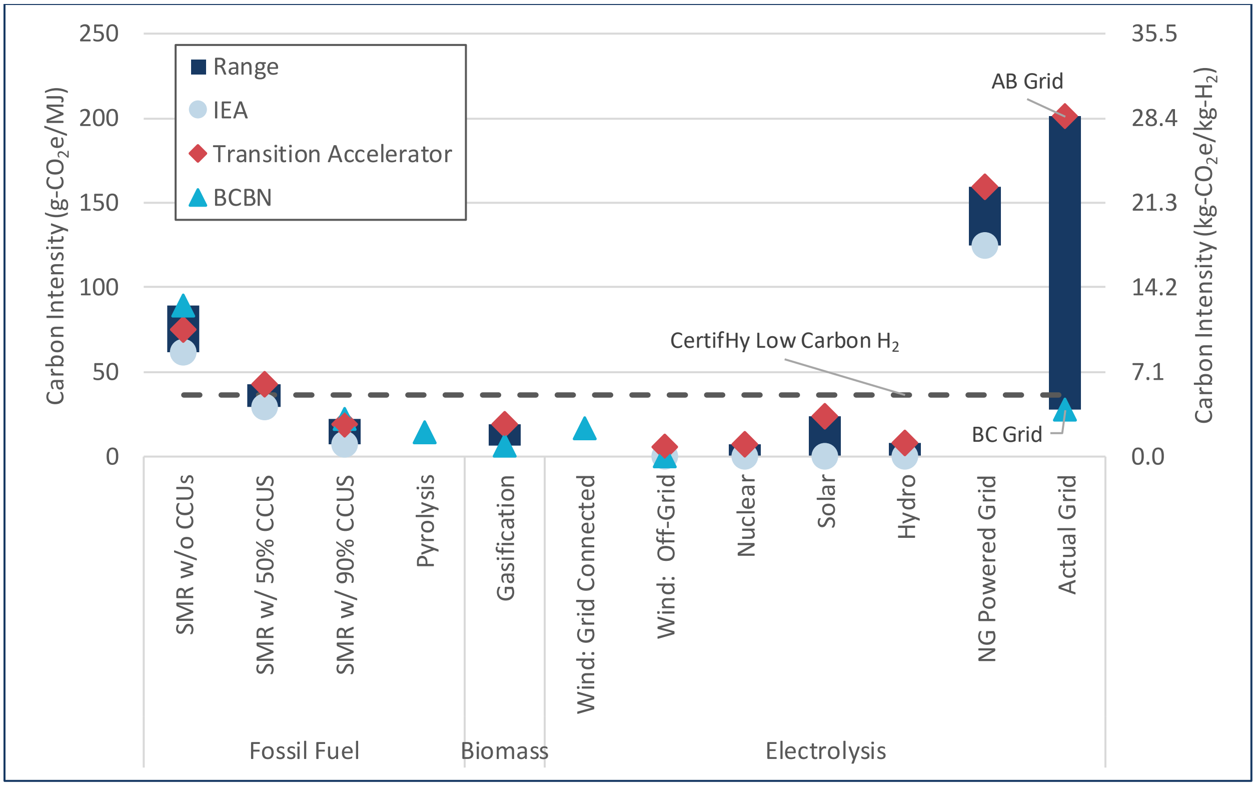


Figure 17 – Carbon Intensities of Hydrogen from Different Production Pathways[1,2,1,4]

It will be important for Canada to develop and adopt national definitions and standards for 'clean' hydrogen, whereby CI thresholds are established and can be independently certified. Hydrogen's decarbonization benefits will only be realized if Canada adopts low CI hydrogen, and any government investment in the development of new supply in Canada needs to reflect this. It is recommended that Canada coordinate efforts underway internationally, to facilitate trade in the longer term as well as benefit from extensive efforts that have already been initiated to quantitatively define and measure hydrogen CI from a range of pathways. For example, the European Commission has initiated a pilot program called CerifHy to develop an EU-wide Guarantee of Origin scheme for green and low carbon hydrogen that considers both the origin of the hydrogen and its greenhouse gas (GHG) intensity. The recommended threshold for GHG intensity is set at a 60% below the intensity of hydrogen produced from natural gas, currently set at 36.4 gCO_{2e}/MJ.[2]

Over time, the mix of production pathways will shift based on their overall CI reduction and their cost per tonne of CO_2 abated. This will likely eventually go from a blend of fossil fuel derived hydrogen with and without CCUS and hydrogen produced via grid connected electrolysis, to non-emitting and renewable sources with very low or zero CI. The timeframe for this transition is dependent on a number of factors including feedstock cost, demand and technical innovation, and market forces that will ultimately drive the production pathway development in Canada. However, the potential low cost of negative emissions means that Canada will likely use low cost hydrocarbons for a long time to come unless strong policy

[1] IEA. 2019. The Future of Hydrogen: Seizing Today's Opportunities.

[1] Asia Pacific Energy Research Centre, "Perspectives on Hydrogen in the APEC Region.pdf," Jun. 2018 [Online]. Available: https://aperc.ieej.or.jp/file/2018/9/12/Perspectives+on+Hydrogen+in+the+APEC+Region.pdf

[1] BloombergNEF: Hydrogen Economy Outlook, March 20, 2020,

[1] BCBN BC Hydrogen Study, Zen and the Art of Clean Energy Solutions Inc., 2019

[2] https://www.certifhy.eu/images/media/files/CertifHy_2_deliverables/CertifHy_H2-criteria-definition_V1-1_2019-03-13_clean_endorsed.pdf

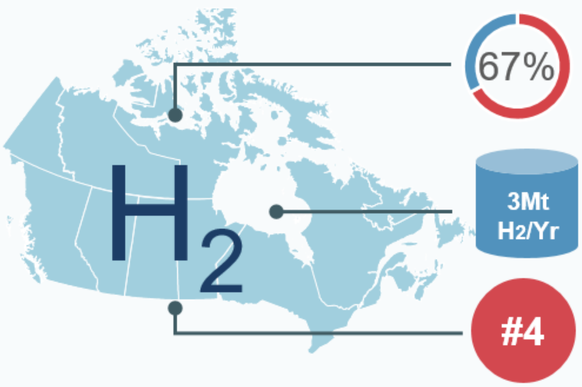
measures are put in place. Production of hydrogen from fossil fuels without CCUS should be coupled with greater than 50% CCUS as soon as possible and move to predominantly greater than 90% CCUS by 2030.

The fossil fuels with CCUS pathway will dominate production until more renewable sources can be built and cost reduction makes the overall energy transition to renewables gain momentum. The drive for fuel switching to direct electrification will increase overall electricity demand over the same timeframe that hydrogen demand grows, and hence the market will make decisions for the best overall blend of pathways for hydrogen production with this as a consideration. It is recommended that in addition to establishing CI thresholds, provinces with input from the Federal Government set longer-term objectives to transition to renewable hydrogen supplies through establishing tiered thresholds of required renewable content over time should the economics make sense when compared against viable but non-renewable clean energy vectors. The CI thresholds and timing will likely vary by province based on local resource availability and economic factors. Canada needs policy to drive adoption of multiple pathways in order to ensure both decarbonization and ultimate sustainability goals are met. Establishing tiered CI thresholds will also ensure that electrolysis assets that are scalable and economic can be deployed to match demand in the early years as demand is growing, and do not get stranded as lower cost centralized hydrogen produced from fossil fuels with CCUS comes online.

One way to establish a balanced supply of clean hydrogen is to require that government funded projects utilize a portion of low carbon hydrogen. Provincial funding programs such as Emissions Reduction Alberta are already setting requirements, such as requiring domestic hydrogen supply, with the goal to stimulate hydrogen production supply chain development together with end-use rollout. Adding renewable content requirements is another important aspect to consider, and in regions with nuclear generation the definition can be focussed on non-emitting hydrogen rather than restricted to renewable. The federal Clean Fuel Standard (CFS) takes a technology neutral approach by using the CI of the fuel to determine eligibility for credits and then amount of credits awarded; it does not specifically provide extra credit for renewable pathways. The design of the CFS will incentivize the use of low CI fuels, thereby driving increasing uptake of lower CI hydrogen production pathways over time.

STAKEHOLDER INPUT: HYDROGEN PRODUCTION

Opportunities



- *Sixty-seven percent of Canada's electricity comes from renewable resources and 82% from non-GHG emitting sources which could be used for electrolysis*
- *Canada is one of the top ten global producers of hydrogen today, producing an estimated 3 million tonnes annually via steam methane reformation (SMR) of natural gas.*
- *Canada is the world's fourth largest producer and sixth largest exporter of natural gas.*

Challenges

- *Bias against certain pathways puts overall hydrogen industry at disadvantage and unlevel playing field in near term*
- *CI of grid for electrolysis may be very high in some regions for near-mid term*
- *Regionality of CCUS, lack of acceptance and concern over long term stability*
- *Predictable, long-term demand is critical before industry can invest in projects*
- *Cost of electricity for electrolysis pathway driven by peak demand and no special rate tariffs.*
- *Large capital investment to scale production requires demand to grow concurrently*

Findings

- *Focus on carbon intensity of hydrogen as primary near term performance-based metric.*
- *Government support for supply development to be limited to low CI pathways, with clear threshold set and independent certification capabilities established. Align with international standardization efforts (E.g. CertifHy @ 36.4 gCO_2e/MJ).*
- *Transition to increasing hydrogen with low to net-zero content is needed over time. Set increasing thresholds for renewable content in government supported projects over time. (e.g. 33% now to 50% by 2050)*
- *Strategic focus for Canada should be on CCUS innovation and engineering expertise given potential for low CI, low cost hydrogen derived from fossil fuels that rely on bulk CCUS potential.*

HYDROGEN STORAGE & DISTRIBUTION

Hydrogen can be stored and transported from the point of production to point of use in a number of ways. Storage and distribution must be considered from the outset as regional hydrogen deployment HUBs are built up across Canada. This part of the value chain has significant economic and emissions implications which affect the overall hydrogen delivered cost and GHG lifecycle emissions.

Hydrogen Storage

Hydrogen's low volumetric energy density makes storage a challenge, both as a bulk commodity at the point of production and in end-use applications such as fuel storage on-board vehicles. Physical storage, materials--based storage, and chemical carrier storage are the broad categories defining how hydrogen can be stored. The method of hydrogen storage is often based on the end-use requirement, including weight and volume available for energy storage.

Physical storage refers to hydrogen stored as either a compressed gas in high pressure cylinders, or as a cryogenic liquid in specialty insulated tanks. In end-use applications, such as on board vehicles, gaseous hydrogen is typically stored in high-pressure tanks with pressures ranging from 350 to 700 bar (5,000 to 10,000 psi). Hydrogen tanks for forklifts, buses and heavy-duty vehicles today generally use hydrogen compressed to a pressure of 350 bar. Light-duty vehicles store hydrogen at 700 bar as higher pressures allow for smaller tanks which can be fit more easily into conventional vehicle designs. In the future, liquid hydrogen may be used for onboard storage for certain applications such as trucks, similar to LNG trucks currently available. Bulk hydrogen for non-mobile applications can be stored as a compressed gas in tanks above and below ground, as liquid hydrogen in large insulated tanks, and in natural gas pipelines, salt caverns, and depleted wells. As volumes grow, for example if hydrogen is used to provide daily or seasonal energy storage, the ability to utilize existing pipeline networks or geological storage options becomes necessary due to both practical footprint considerations and cost.

Gaseous hydrogen can be stored effectively underground in salt caverns, as has been proven in projects in the UK, US, and throughout Europe. These regions are targeting the use of hydrogen for utility scale energy storage where bulk storage is required for technical and economic viability. Engineered salt caverns are utilized for NG storage in many provinces in Canada. These caverns are created by first boring a hole to storage depths and creating the storage space via solution mining, which dissolves the salt by pumping in fresh water and pulling out the brine stream. The compact structure and composition of salt rock formations make the structures inherently gas tight, and the cavern's only surface access is the borehole, which is plugged to prevent leakage. Dried and compressed hydrogen can be injected through the borehole and effectively stored in the cavern indefinitely. As demand for hydrogen grows around the world, depleted gas wells are also being considered for bulk storage of hydrogen and offer mid-term potential in Canada in a number of provinces.

Storage of hydrogen as a cryogenic liquid is another physical storage method. Canada has hydrogen liquefaction assets in both Quebec and Ontario, owned and operated by large industrial gas companies. Liquid hydrogen (LH_2) is a far denser energy carrier than gaseous hydrogen. However, hydrogen liquefies at -253°C , and requires approximately 10 kwh/kg-H_2 of energy to cool the gas to the liquid state, which is approximately 30% of the heating value of the hydrogen, resulting in increased economic costs. LH_2 must be stored at cryogenic temperature in insulated storage tanks to avoid boil off or evaporation of hydrogen similar to how LNG is stored. Moving hydrogen as a liquid becomes cost effective as higher quantities are needed. Liquid storage is also effective where the footprint is constrained at end-use locations, such as at retail fueling stations for light- and heavy-duty vehicles. Liquid hydrogen is typically vaporized and dispensed in gaseous form for most fuel cell vehicle applications today. However, applications such as rail or large marine vessels require high amounts of fuel and are considering storing liquid hydrogen onboard.

Emerging technologies allow hydrogen to be stored in the form of compounds called chemical carriers. There is more hydrogen in a litre of gasoline than in a litre of liquid hydrogen. Hence, liquid chemical carriers are easy to handle and can contain large quantities of hydrogen by volume. Methylcyclohexane (MCH) and ammonia (NH_3) are the most common chemical carriers used to store hydrogen.

Hydrogen can also be stored by adsorbing the gas on powders. One advantage of this method is that the amounts of energy required to adsorb (bind) the hydrogen to the powder should be less than required to form chemical bonds, as per the chemical storage methods above. As technologies advance, adsorbent storage may make it possible to store relatively high densities of hydrogen – comparable to compressed gases – at lower pressures. While promising technologies are available, more research is needed to show ultimate potential.

Hydrogen Distribution

Gaseous hydrogen is primarily transported in tube trailer trucks today, at pressures of up to 250 bar with 180-200 bar being more typical. Transport Canada regulates transport of gaseous hydrogen through the Transport of Dangerous Goods (TDG) Regulations. Steel tube trailers are most commonly employed for gaseous delivery today, but weight regulations limit how much can be delivered by each truck. A number of companies are developing 450 bar hydrogen storage delivery systems using composite materials to increase the amount of hydrogen that can be delivered by each truck, thereby reducing costs and transportation emissions.

Cryogenic liquid hydrogen is transported in liquid super-insulated, cryogenic tanker trucks. For hydrogen distribution at longer distances in moderate amounts where dedicated hydrogen pipelines are not an option, liquified hydrogen is currently the most economical distribution method due to its significantly higher energy density.

Distribution can add significantly to the final delivered cost of the fuel. The cost of delivering hydrogen as a compressed gas or a cryogenic liquid by truck is a function of distance; estimated costs from a recent BC study are shown in Figure 18.

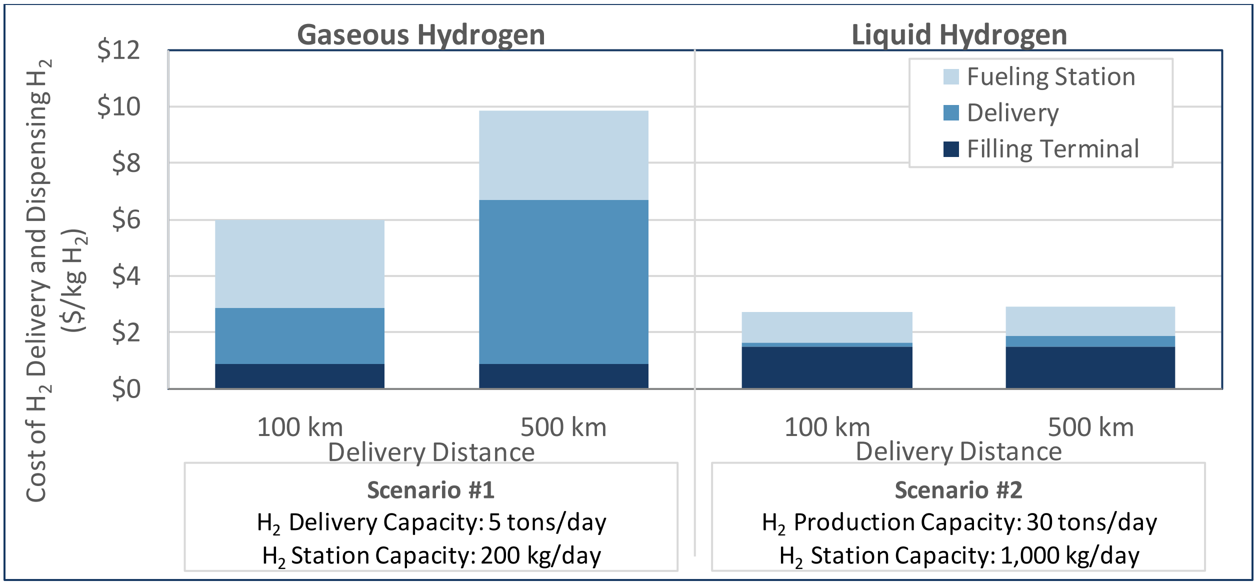


Figure 18 – Truck-Based Delivery Cost for Hydrogen as a Compressed Gas and Cryogenic Liquid[1]

Natural gas pipelines can be used to both store and transport hydrogen. Canada has one of the world's largest pipeline networks delivering natural gas from production areas to markets in both Canada and the US.

Hydrogen can be blended into NG pipelines, typically at pressures less than 100 bar, taking advantage of the inherent storage capacity in the network. Once blended into the NG pipeline, the hydrogen-NG mixture can be used in many applications in place of pure NG. Blend ratios of up to 20% hydrogen are being trialed around the world, with limited impact on infrastructure and end-use appliances. While there is a significant technology development focused on separation technologies, it is currently difficult to separate the hydrogen from the NG once blended. This may become viable in the mid term and would allow the separated hydrogen to be used in fuel cell applications.

Where pure hydrogen is required, dedicated hydrogen pipeline systems may become an attractive option for low cost transportation of hydrogen at scale, for example Figure 19 shows an existing dedicated hydrogen pipeline. The challenge with building hydrogen pipelines is the initial investment

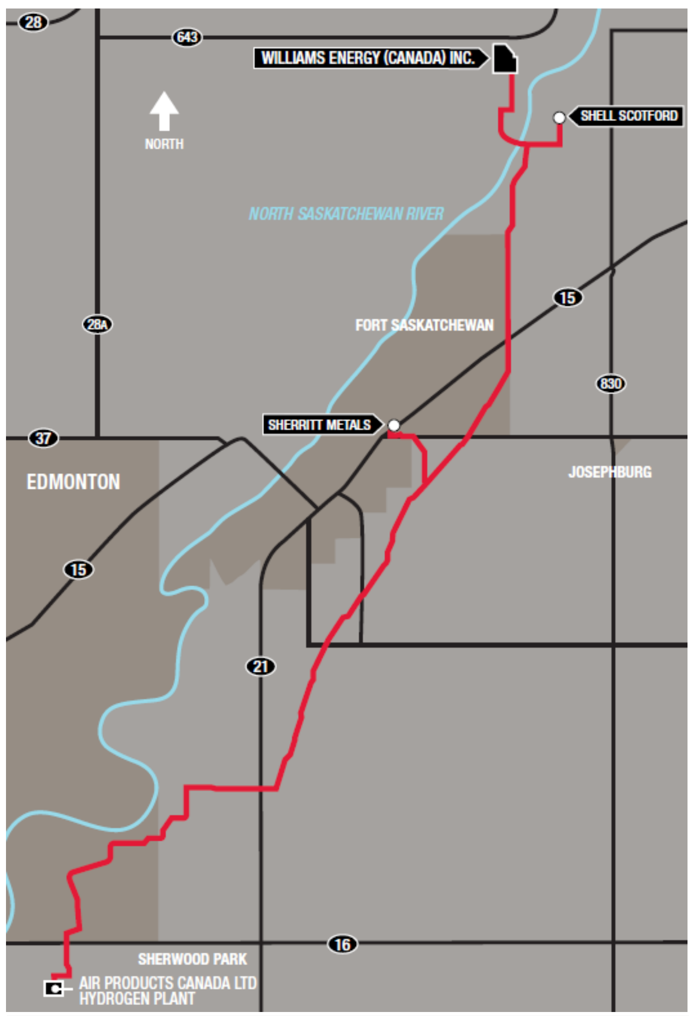


Figure 19 – Air Products Hydrogen Pipeline in Alberta

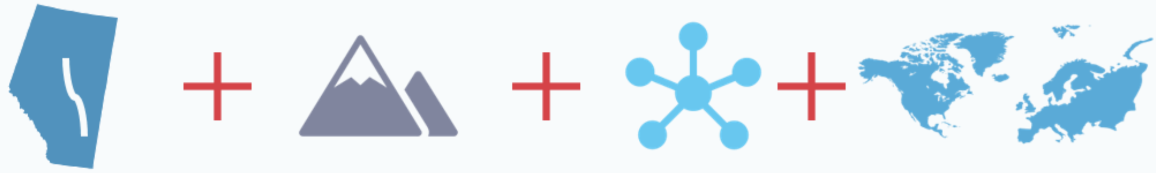
[1] BC Hydrogen Study, Zen and the Art of Clean Energy Solutions Inc., 2019

needed, and the risk of making these large capital investments while demand is growing and uncertain. Building new NG pipelines to allow for future conversion to hydrogen is an important consideration for NG utilities investing in new infrastructure. This is particularly true in regions like the Maritimes where the NG networks are still relatively new and in the growth stage. The US DOE has established dedicated technical targets for hydrogen pipelines including target capital costs of $520,000 $/mile[1] as a long-term target. Similar to the US, a backbone network of hydrogen pipelines could be a strategic infrastructure asset for Canada. This backbone would be fundamental to facilitating trade and cooperation across provinces. Once the infrastructure is in place, this is by far the lowest cost and lowest emissions means of bulk transportation. It is recommended that a dedicated infrastructure group study this potential further.

[1] https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-delivery

STAKEHOLDER INPUT: DISTRIBUTION & STORAGE

Opportunities



- *Canada already has dedicated hydrogen pipelines in Alberta, and an expanded buildout could give Canada a hydrogen advantage*
- *Canada has unique geological reserves including salt caverns and depleted NG wells that can be leveraged for bulk hydrogen storage*
- *Canada's extensive natural gas pipeline network can be leveraged to both store and transport hydrogen*
- *Hydrogen liquefaction assets will position Canada to distribute hydrogen locally and to global markets*

Challenges

Canada is lagging other countries in developing standards for hydrogen in NG pipelines

Storage and transmission can be best optimized when regions collaborate across provincial boundaries

Hydrogen transportation costs can be significant if key infrastructure is lacking

Technical limitations exist for bulk storage and transport on rail and ship

Liquefaction is energy intensive and presents safety challenges, but is required for large scale distribution

Lack of technical data on feasibility of leveraging and modifying Canada's pipeline infrastructure to support large-scale hydrogen distribution

Findings

- *Fast-track regulatory approvals for high pressure gaseous distribution in Canada (450 bar)*
- *Accelerate updating Canadian codes & standards related to pipeline blending*
- *Begin scaling up natural gas injection and power-to-gas demonstrations in different regions including investment support, policy/regulatory incentives and support for R&D and innovation*
- *Scale H_2 transport and distribution networks starting with refuelling station networks in urban areas and in industrial clusters*
- *Invest in strategic liquefaction assets in Western Canada to complement Eastern Canadian assets*

4. Hydrogen End-Use Opportunities

The potential for hydrogen use in Canada is as diverse as the pathways to create it. Adoption of hydrogen will be focused on energy-intensive applications where it offers advantages over alternative low-carbon options. This includes using hydrogen as a fuel for long-range transportation and power generation, to provide heat for industry and buildings, and as a feedstock for heavy industrial processes, like steel and cement making. Domestic deployment of hydrogen will be critical to supporting Canada's world-leading hydrogen and fuel cell sector, as well as to meeting our climate change objectives.

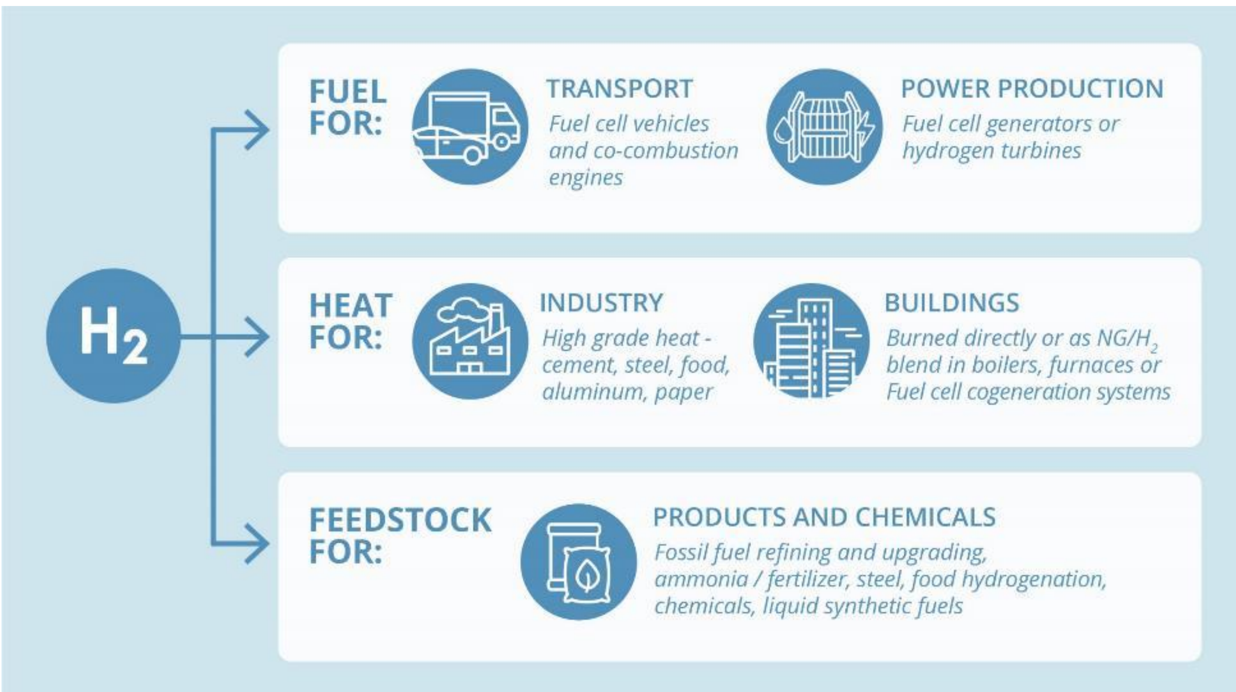
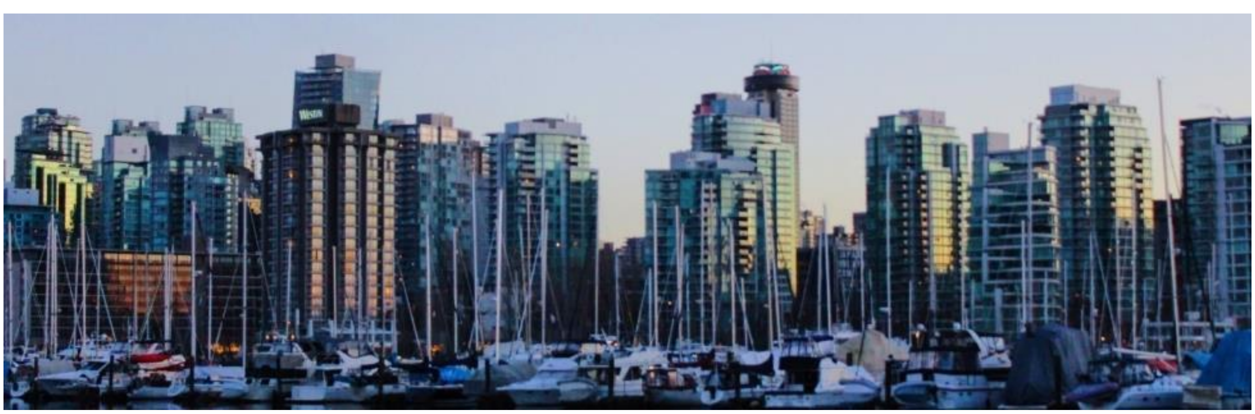


Figure 20 – Hydrogen End-Uses



FUEL FOR TRANSPORTATION

Hydrogen can be used in transportation applications through several different pathways as shown in Figure 21.

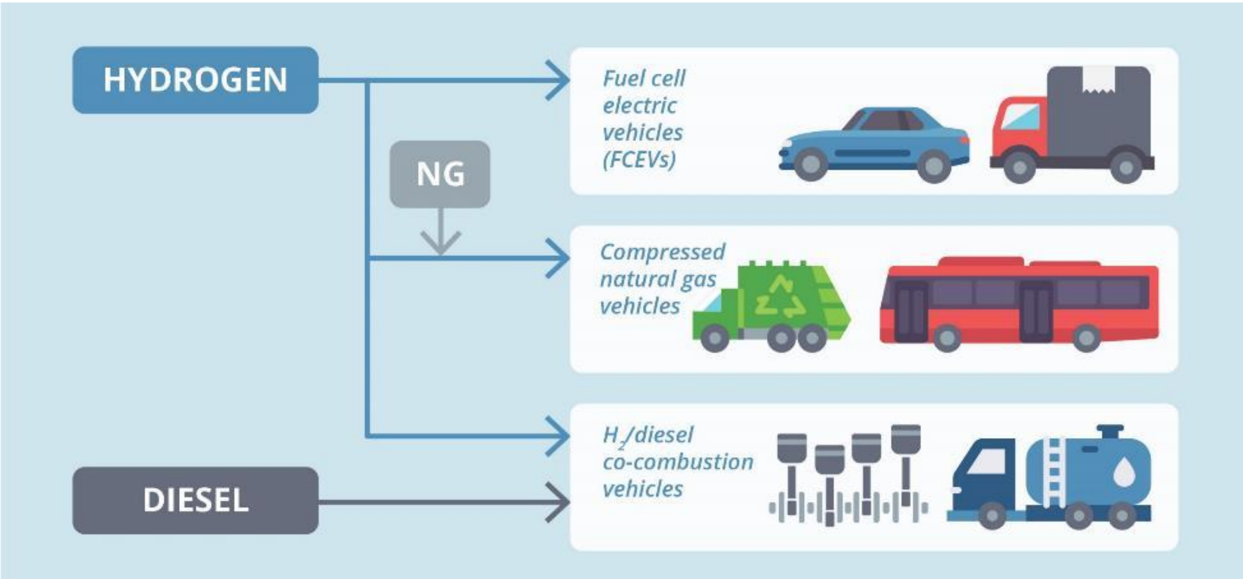


Figure 21 – Hydrogen Uses in Transportation

Hydrogen can be used directly as a fuel in fuel cell electric vehicles (FCEVs), which have two times the efficiency of combustion engines and zero emissions at the tailpipe. Fuel cell light-duty passenger vehicles and transit buses are commercially available today globally and deployed in limited numbers in Canada. Hydrogen FCEVs show strong promise in long-haul, heavy-duty trucking applications where batteries have limitations. The recently approved zero-emission truck regulation in California is driving significant activity by fuel cell system developers, tier 1 engine suppliers, and vehicle OEMs[1]. The focus is on quickly moving beyond the current pilot demonstration phase and developing commercially available medium- and heavy- duty trucks for the North American market in the next few years. Specialty industrial vehicles, trains, marine, and aviation applications are in the pilot demonstration phase and show long-term promise due to the high energy demands in these applications. In Canada, FCEVs can offer advantages in remote and Indigenous communities in colder climates where battery chemistries are negatively impacted. Fuel cells do not suffer the same inherent performance degradation in cold temperatures, and waste heat from the fuel cells can be used for cabin heating to further differentiate extended range of FCEVs in these cold climates.

In addition to being used directly as a fuel in FCEVs, hydrogen can enable higher amounts of renewable gas in natural gas supply networks that provide fuel for compressed natural gas (CNG) vehicles. For example, in British Columbia efforts are underway to recognize hydrogen as an eligible renewable gas under the CleanBC goal to achieve 15% RNG in the natural gas distribution system by 2030. Demand from CNG fleet operators to use lower emitting renewable gas is high, and hydrogen can help to meet that demand. There can be technical challenges related to using an H_2/CNG blend in some vehicles, including tank embrittlement in older type tanks, as well as NO_x emissions. However, with the right materials and engineering a hydrogen / CNG blend can reduce emissions of CNG vehicles and has been demonstrated

[1] Advanced Clean Truck regulation enacted by California Air Resources Board on June 25, 2020. https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks

in several pilot projects. As hydrogen separation technology matures and more hydrogen is present over a wider portion of the NG network, there is the potential for fueling stations with dual fuel sources – CNG and hydrogen – where the fuels are separated at the point of use.

Hydrogen can also be used in conjunction with diesel in internal combustion engine trucks using co-combustion technology. Co-combustion offers the advantage of lower entry cost for end-users, as existing diesel engines can be retrofit. However, these engines do not provide the efficiency advantages of fuel cells and they only reduce tailpipe emissions approximately proportionally to the percentage of hydrogen injected, which is anticipated to reach levels of up to 30%. Moreover, combusting hydrogen can lead to increased NO_x emissions. This technology is generally seen as an intermediate steppingstone toward the transition to FCEVs, and can play an important role in supporting hydrogen demand in the near term. This could help build out hydrogen fuelling infrastructure that will be compatible with heavy-duty FCEV trucks as that technology moves from pilot to commercial introduction.

Light-Duty Vehicles

Hydrogen will play an important role alongside electrification in the transition to zero-emission light-duty vehicles. The Government of Canada has set federal targets for zero-emission vehicles to reach 10% of light-duty vehicles sales per year by 2025, 30% by 2030 and 100% by 2040. Canada considers battery electric vehicles (BEV), fuel cell electric vehicles (FCEV), and plug-in hybrid electric vehicles (PHEV) as ZEVs. BC and Quebec have led provincially with the adoption of ZEV purchase incentives and sales regulations, and both provinces have started to deploy hydrogen fueling infrastructure and FCEVs in limited quantities. To date, approximately 110 light-duty vehicles are in operation in Canada, supported by 3 retail fueling stations in BC, 1 in Quebec, and 1 in Ontario. Four new stations are under development in BC, which will represent an important milestone as vehicle OEMs have indicated that 7-8 stations are needed in a region for coverage and redundancy to enable wider rollout of vehicles. BC also just announced funding for an incremental 10 new stations to continue to expand the network. It is expected that an additional ~150 LD vehicles will be deployed in the coming months as the new stations come online.

BEVs are expected to take a significant portion of the market share for light-duty applications in Canada. FCEVs offer choice for vehicle owners preferring larger vehicles, extended range, fast refueling, and no-compromise performance in cold climates. Canadian consumers have shown increasing demand for larger vehicles, with 80% of nationwide spending on new vehicles in 2019 going to trucks, vans, or SUVs.[2] This is an indication that consumers will continue to want choice and will not always focus on picking the highest efficiency vehicle option, but rather will weigh performance and vehicle size preferences in decision making. Trends such as autonomous driving and ride

Figure 22 – Hyundai Nexo in Vancouver's Modo Carshare Network[1]

[1] Modo. (2019). Image from: *Press Release: Hyundai NEXO Fuel Cell sees success with Modo, Vancouver-based carsharing co-operative*. https://modo.coop/blog/press-release-hyundai-nexo-fuel-cell-sees-success-with-modo-vancouver-based-carsharing-co-operative/

[2] Source: Statistics Canada. Table 20-10-0002-01 New motor vehicle sales, by type of vehicle

sharing may also drive greater demand for FCEVs given the higher energy intensive duty cycles required for these applications which are well served by hydrogen. Battery and charging technology continue to advance at a rapid pace, and larger vehicles with extended range are expected to reach the market in the near term. Ultimately both BEVs and FCEVs will have a role in decarbonizing LDVs.

FCEVs are likely to be more attractive for drivers in Canadian urban centers where a higher proportion of households live in multi-unit residential buildings (condominiums, apartments, townhouses with shared garages) where cost and strata bylaws can make retrofits of home charging stations expensive and difficult, providing they feel well-served by hydrogen fueling infrastructure. In addition, households which rely on street parking may opt for FCEVs over BEVs due to convenience. As market penetration rates of BEVs increase in urban centers, electric grid energy and demand capacity for vehicle charging may present an additional constraint. The addition of new electrical substations and distribution networks can be prohibitively expensive, and land may not be available. Hydrogen fueling can offer an important option to optimize overall ZEV infrastructure costs.

Although light-duty FCEVs are currently available on the market, they are still produced at a relatively small scale and one of the greatest impediments to deployment in Canada in the near-term is supply. Availability of refueling infrastructure is another key challenge, and the two are related as vehicle supply is limited in part because OEMs will deploy their limited number of vehicles only in regions with installed retail fueling networks. Regions with a combination of ZEV regulations and incentive programs to stimulate the buildout of fueling infrastructure have been the most successful in attracting deployments of FCEVs. Strategic regional partnerships leveraging public/private procurement can be another effective mechanism to solve this dual challenge.

Since FCEVs are currently produced in small volumes, they remain more expensive than comparable ICE vehicles or BEVs. Until technology advancements and production scale drive down costs, consumer subsidies will be important to support adoption. Incentive programs in Canada have price caps in place that exclude FCEVs at this time, due to their high costs[1]. One option to address this impediment to consumer adoption of FCEVs would be to stage incentive programs based on the maturity of each technology.

The adoption rate of FCEVs in Canada will be highly dependent on cost reduction driven by manufacturing at scale, the commitment to achieving national ZEV targets, as well as provincial policies and regulations around ZEVs and buildout of hydrogen fueling infrastructure.

Medium- and Heavy-Duty Vehicles

Buses

Public transit agencies around the world are shifting towards low- and zero-emission vehicles. Battery electric buses (BEBs) and Fuel Cell Electric Buses (FCEBs) are the two powertrains that are considered zero emission in transit applications. FCEBs are commercially available today, with more than 2000

Figure 23 – New Flyer's 40' Fuel Cell Electric Bus (Retrieved from NewFlyer Website)

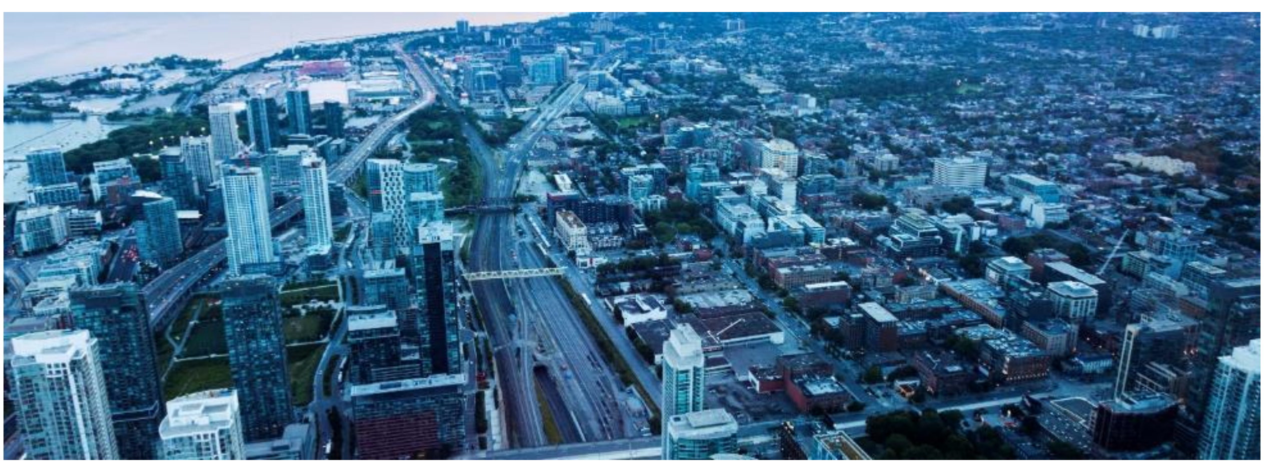
[1] https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles/list-eligible-vehicles-under-izev-program

FCEBs[1] in service worldwide, and approximately half of those are powered by Canadian heavy-duty fuel cell engine technology. With over 15 years on the road and millions of kilometers in passenger service in a range of hot and cold climates, FCEBs have proven their performance. Canadian companies such as New Flyer Industries, Ballard Power Systems, Hydrogenics, and Dana TM4 hold positions in the FCEB value chain, offering a true 'Made-in-Canada' solution.

FCEB is the only zero emission technology that can match the performance of conventional diesel buses and are advantageous compared to BEBs on long routes with higher power requirements. FCEBs can also provide a one-to-one replacement ratio, meaning that transit agencies do not need to buy more vehicles to provide the same level of service as conventional buses. This is important from both a up-front cost and footprint perspective, as often agencies struggle to fit ZEV fleets into their constrained depot space. FCEBs can be refueled at comparable speeds and in a similar way as CNG buses, whereas BEBs require much longer charging times today.

California has been leading the way in zero emission transit in North America, with the adoption of the Innovative Clean Transit regulation (ICT) in 2018. This regulation requires that 100% of all new bus purchases be ZEB by 2029, and by 2040 all buses on the road in California must be zero emission. Large transit agencies were required to file transition plans with the California Air Resources Board (CARB) in summer 2020. As agencies moved from thinking about small scale pilots to planning full transitions, there has been an increase in interest for hydrogen FCEBs. Energy resilience considerations have also come into play, as several days of liquid hydrogen fuel can be stored on site in a compact footprint, providing continuity in service even in the case of grid brownouts that are increasing in frequency in California. California's deployments provide an excellent learning opportunity for Canadian transit agencies exploring ZEB options.

There are challenges limiting deployment of FCEBs in Canada today. There is currently no regulatory driver for agencies to transition to zero emission. While some agencies are exploring alternative fuel strategies to reduce emissions, a national commitment to zero-emission public transit would increase the pace of transition to full zero emission versus driving incremental change. Another challenge is that the initial deployment requires a significant capital investment for fueling infrastructure, and upgrades to maintenance facilities if the depot is not equipped with safety systems for CNG buses. While a strong business case can be made for cost effectiveness, compactness, and operational efficiency of hydrogen fueling over depot charging at scale (e.g. >20 buses), this makes it difficult for agencies to run an initial pilot to get familiar with the technology and train staff, a gating step in broader rollout.



[1] https://www.ballard.com/docs/default-source/web-pdf's/white-paper_fuel-cell-buses-for-france_final-english-web.pdf?sfvrsn=939bc280_0

Canadian cities need public transportation, and it must be zero emission for Canada to become carbon neutral and to improve air quality in urban centers. The zero-emission bus initiative[1] underway in Canada encourages government to support school boards and municipalities in purchasing 5000 zero-emission buses over the next 5 years. Canada's 'made-in-Canada' FCEB solution will provide economic value and critical local reference projects to the sector if fuel cell electric buses are a portion of the mix. There is an initiative underway to encourage 1000 of the 5000 buses to be powered by hydrogen. These buses are well suited to longer routes and cold weather climates that Canadian transit agencies service.

The adoption of FCEBs in Canada will be dependent on a successful pilot depot conversion in the next 5-7 years in order to gain acceptance and understanding of the technology among local agencies, and to test operational benefits on extended routes in Canada's cold climates. A depot conversion will also provide an opportunity to test the updated Canadian Hydrogen Installation Code published for review and provide experience to AHJs in terms of siting at-scale infrastructure at a depot. Bus costs are coming down due to increasing demand in other countries, and Canada could help drive this by coordinating larger procurements across agencies.

Trucks

Fuel cells are expected to play a significant role in trucking in applications where hydrogen's high gravimetric energy density combined with fast fueling times offer strategic benefits. For example, in heavy-duty trucks travelling long distances with heavy payloads, the weight of the batteries to provide the energy needed would result in reduced cargo load carrying capacity that is unacceptable to operators. Long charging times could also impact operations negatively in an industry where the bottom line is driven by the ability to move goods as quickly as possible. While showing significant promise, fuel cell trucks are in the pilot demonstration phase and are not yet commercially available.

Figure 24 – Fuel Cell Electric Drayage Truck (Photo curtesy of Ballard Power Systems)

The past few years have seen heightened interest in fuel cells for class 8 long-haul trucks, known colloquially as freight trucks, semi-trucks or tractor-trailers. Nikola Motor, Toyota, Daimler, and Hyundai are all developing fuel cell powertrains for this market segment. Cummins Inc. acquired Canadian Hydrogenics Corporation and has been investing heavily in development. A number of demonstration projects have been piloted, including the Alberta Zero-Emissions Truck Electrification Collaboration (AZETEC) project, which will trial two class 8 fuel cell trucks on the corridor between Edmonton and Calgary using a Canadian-made hydrogen fuel cell propulsion system.[2] The initial project will start with two fuel cell vehicles and one refuelling station, with plans to expand in Phase 2 as part of the Alberta Industrial Heartland Hydrogen initiative.

[1] https://cutaactu.ca/en/blog-posts/new-federal-government-unveils-its-priorities

[2] Lowey, M. JWN. (2019). *$15-million Project to test Hydrogen Fuel in Alberta's Freight Transportation Sector*. Retrieved from https://www.jwnenergy.com/article/2019/3/15-million-project-test-hydrogen-fuel-albertas-freight-transportation-sector/

In June 2020, California adopted a rule requiring that more than half the trucks sold in the state be zero emission by 2035. This regulation aims to improve local air quality, a major health issue in the state that is negatively impacted by diesel truck emissions particularly in freight corridors, many of which run through disadvantaged communities. The regulation will also reduce GHG emissions, contributing to decarbonization objectives. This regulation has led to acceleration of activity in fuel cell truck development, and Canada stands to benefit as more commercial fuel cell trucks become available.

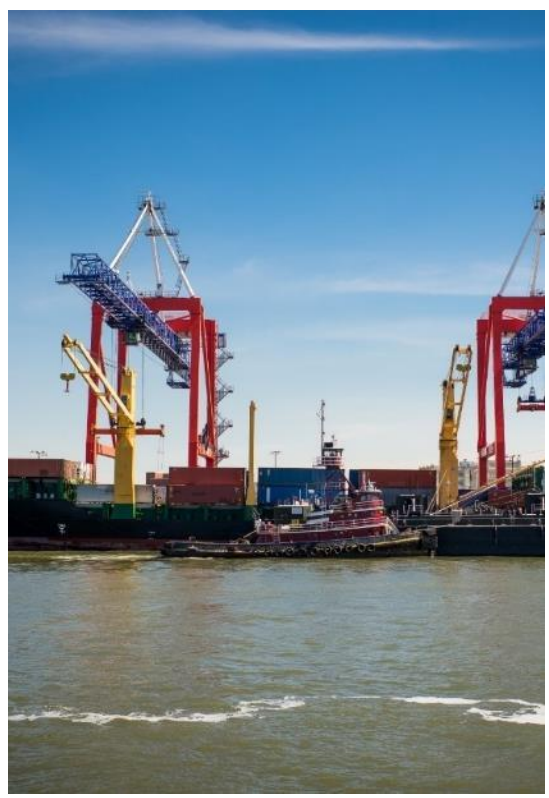
The current pilot under development in Alberta will be an important proof point for hydrogen deployment in the trucking sector, as will market evolution driven by the recently adopted mandate in California. Ultimately Canada will need a zero-emission option for long haul trucking to reach decarbonization goals. In September 2019, Canada was the first nation to endorse a pledge through the Global Commercial Vehicle Drive to Zero initiative to speed adoption of zero-emission and near-zero emission medium- and heavy-duty vehicles in urban communities by 2025 and achieve full market penetration by 2040. Commitments made to drive action in support of that pledge will impact the pace of adoption.

Other Transportation Applications

Goods Movement Equipment, Ports

There is a range of goods movement equipment powered by hydrogen fuel cells in operation today, with varying levels of commercial readiness. Fuel cell forklift trucks are commercial, with more than 35,000 units in operation across North America. Most deployments have been in the US in high-throughput distribution centers where the fuel cells offer a compelling business case over lead acid batteries through productivity improvements. The US Federal tax credit for fuel cell systems was instrumental in establishing this market and favored deployments in the US over Canada. However, there are fuel cell forklift trucks in both Alberta and Ontario with more deployments expected given the commercial competitiveness of these units.

Sea ports are users of heavy diesel equipment and are under pressure to reduce emissions that lead to poor air quality and contribute to global warming. Ports can be hosts for early deployment hubs of fuel cell equipment, with multi-modal transportation applications converging on a single location that can share hydrogen infrastructure at scale. Equipment used at ports tends to be high power with intesive duty cycles and can provide the fuel demand needed in a single location to drive scale and cost-effective deployment of fuel. Other goods movement equipment that can be deployed at ports includes drayage trucks, yard trucks, gantry cranes, straddle carriers, and rail yard switchers. Hydrogen fuel cell generators can also provide shore power for vessels in harbor, and power for transport refrigeration units staged at the port. Figure 25 shows the location of Canada's major ports. While the total number of vehicles may be small in terms of the overall opportunity for Canada, lighthouse projects hosted by ports can demonstrate the benefits of multiple end-use applications sharing common infrastructure and could be a significant catalyst for the sector in the next 5 years.



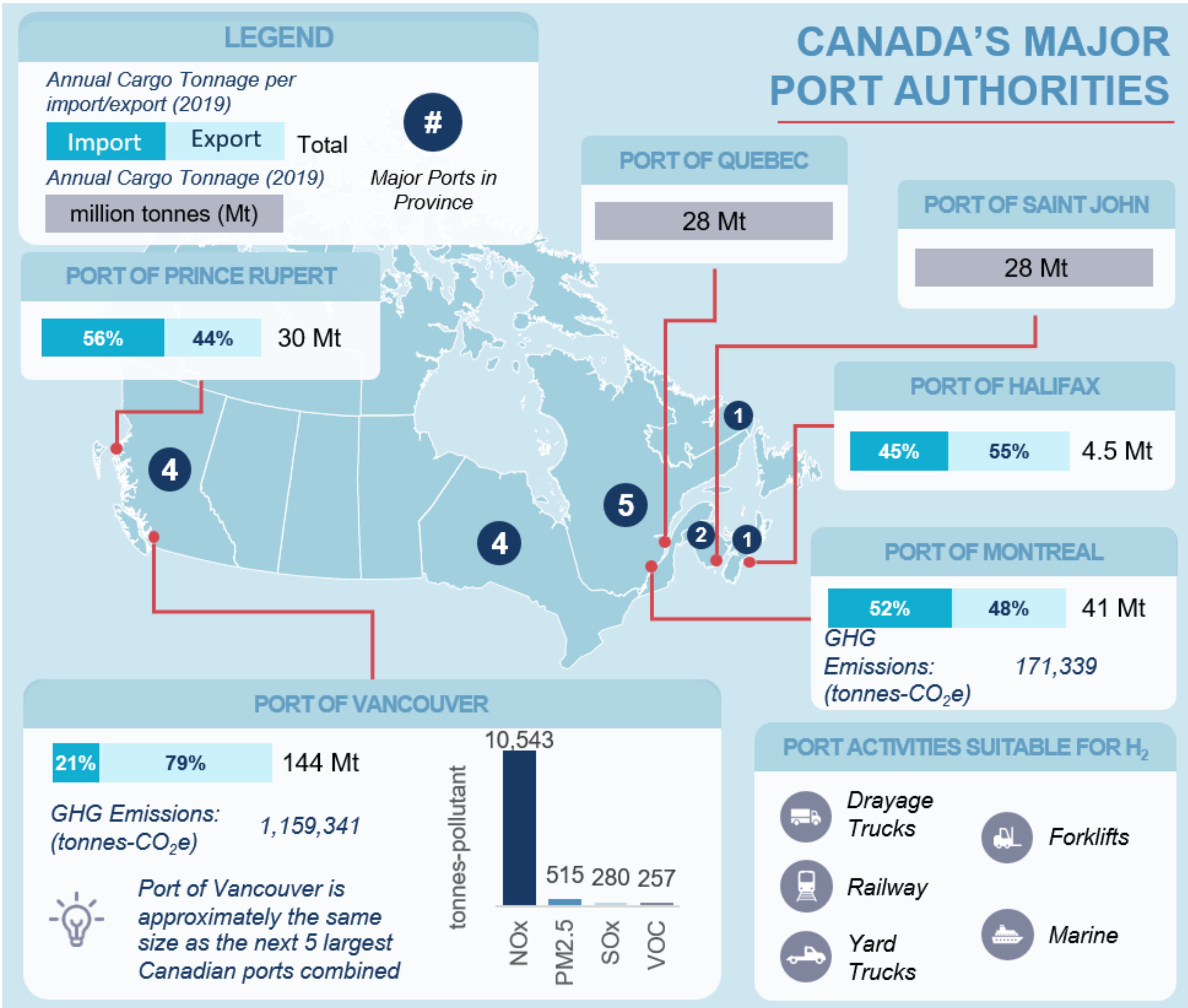


Figure 25 – Canada's Ports as Hosts for Early Hydrogen Deployment HUBs

Mining

There is a similar value proposition for hydrogen displacement of diesel in Canada's mining operations to reduce emissions. Canada's mining industry is one of the largest in the world. Producing more than 60 metals and minerals, Canada is among the top five worldwide producers of 14 different commodity metals and minerals[1]. Mines in northern and remote regions are largely dependent on expensive, high emission diesel power. Stakeholder consultation indicated that Canada's mining sector consumes approximately 2 billion litres of diesel on an annual basis. Hydrogen presents an opportunity to reduce widespread reliance on diesel power for both above ground and underground mining vehicles and can also be integrated into microgrid stationary power systems.

[1] https://www.statista.com/topics/3067/canada-s-mining-industry/#:~:text=Canada's%20mining%20industry%20is%20one,different%20commodity%20metals%20and%20minerals.

In heavy-duty mining vehicles, the high gravimetric energy density and fast fueling times offered by hydrogen in FCEVs provide technical and operational benefits and higher productivity. Zero emission fuel cells used in underground mining equipment eliminate diesel combustion exhaust emissions such as carbon monoxide, NO_X, and PM, and this can ultimately reduce the ventilation requirements in mines which can contribute 30-40%[1] of a mine's total operating costs. Heavy-duty vehicles powered by hydrogen can also reduce emissions from Canada's oil sands mines.

The Canadian Minerals and Metals Plan (CMMP) aims to capitalize on opportunities to strengthen Canada's competitive position within the global mining sector. The CMMP emphasizes the importance of developing and adopting clean technologies and alternative energy sources, such as hydrogen. As mining companies are faced with mounting social and economic pressure, it is evident they may need to go beyond what is demanded by law and the applicable industry environmental, social, and other standards if they wish to gain, or maintain, their "social license" to operate. NRCan's CanmetMINING have been studying and testing the potential for hydrogen in mines, including understanding safety considerations of bringing hydrogen into underground mines. This initiative has played an important role in informing Canada's hydrogen safety code development and will serve as a hub of information for the mining sector to understand opportunities for hydrogen in their operations.

Demonstrations of hydrogen in mining applications started in the early 2000s. In Canada NRCan supported a project at the Raglan Nickel Mine in Northern Quebec starting in 2015 where hydrogen is used as an energy storage solution to reduce diesel consumption in the site's stationary power generation system. Despite early demonstrations, the sector has been slow to adopt hydrogen in any meaningful way. However, there appears to be momentum in industry to start deploying hydrogen in mining operations and Canadian companies are playing a role. A number of mining companies are exploring fuel cells for ultra-heavy-duty haul trucks. Each of these vehicles is anticipated to use approximately 1 TPD of hydrogen, equivalent to running ~33 buses, showing the potential for a single mine site to deploy hydrogen at significant scale.

To move beyond single vehicle demonstrations, it will be important for OEMs such as Komatsu and Caterpillar to commit to developing commercially available hydrogen-powered equipment. Costs and a demonstrated business case continue to be a challenge in this sector, and ultimately hydrogen must be considered as part of the overall integrated ecosystem in the mining operations, together with other renewables, to optimize performance and economics.

Collaboration with other regions can help Canada advance deployment of hydrogen in mines. In July 2020, the Canadian Hydrogen and Fuel Cell Association (CHFCA) and Australian Hydrogen Council (AHC) signed a Memorandum of Understanding (MOU) to strengthen collaboration between Canada and Australia in the commercial deployment of zero-emission hydrogen and fuel cell technologies, including identifying opportunities for joint projects in mining. While international collaborations are important, Canada must also consider how deployment of made-in-Canada solutions could provide a competitive advantage to Canada's mining companies that are operating in an intensively competitive sector and protect potentially valuable IP. It will be important to see a Canadian hydrogen mining project as a proof point that the sector will consider adoption of hydrogen as a replacement to diesel, and the first step will be support for a feasibility study that looks at hydrogen as part of the overall mining operations.

[1] http://www.fchea.org/in-transition/2020/3/16/a-case-for-hydrogen-to-decarbonize-mining

Rail

Rail, marine and aviation applications are well suited to hydrogen because their energy intense duty cycles and long ranges make them particularly hard to electrify. There is increasing interest in hydrogen fuel cells for these applications, but to date activity has been primarily focused on European and Asian markets. These do show strong potential in Canada over the longer term, and early pilots in rail and marine can be integrated into port demonstration hubs leveraging solutions being developed for other markets to enable Canada to leapfrog from its current position.

Figure 26 – Alstom Hydrail with Hydrogenics Engine (Photo courtesy of Alstom)[2]

Hydrail offers a cost-effective way to electrify rail service compared with the traditional electrification approaches using overhead catenary wires or a third rail. Greenhouse gas emissions from diesel trains are a significant contributor to global warming and transit trains produce local air contaminant emissions that contribute to poor air quality in urban areas. Authorities are under growing pressure to reduce carbon emissions from rail service, but other electrification options are costly and require massive infrastructure upgrades. Hydrail trains require no electrification infrastructure, but rather run on existing unmodified tracks. Hydrail enables a gradual transition to electrification, one train at a time, versus alternative infrastructure rebuilds that disrupt service and require an upfront investment to electrify all trains concurrently.

Canadian companies are playing an instrumental role in the value chain in hydrail applications. Ontario-based Hydrogenics provided the fuel cell systems for the first commercial hydrogen powered trains that entered service in in Germany in 2018, built by French train manufacturer Alstom. The trains are capable of travelling 1,000 km without refuelling, which is comparable to a diesel alternative.[1] BC-based Ballard Power Systems is working on hydrail projects in Europe and in China. To date no hydrail trains have been deployed in Canada, but there has been interest supported by studies to investigate viability.

Canada is home to a large and well-developed coast-to-coast rail system that transports mainly freight, with 49,422 km of track.[3] The sector is dominated by CN, CP, and Via Rail which are regulated by the Railway Safety Act.

[1] Agence France-Presse. (2018). *Germany Launches World's First Hydrogen-Powered Train*. Retrieved from https://www.theguardian.com/environment/2018/sep/17/germany-launches-worlds-first-hydrogen-powered-train

[2] Alstom. (2019). *Alstom to tests its hydrogen fuel cell train in the Netherlands.* Retrieved from https://www.alstom.com/press-releases-news/2019/10/alstom-test-its-hydrogen-fuel-cell-train-netherlands

[3] Transport Canada, Overview of the Hydrogen Rail Status in Canada, March 2019

Figure 27 – Canada's Coast to Coast Rail System

Passenger rail transport in Canada serves 450 communities, with 12,500 km of rail. The most widely used passenger rail is along the Quebec City – Windsor Corridor, moving some 4 million passengers/year. Toronto, Montreal and Vancouver are host to commuter rail systems, and Calgary, Edmonton, and Ottawa currently have light rail systems in operation with new systems in construction in Edmonton, Waterloo and Toronto.

The most comprehensive look at Hydrail in Canada to date has been through the Metrolinx Hydrail study, published in 2018 to look at the feasibility of using hydrogen fuel cell (HFC) trains to electrify the GO networks as an alternative to electrification using conventional overhead wires in Ontario. The study concludes that it is technically and economically feasible to build and operate the GO network using HFC-powered rail vehicles, and the costs of building and operating a Hydrail System are equivalent to that of a conventional overhead electrification system. Implementation of a Hydrail system of this scale and complexity would be innovative and provides a unique set of risks and benefits that Canada could be at the forefront of studying. While no firm commitment to selecting Hydrail has been made, Metrolinx is intending to engage a contractor to upgrade the GO network using a Design-Build-Finance-Operate-Maintain (DBFOM) model. As part of the tender process, bidders will be able to propose both hydrail and overhead wire technology to electrify the GO network.

There are also hydrail passenger train projects proposed in BC both in the Fraser Valley corridor and the Okanagan, though neither has yet moved to the implementation phase.

While no concrete hydrail projects have been initiated in Canada, it is expected that advancements led by Europe and Asia using Canadian core IP will eventually lead to domestic deployments. Applications in Canada could include: rail yard switchers / shunt locomotives, passenger rail, and freight locomotives. Early studies assessing freight applicability of hydrail concluded that hydrail for freight switching is technically and economically feasible.[1] Retrofitting locomotives and replacing diesel engines with zero-emission fuel cell engines is a viable and cost-effective alternative to purpose built hydrail trains, which is an important opportunity given the long (50 year+) lifecycle of locomotives.

[1] Change2Energy Services, Assessment of the Design, Deployment Characteristics and Requirements of a Hydrogen Fuel Cell Powered Switcher Locomotive, June 2020

Marine

Marine applications also show strong potential for hydrogen adoption in Canada. Potential applications include hydrogen fuel cell propulsion systems as well as auxiliary power systems for ships. Fuel cell systems can also provide shore power for ships in harbor. The International Maritime Organization (IMO) is driving aggressive emissions reductions in the shipping industry through adopted emissions and energy-efficiency regulations. The IMO has identified ammonia (made with renewable hydrogen) and hydrogen used directly as a fuel as potential fuels of the future in a decarbonized shipping industry.

Early applications for hydrogen in marine include ferries, tugboats, and coastal and inland barges. Canada's extensive waterways make it home to over 180 different ferry routes with a route presently operating in each province and the majority of the territories. These ferries represent a mix of private and publicly operated routes as well as a mix of passenger, freight, and mixed-use ferries[1]. Canada does not currently have any marine hydrogen deployments, but a variety of studies have been initiated in the Maritimes, Ontario, and BC. Canada can benefit from activities led primarily out of Europe, such as hydrogen-powered car ferries under development in Norway.

Aviation

Hydrogen can play a role in the aviation sector as well, with hydrogen's high gravimetric energy density offering significant advantages as an aviation fuel. Hydrogen fuel cell power may also have a role in providing energy for on-board systems, reducing overall jet fuel consumption. While not yet commercial, there are a wide range of applications in the study and pilot demonstration phase. Applications range from Unmanned Aerial Vehicles (UAVs), or drones, to propulsion systems in manned aircraft. Big players like Audi, Aston Martin, Boeing, Daimler and most recently Hyundai, through their new urban Air Mobility Division, are exploring alternative approaches to aviation enabled by zero-emission technologies[2]. These news modes of transport could radically change mobility options in urban environments, reducing ground level congestion and reducing both GHG emissions and local criteria pollutants. In September 2020, Airbus unveiled three hydrogen-powered aircraft concepts that could enter service by 2035.[3] In some aviation concepts hydrogen is being considered as a fuel for auxiliary power units, rather than as the primary propulsion fuel.

The main alternative to hydrogen in zero emission aviation is lithium ion batteries. Hydrogen can offer advantages over lithium ion batteries given the higher energy density that can be achieved in heavier duty cycle applications, and the shorter refueling times. These advantages enable longer range and greater load-bearing capacity. UAVs for both commercial and military applications incorporating hydrogen fuel cells have been gaining traction. In 2019, Plug Power acquired Montreal-based EnergyOr to integrate the small, ultra-lightweight fuel cell technology into their product line.

Canada's aerospace industry contributes over 200,000 jobs and $25B annually to the Canadian Economy[4]. The sector is under intense pressure to maintain Canada's position in a climate with increasing competition, to tackle GHG emissions, and to address major industry disruptions caused by COVID-19. The industry has identified hydrogen fuel cells and hydrogen combustion as promising options to reduce CO_2 emissions.

[1] https://canadianferry.ca/ferries-in-canada/

[2] https://newatlas.com/aircraft/hyundai-nasa-expert-flying-car-division/

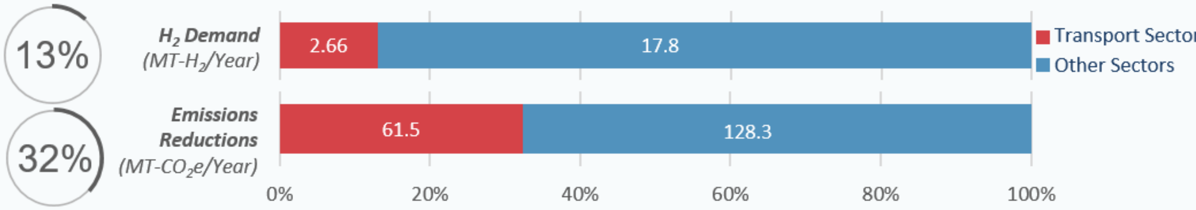
[3] https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html

[4] AIAC, 2019

STAKEHOLDER INPUT: TRANSPORTATION

Opportunities

Transportation Sector Contribution in 2050 Transformative Scenario



- *1 in 4 LD vehicles could be an FCEV by 2050*
- *Fuel cells offer greatest advantages over batteries in HD applications with high payloads, long ranges, & intensive duty cycles*

5MM	160k	6500
Light-duty vehicles	*Trucks*	*Buses*

Challenges

Lack of available hydrogen fueling infrastructure; requires clusters of 7-8 stations before vehicle OEMs will roll out FCEVs to a region

Higher vehicle costs due to lower maturity level and lower volumes

Perceived competition with BEVs vs complementary technology with each playing important role; for example, in heavy duty sector

Proven, commercially viable on-road applications, lack of vehicle supply impedes uptake. Other modes (e.g. rail, marine) in early deployment

Findings

- *Stronger policy / regulation supported by incentives and infrastructure investments to drive adoption of zero emission vehicles*
- *Existing programs / policies should reflect lower market maturity of fuel cell vehicles compared to other alternatives*
- *Coordinated H_2 fueling infrastructure investment plan, focused on hub regions and expanding to connector stations for both LD (700 bar) and HD (350 bar), co-located where possible*
- *High profile full depot FCEB pilot project to raise awareness and share data for transition planning*
- *Requirement for Canadian Transit Agencies to develop zero emission transition plans*
- *Federal ZEV procurement policy to add to demand certainty*
- *Pilot deployments of lower TRL transportation – trucks, rail, marine, aviation*

FUEL FOR POWER GENERATION

Hydrogen can be used as a fuel for power production through either hydrogen combustion in turbines or use in stationary fuel cell power plants. Combustion turbines designed to combust a blend of hydrogen and natural gas are currently commercially available. Existing natural gas turbines could likely operate with a blended hydrogen/natural gas fuel supply of up to 10% to 15% hydrogen by volume. However, major modifications to or replacement of infrastructure and equipment would be required to combust larger proportions of hydrogen in existing power plants. Turbines capable of combusting 100% hydrogen are in development and are expected by 2030. Hydrogen can also provide load management capabilities, daily and even seasonal utility scale energy storage capabilities, and is an enabler for the growing variable renewable power sector.

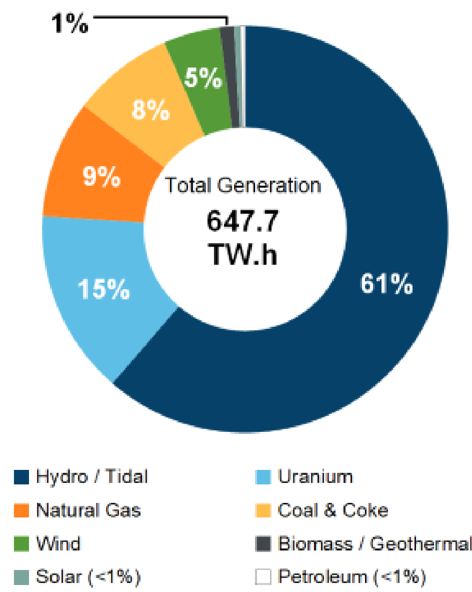


Figure 28 – Electricity Generation by Fuel Type in Canada, 2018, source: Canada Energy Regulator

While Canada's electricity grid is on average considered low carbon intensity, some regions are significantly higher than the average and rely on combustion of fossil fuels to produce power. Overall, approximately 17% of Canada's grid power is supplied via combustion of fossil fuels. Low carbon intensity hydrogen can help to reduce emissions related to power generation and can help green the electricity grid.[1] It is expected that the levelized cost of electricity from hydrogen-fueled combustion turbines will decrease and become cost-competitive on a lifecycle basis with natural gas-fueled combustion turbines by 2050.[2]

In Alberta for example, hydrogen made via conversion of NG or petroleum, with carbon abatement could be used in place of natural gas-powered turbines to provide dispatchable power. Nunavut is reliant on diesel for electricity generation, and hydrogen, either imported in liquid form similar to current diesel supply or generated locally through electrolysis from non-emitting electricity, can help to reduce the carbon intensity of electricity in the region as well as improve local air quality. Other provinces that are reliant on carbon emitting fossil fuels for power generation and that could benefit from low carbon intensity hydrogen for power generation include Saskatchewan, Nova Scotia, Northwest Territories, and New Brunswick.

[1] CER. (2018). *Provincial and Territorial Energy Profiles – Canada.* Retrieved from https://www.cer-rec.gc.ca/nrg/ntgrtd/mrkt/nrgsstmprfls/cda-eng.html

[2] IEA technology perspecitves 2020

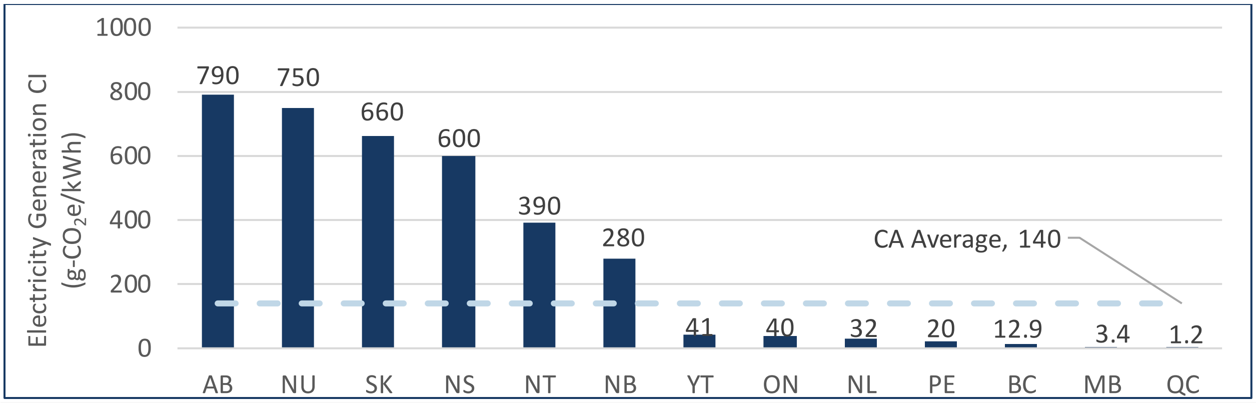


Figure 29 – Carbon Intensity of Provincial Electricity Generation Sources

Japan has been leading the way with vision for large scale power production, using imported hydrogen generating power through turbines. An 80 MW plant recently started operation, and their goal is to have a 1 GW plant in operation by 2030. Europe is also exploring the potential for power generation through both hydrogen turbines and turbines that run on a blend of hydrogen and natural gas. This technology will only be economically viable in Canada if large scale supply of low cost, low carbon intensity hydrogen is available.

Hydrogen as a utility scale energy storage vector can be an enabler for increased renewable penetration in the grid. Hydrogen can be produced via electrolysis from variable renewable power sources such as wind and solar, where power is not needed during off-peak times or the power producer can only secure low or even negative rates. Integrating hydrogen as energy storage can result in an improved business case. Hydrogen storage is a key factor in determining the feasibility of hydrogen use in the power sector, factors such as: geological location, volume stored and duration stored play a role in the cost of storing the hydrogen. The hydrogen can either be stored on site and used to produce electricity during peak demand times via a turbine or PEM fuel cell, or can be injected into the natural gas network as a means to decarbonize natural gas, or alternatively fed into dedicated hydrogen pipelines and used as a high-value transportation fuel or used as an industrial feedstock.

Hydrogen made from surplus renewable electricity via electrolysis and injected into the natural gas network is commonly referred to as power-to-gas (P2G). P2G provides a means of connecting the electric and natural gas energy systems; it can also be a key enabler of the transition from a fossil natural gas grid to a decarbonized one. Rising P2G interest in Europe has been driven by aggressive GHG reduction targets and an increasing supply of variable renewable electricity.

There are a few P2G projects in development in Canada. Canada's first P2G facility began operation in Ontario in July 2018 when a 2.5 MW PEM electrolyzer from Hydrogenics was installed under contract to the Ontario Independent Electricity System Operator (IESO). The electrolyzer provides grid energy demand response functions to the IESO and the hydrogen produced is injected into the Enbridge gas distribution network. There are several projects in development elsewhere in Canada, ranging in scale up to ~ 150 MW.

Hydrogen can also be integrated into renewable energy systems in remote and indigenous communities in Canada. Remote communities are defined as not being connected to North America's integrated electrical or natural gas grids, and they rely on costly and GHG emitting diesel generated electricity. Diesel generators are a source of criteria air contaminants, especially in small communities where air quality and health impacts may be an issue. Diesel can be displaced with either imported or locally produced hydrogen. The hydrogen can supply a microgrid system, either centralized, or distributed with co-generation of heat and power. Renewable energy sources can also be incorporated to produce hydrogen using electrolysis, reducing reliance on imported fuel.

HEAT FOR INDUSTRY & BUILDINGS

As a heating fuel, hydrogen is a cleaner-burning molecule that can be a substitute for combustion of fossil fuels in applications where high-grade heat is needed and where electric heating is not the best option. Hydrogen can be burned directly or blended with natural gas to reduce carbon emissions.

Heat for Industry

The industrial sector uses natural gas as a source of process heat, as a fuel for the generation of steam. When natural gas is combusted to generate heat, carbon emissions are released. It is very challenging to capture carbon emissions at the point of use outside of large industrial plants where there is the potential for capturing CO_2 from concentrated flue gas.

Canada's oil and gas sector is a significant contributor to GHG emissions, responsible for 26% of 2018 total emissions[1]. Low CI hydrogen can offer emissions reduction benefits in both upstream extraction (combusted as heat source) and downstream refining (used as a chemical feedstock, discussed in Hydrogen as a Feedstock section) processes. For example, in upstream operations, low CI hydrogen can replace natural gas combusted to produce steam for steam-assisted gravity drainage (SAGD) in-situ bitumen production. Hydrogen can lower the CI of conventional refined petroleum products in this way, offering a compliance pathway for the federal Clean Fuel Standard.

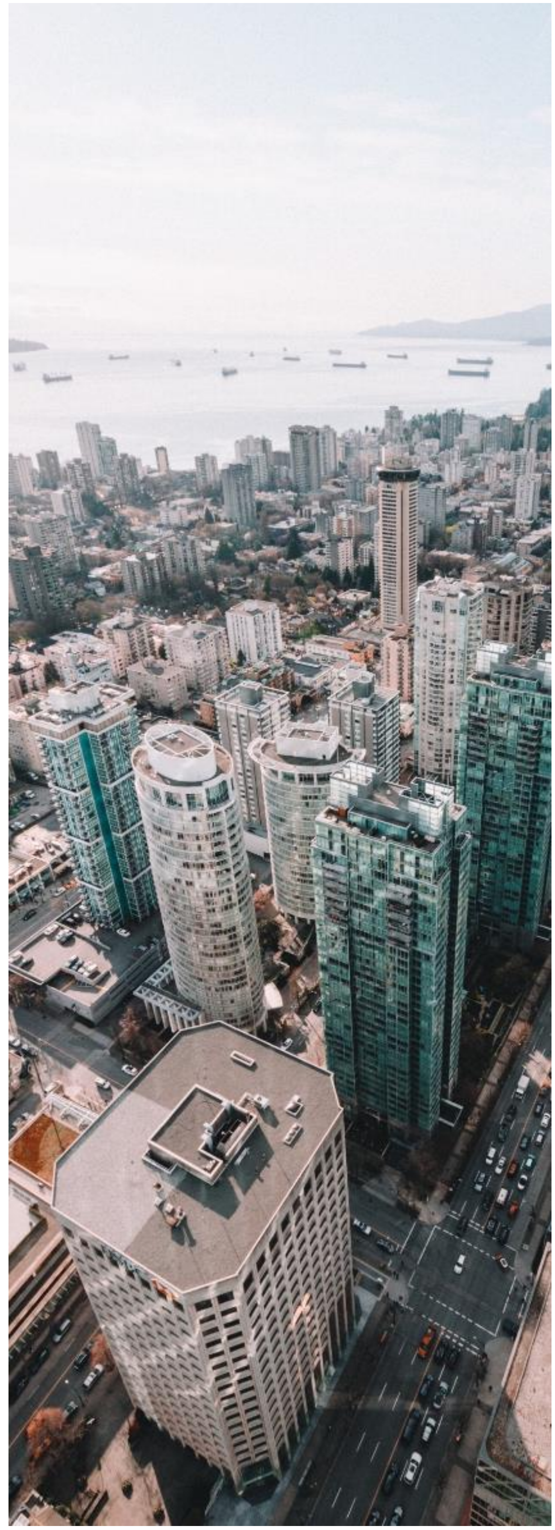
Other heavy industry in Canada that relies on large amounts of high-grade heat production includes cement manufacturing and the pulp and paper sector, and any industrial processes relying on steam production. These sectors can also reduce emissions by converting to blends of hydrogen and natural gas or pure hydrogen for heat production. A number of these sectors in Canada are investigating the opportunity to lower emissions through the use of hydrogen.

Integration of hydrogen generated via electrolysis directly at large industrial facilities can offer value-added benefits. For example, some of these sectors can leverage oxygen and / or waste heat produced in the electrolysis process. Oxygen can enhance combustion and enable a wider range of feedstocks to be used in cement kilns, and can be used in the pulp process in place of merchant oxygen. Industrial facilities typically have made investments in substations, which enables lower electricity rate tariffs and lower cost hydrogen. Hydrogen production for these industrial sectors can offer an opportunity to diversify business if excess hydrogen is produced and sold to generate a new revenue stream.

[1] Environment and Climate Change Canada. (2020). *National Inventory Report 1990 – 2018: Greenhouse Gas Sources and Sinks in Canada*. Retrieved from http://publications.gc.ca/collections/collection_2020/eccc/En81-4-1-2018-eng.pdf

Heat for Buildings

Hydrogen can also play a role in reducing emissions in heating applications in the built environment. Natural gas utilities are looking to decarbonize the natural gas grid by introducing both RNG and hydrogen as alternative low carbon chemical fuels. Canada's cold climate results in space heating accounting for >60% of energy use in the home, with water heating coming in second at >19%[1]. Natural gas is used for both in some provinces in Canada, and hydrogen is gaining increasing attention from utilities given it can be produced in high capacities compared to RNG which is in limited supply.



Several jurisdictions worldwide are piloting the blending of hydrogen into their natural gas systems as part of efforts to reduce emissions associated with home heating. Hydrogen blending has been started in Germany, Dunkerque in France (hydrogen blending of up to 20% in the GRHYD demonstration project), and Keele in the UK (hydrogen blending of up to 20% in the HyDeploy project at Keele University in 2019). The H21 Leeds City Gate project plans to convert Leeds into a city that is 100% fueled with hydrogen by 2028[2].

Technical Considerations

Implementing hydrogen blends into the natural gas network for use in both industrial applications and the built environment can impact pipelines, gas properties and safety systems, metering equipment, and end-use equipment and appliances. Many gas utilities around the world, including Canadian natural gas utilities in partnership with the Canadian Gas Association, are working to understand and overcome technical challenges around introducing hydrogen as a blend. Technical considerations include the following:

Material Compatibility - Embrittlement

Some metal pipes can degrade when exposed to hydrogen over long periods, particularly for the higher hydrogen concentrations and pressures that may occur when it is injected into high-pressure natural gas transmission systems. Embrittlement effects depend on the type of steel and on operating conditions and must be assessed on a case-by-case basis.

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[1] NRCan. (2017). *Residential Sector*. Retrieved from https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/handbook_res_00.cfm

[2] https://rienergia.staffettaonline.com/articolo/33278/Hydrogen+is+the+key+for+a+green+European+gas+network/Chatzimarkakis#:~:text=In%20the%20Hydrogen%20Roadmap%20Europe,7%25%20by%20volume%20until%202030.&text=By%202050%2C%20hydrogen%20could%20provide,by%20European%20households%20for%20heating.

Natural gas transmission pipelines in Canada are typically made of high-strength steels and operate at higher pressures compared to distribution networks, making them more susceptible to hydrogen embrittlement. The steels used for natural gas distribution systems are not generally susceptible to hydrogen-induced embrittlement under normal operation. Other metallic pipes including iron (ductile, cast and wrought) and copper are free from embrittlement concerns as are the polyethylene (PE), polyvinylchloride (PVC) and elastomeric materials more common in recently installed natural gas distribution networks.

Pipeline Standards and Policy

The amount of hydrogen presently allowed in natural gas infrastructure is limited by country-specific codes and standards. International standards currently range from allowing hydrogen injection values of 0.1% (vol.) in the United Kingdom (UK) and Belgium to 12% (vol.) in Holland, and many countries are actively working to update or introduce standards. Standards defining hydrogen quality and allocable contamination levels are also needed. Hydrogen injection and quality standards have yet to be established in Canada and elsewhere in North America, and development of these standards is a critical step in enabling hydrogen blending in Canadian Provinces and Territories. Inter-provincial coordination is required given that pipelines cross borders in some cases.

Gas Properties and Safety Systems

Hydrogen has a lower volumetric energy density than natural gas. At any pressure, the volumetric energy density of hydrogen is about one third that of natural gas. Therefore, hydrogen injected into natural gas networks will result in a mixture with less energy on a volume basis. Delivering the same amounts of energy to end users would therefore necessitate increased volumetric flows. To accommodate higher flows as blend ratios increase, pipelines and distribution networks will need to increase system pressure and increase the density of the gas mixture flowing through the pipeline. Pipelines' pressure ratings may therefore constrain the amount of hydrogen injection into existing natural gas infrastructure.

Gas properties such as explosivity, flammability, ignition, dispersion, and ability to add odorants for leak detection are all different with hydrogen blends versus pure natural gas systems. Modeling and testing have been initiative to understand impacts and identify where safety systems need to be updated to accommodate blends. General findings indicate that blends of up to 20% hydrogen do not require modifications to safety systems. Further analysis and testing in the Canadian context is needed, and results will likely vary based on local natural gas networks.

Gas Metering

Hydrogen blends can influence the accuracy of existing gas meters. Studies have shown that gas meters would not need to be tuned for low hydrogen blend levels.[1] However, further validation testing is needed and new meters may be required for higher blending levels.

Appliances and End-Use Equipment

Appliances must be able to operate safely and at equivalent performance levels in order to introduce hydrogen blends into the built environment without requiring retrofit. Testing in Canada and other regions such as the UK and Australia implementing hydrogen blending shows that ratios up to 30% do not impact appliances[2] such as natural gas stoves, furnaces and fireplaces. Beyond those levels, modifications such as new burners may be required. Industrial equipment such as turbines, compressors, and boilers can also be impacted by hydrogen blends, as can some older CNG tank materials. For example, hydrogen

[1] Zen Clean Energy Solutions (2019). British Columbia Hydrogen Study.

[2] ATCO (2020). Retrieved from: https://www.atco.com/en-ca/for-home/natural-gas/hydrogen.html

produces more water vapour than natural gas for the same amount of energy delivered when combusted, which can lead to more condensate in boilers. In compressors designed to be leak tight for natural gas, hydrogen leakage can occur. Hydrogen also produces lower radiant heat than natural gas, which can impact industrial heating applications. Introduction of hydrogen blends with industrial customers will require significant study and pilot testing and must be evaluated on a case by case basis.

Canadian Context

While the allowable concentrations of hydrogen in natural gas pipeline networks remains an area of active research and evaluation, recent studies have concluded that transmission pipelines can accept hydrogen concentrations of between 5% and 20% (by volume) with minimal risk.[1] Hydrogen blending limits can be overcome by localizing portions of the natural gas infrastructure or end customers who can tolerate higher hydrogen concentrations, with the potential to have 100% dedicated pipelines in some regions of Canada.

Enbridge Gas in Ontario is one of the first utilities to propose a demonstration to blend hydrogen into the natural gas network, and BC and Quebec have enacted provincial policies that have stimulated R&D and development of pilot projects for blending hydrogen into the NG grid. ATCO in Alberta has announced a blending project in Fort Saskatchewan, Alberta where up to 5% hydrogen by volume will be blended in a section of the residential gas distribution network starting in 2021. Stakeholder engagement identified up to nine hydrogen projects currently being developed by utilities in Canada. However, hydrogen injection standards have yet to be established Canada and this is a challenge for broader rollout. Technical specifications and interface requirements for hydrogen blending will need to be established and pilot projects will support development of these standards.

Ultimately, utilities recognize that in a net-zero energy system of the future, distributed combustion of fossil fuels must stop, and this is a threat to their business. Renewable natural gas and landfill gas can displace natural gas, but supply is limited. Hydrogen produced at scale can be the long-term answer for Canada's natural gas utilities to stay relevant in a carbon-constrained future. Hydrogen provides an opportunity to utilize Canada's valuable natural gas pipeline infrastructure investments to deliver energy intense low carbon fuel for high-grade heating applications where electric heating is not the best option. In regions with heat pumps, hydrogen can also be used to provide heat during winter season with hybrid heating systems.

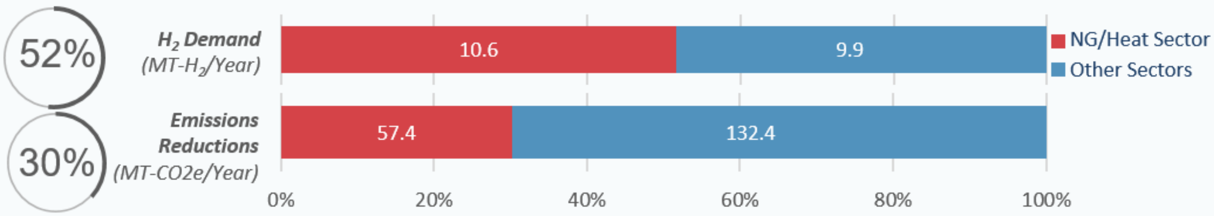
Blending low carbon intensity hydrogen into Canada's natural gas networks, for use in both industry and the built environment, provides the largest potential demand opportunity for hydrogen. However, it is also the most economically challenging given today's low-cost natural gas commodity prices in Canada, and when combusted, there is no efficiency improvement as there is in fuel cell applications. One benefit of hydrogen use in the natural gas network is that the hydrogen can be produced in bulk quantities close to injection points into the natural gas network, and does not have to be compressed to high pressures.

[1] Yoo Y., et al., (2017). *Review of Hydrogen Tolerance of Key Power-to-Gas (P2G) Components and Systems in Canada*. NRC-EME-55882. Retrieved from https://nrc-publications.canada.ca/eng/view/fulltext/?id=94a036f4-0e60-4433-add5-9479350f74de

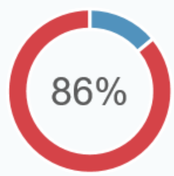
STAKEHOLDER INPUT: HEAT FOR INDUSTRY & BUILDINGS

Opportunities

Decarbonized NG Networks & Heat Contribution in 2050 Transformative Scenario



- *By 2050, H_2 could make 86% by volume on average of the fuel in the gas network*



- *Blending of H_2 in the gas network at a low level is technically feasible today*

Challenges

Safety and reliability must be successfully proven in pilot stage before technology can be fully adopted

Impact to gas properties and equipment limitations complicate the direct substitution of H_2 into industrial processes

Natural gas is currently low cost in many parts of Canada, and while H_2 can compete with RNG the higher cost is a challenge particularly for industry

Lack of standards and research into defining blending limits in Canada

Findings

- *Define plan & approach to safely increase H_2 blending percentages, include regulators, AHJs and international organizations and standards bodies*
- *Develop and implement a federal Clean Fuel Standard to mandate the steady ratcheting down of fuel carbon intensities through upstream, process & end-use improvements*
- *Develop suite of public tools (e.g. TCO model) & resources to help end-users evaluate H_2 options*
- *Expand pilots for H_2-integrated mini-grids at industrial sites and along strategic transportation corridors to pool sources of supply and demand*
- *Increase research and development into end-use equipment and applications including boilers, safety and monitoring equipment, and embrittlement issues*
- *Increase awareness around hydrogen as option for low carbon heating, e.g. with municipalities*

FEEDSTOCK FOR INDUSTRY

The largest current use for hydrogen, both in Canada and globally, is as a feedstock in emission-intensive industrial sectors. The top four single uses of hydrogen today (in both pure and mixed forms) are: oil refining (33%), ammonia production (27%), methanol production (11%) and steel production via the direct reduction of iron ore (3%).[1] Most of this feedstock hydrogen is currently produced via SMR of natural gas without CCUS. Low CI hydrogen presents a major opportunity for these industries to lower the carbon intensity of their products and overall emissions.

Carbon pricing and regulations like the Clean Fuel Standard are expected to drive demand for clean hydrogen in these industries. However, most industrial applications are capital intensive and slow to change so large-scale demonstration could take up 10 years to materialize. These demonstration projects will also depend on significant financial support, policy support, technology enhancements, and energy market reform. The future competitiveness of hydrogen use in industrial applications will depend on the development of low-cost, low CI hydrogen production pathways such as electrolysis and SMR+CCUS.

Oil and Gas Industry

Hydrotreatment and hydrocracking are the two main uses for hydrogen in the oil and gas sector. In hydrotreatment, impurities such as sulphur are removed from the raw fuel stocks (e.g. crude oil and bitumen) to lower the sulphur content which causes air pollution when burned. Hydrocracking is a way to break up the heavy residual oils into higher-value products such as kerosene, gasoline, and diesel. For bitumen processing, around 10kg of hydrogen is need for each tonne of bitumen produced. For biofuels made from animal fats or vegetable oils, 38kg of hydrogen is required.[2]

The IEA projects a 7% increase in demand for hydrogen in the oil and gas sector under existing policies[3]. Tighter pollution regulations will increase demand for hydrogen as a feedstock but will also result in an overall decrease in fossil fuel demand. In the longer term the demand for hydrogen in this sector will also be highly dependent on the use of oil and gas as end-use fuels in a decarbonizing world.

The majority of hydrogen required for refining is produced on-site either from dedicated production facilities or as a by-product. Because of this integration of hydrogen production within refining facilities, production is primarily supplied by natural gas reforming methods or naphtha reforming. On-site hydrogen production is unable to address the hydrogen demand of larger refineries and these facilities

[1] IEA. 2019. The Future of Hydrogen: Seizing Today's Opportunities.

[2] Ibid.

[3] Ibid.

will typically rely on merchant gas suppliers. This option is particularly important for densely industrialized areas where shared hydrogen pipelines can be built to serve multiple customers.

The most significant opportunity to reduce emissions associated with hydrogen in midstream oil and gas is retrofitting existing conversion technology with carbon capture and storage. Hydrogen use is responsible for about 20% of global emission from refining (~230MtCO_2e/yr), according to the IEA. The Alberta Carbon Trunk Line project is an example of an operating CCUS plant which has been successfully implemented and is currently capturing around 4.5 tonnes CO_2/day (See Figure 30).[1]

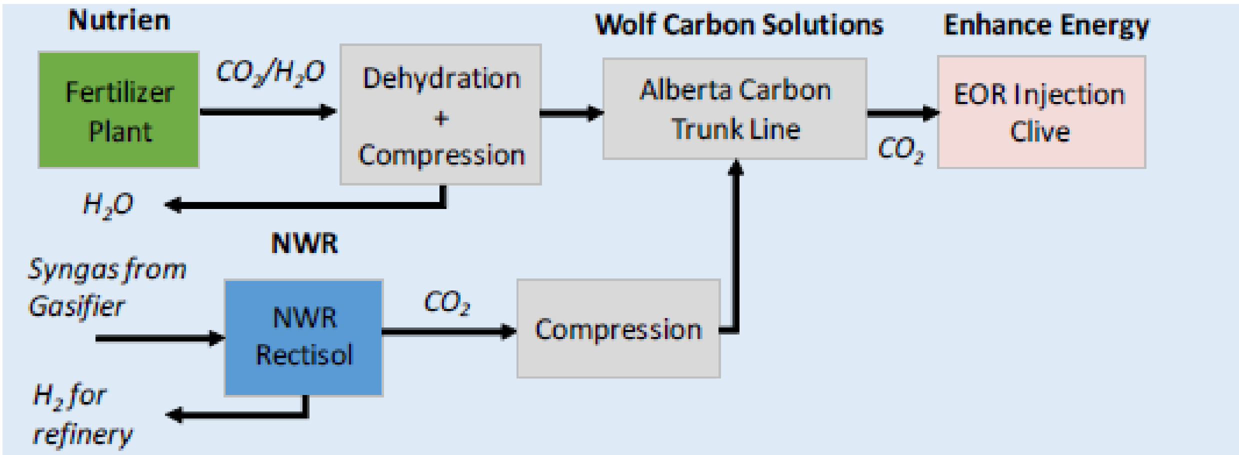


Figure 30 – The Alberta Carbon Trunk Line project[1]

There is also some potential to use electrolytic hydrogen in fuel upgrading, although the costs and carbon intensity of this pathway would depend heavily on the electricity source and the fuel end-use. Hydrogen can also replace natural gas in upstream operations, particularly in the oil sands where heat generation for extraction is a large source of emissions. In the Canadian context, this has the special potential to help decarbonize a portion of oil sands operations in Alberta.

Synthetic Fuels

Availability of low cost, low CI hydrogen has the potential to create new industry in Canada as well. This includes synthetic liquid fuel production, an innovative process combining non-emitting hydrogen and carbon captured from the air to produce carbon-neutral, energy dense liquid fuels that are well suited to applications such as aviation and large marine vessels.

Chemicals and Ammonia Production

Global demand for hydrogen in the chemical industry is mainly split between ammonia production at 31Mt H_2/yr and methanol production at 12MtH_2/yr. Other minor applications, such as plastics, solvents, and explosives account for approximately 3MtH_2/yr[2]. Ammonia (NH_3)is the main ingredient in nitrogen fertilizers such as urea and ammonium nitrate and is produced at large scale in Canada. Methanol (CH_3OH), also known as methyl alcohol is used for a variety of industrial processes and as a precursor to other chemicals such as formaldehyde, acetic acid, and many specialized chemicals.

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

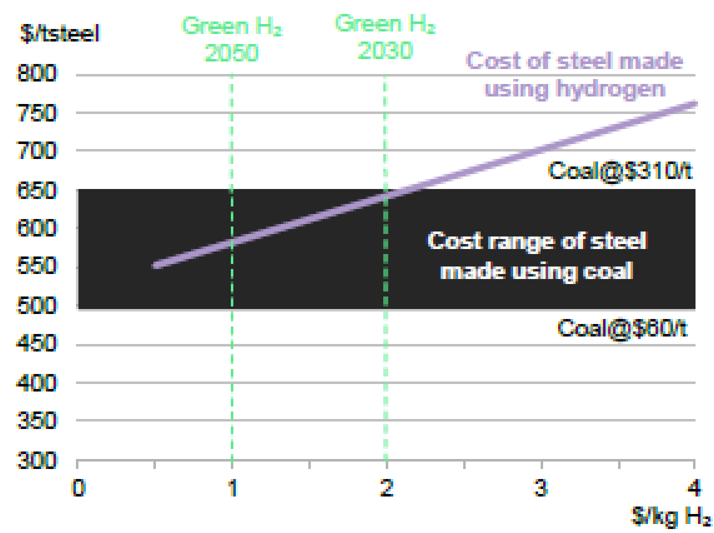
[2] IEA. 2019. The Future of Hydrogen: Seizing Today's Opportunities.

Demand for hydrogen in the chemicals industry is expected to grow from 46 Mt/yr today to 57 Mt/yr by 2030, driven by diverse industrial applications. The CO_2 emissions generated globally from ammonia and methanol production are around 630 Mt-CO_2/yr, with hydrogen production accounting for a large percentage. As with oil refining, the vast majority of this hydrogen (65% for ammonia and 30% for methanol) is produced from fossil fuel sources, with the rest coming from coal and by-product industrial processes. Adding CCUS to the hydrogen production pathways or using electrolytic hydrogen for these products would significantly decrease their overall carbon intensities.

Iron and Steel Production

The demand hydrogen in iron and steel production is the fourth largest after oil and gas and chemicals at 4MtH_2/yr.[1] As with the oil and chemical sectors, the hydrogen is used both as a feedstock and as a process fuel and is mostly derived from fossil fuel sources without CCUS.

Hydrogen is used in the direct reduction of iron-electric arc furnace (DRI-EAF) method of steel production which accounts for 7% of primary (i.e. non-recycled) steel production globally. By 2030 the hydrogen requirements for the DRI-EAF route could more than double, according to the IEA. By 2050 this method could be main process for primary steel production and lead to a 15X increase in hydrogen demand.



Source: BloombergNEF. Note: levelized costs do not include carbon prices.

Figure 31 – Levelized Cost of Steel Production

Today, steel production is one of the world's largest emitters of CO_2, accounting for about 7 to 9 per cent of global CO_2 emissions from the global use of fossil fuels.[2] There are several ways the CO_2 emissions from steel production can be avoided or reduced. Most are still experimental or in the pilot phase but could substantially increase demand for hydrogen if implemented at scale. DRI-EAF using low-CI hydrogen as a reducing agent instead of coal, avoids the carbon emissions in the process. Currently pilot plants using this approach can run on up to 30 percent supplemental hydrogen, but higher percentages are technically feasible. Several ongoing global projects are currently testing the use of hydrogen for steelmaking. HYBRIT, a recently formed Swedish joint venture by SSAB, LKAB, and Vattenfall, is demonstrating low-carbon steelmaking using DRI with hydrogen from water electrolysis.[3]

[1] Ibid.

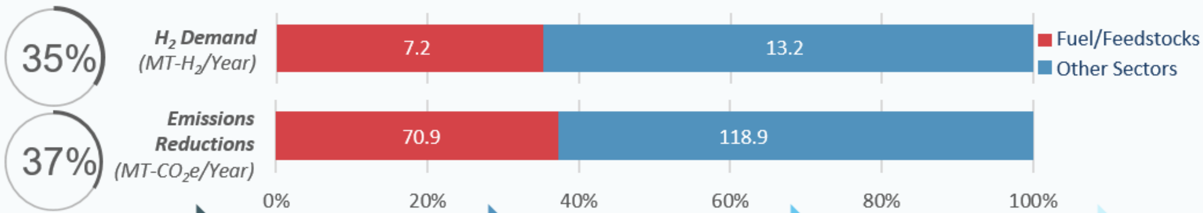
[2] World Steel Association. (2019a). Steel Facts. Retrieved from https://www.worldsteel.org/about-steel/steel-facts.html

[3] US Fuel Cell & Hydrogen Energy Association. *Road Map to a US Hydrogen Economy.* 2019.

STAKEHOLDER INPUT: INDUSTRIAL FEEDSTOCK

Opportunities

Fuel Production & Feedstocks Contribution in 2050 Transformative Scenario



Canada has electricity, fossil fuel reserves, CCUS potential, and a specialized workforce that can pivot into a new Low Carbon Fuel industry

The petroleum/ petrochem industry is already the largest user of H_2 and up-/mid-stream demand could grow substantially

The proposed federal Clean Fuel Standard has potential to drive significant GHG reductions and spur technology development for export

H_2 can be used as an energy source and feedstock in steel and ammonia production, displacing significant amounts of coal and NG

Challenges

Fuel production and industrial processes are optimized for scale and continuous operations; pilot scale projects can be less effective

Process, equipment, and safety implications of hydrogen blending into essential feedstocks needs to be understood and derisked

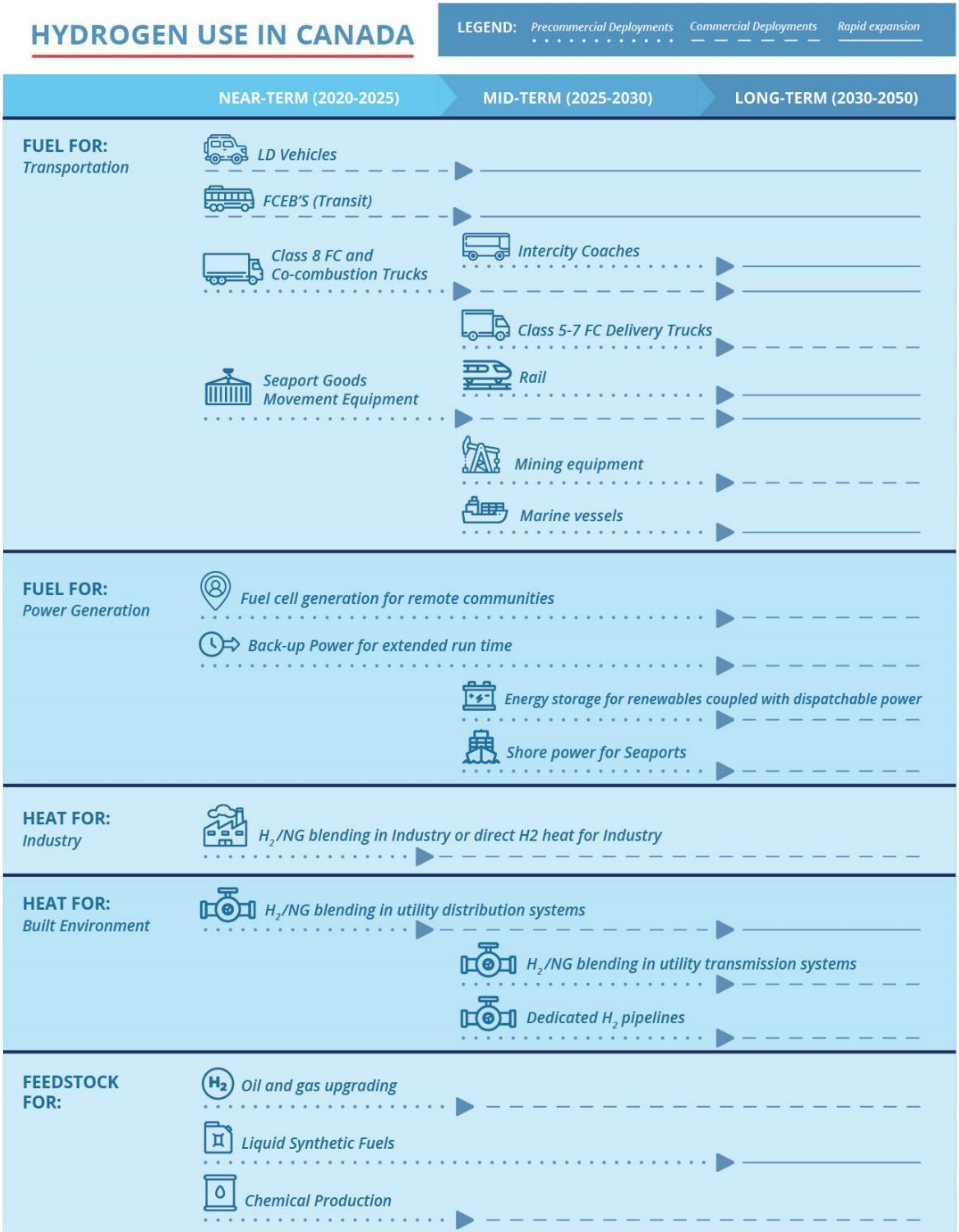
Predictable, long-term demand for LCF and industrial products is critical before industry can invest in these projects

CO_2 storage requirements will be significant in long term transition of sector

Findings

- *Ensure Canada's path to 2050 includes hydrogen and low carbon fuels as key components*
- *Implement CFS and recognize hydrogen role in pathways definitions*
- *Explore synergies between hydrogen and other bio-based renewable fuels, such as liquid biofuels, methanol, synthetic fuels, biogas and renewable natural gas (RNG)*
- *Ensure policy frameworks provide long term certainty that encourages private sector investment and innovation in actions across the hydrogen value chain, from production to end-use*
- *Begin developing international/overseas markets for exports of LCFs, steel and fertilizer—Canada should actively promote the low carbon intensity of its value-added products internationally*
- *Collaborate across upstream & down-stream industries to ensure supply & demand are matched*
- *Use of low-carbon products in domestic infrastructure could be encouraged to create a local market demand of low-carbon product and de-risk investment*

HYDROGEN USE IN CANADA



5. Putting it All Together: Canada's Hydrogen Opportunity

Hydrogen presents real pan-Canadian opportunities. Each region of the country can utilize their unique resources to produce and deploy hydrogen domestically as well as to supply a growing export market. According to modelling undertaken for this Strategy, hydrogen made through Canada's clean, abundant and diverse pathways has the potential to deliver up to 30% of end-use energy by 2050, while abating up to 190 MT-CO_2e of emissions if deployed in a transformative scenario, across all sectors of the economy from transportation, to power generation, to heating, to industrial applications. Implementing the hydrogen strategy can spark early economic recovery, and by 2050 build a $50B domestic hydrogen sector generating more than 350,000 high paying jobs from coast to coast.

HYDROGEN AS PART OF AN INTEGRATED ENERGY SYSTEM IN CANADA

Canada's hydrogen opportunity will be most optimally realized as regions develop the full hydrogen value chain tailored to local energy profiles and feedstocks for production, with end-uses prioritized to maximize decarbonization and economic benefits in operations specific to the region. Hydrogen's versatility as a fuel provides the ability to fundamentally transform Canada's energy landscape. Like electricity, hydrogen can serve multiple roles within the energy system from the upstream production of liquid fuels through to small-scale consumption in end-use appliances and equipment. However, unlike electricity, hydrogen can be shipped and stored in bulk quantities over extended periods. This allows it to act as a critical energy buffer between unpredictable production and end-use demand fluctuations. This temporal and geographic flexibility provides valuable redundancy and resiliency to the energy system and complements existing carriers such as electricity, natural gas, and liquid fuels. Hydrogen's ability to work as part of an integrated energy system will make it a critical part of the large-scale energy system transformation.

In the same way, road networks, railways and airlines work together to move goods from coast to coast, hydrogen, electricity, and fuel distribution networks can complement one another's strengths to make the whole system much stronger and more efficient (see, Figure 33). This is particularly important for two reasons. The first is the need to electrify as much of the economy as is technically and economically feasible. This includes most light duty forms of transportation, low-grade heat where economic (e.g. buildings), and some industrial processes. Electrification provides the most direct and effective way to decarbonize many sectors of the economy as it decouples energy use from GHG emissions at the point of use. This reduces emissions by improving overall efficiency of the process and it helps make the remaining emissions easier to manage by concentrating them at the point of production. As the electrical grid becomes cleaner, the GHG emissions for all electrified end-uses will come down. Hydrogen can play a role in supporting electrification by acting as an energy carrier for hard to electrify sectors such as high-grade heat, heavy-duty transport, and many industrial processes.

The second way hydrogen can complement wide-spread electrification is by acting as a storage medium and as an interface between the gas and electricity grids. While electricity can be stored in batteries and other chemical forms for days or weeks, the long-term, large-scale, and geographically flexible storage of electricity remains technically challenging and expensive. Hydrogen can be produced and stored when and where it is most convenient, shipped by road, rail, or water, or injected into the natural gas network for later use or reconversion back into electricity. This flexibility is critical as variable renewable energy sources make up an increasing percentage of the electricity generation mix. By providing a flexible source of demand that can ramp up and down as required throughout the day, electrolyzers can convert excess electricity from renewables into hydrogen that can used at later time. Reversing the process, fuels cells can convert hydrogen from storage back into electricity during periods of low sun and wind generation.

While *Section 3: What is Hydrogen?* and *Section 4: Canada's Production & Distribution Opportunities* discussed production pathways and end-uses independently, this section explores how hydrogen might be rolled out from a timing and regionality perspective as part of integrated energy systems. By looking at the overall projected demand for hydrogen by end-use application, possible scenarios are presented to show the range of both decarbonization and economic growth potential that hydrogen could offer in an Incremental versus Transformative Scenario.

Decisions about where hydrogen can most effectively be deployed, as the energy system transforms, will be influenced by economics, carbon abatement potential, function and performance of hydrogen in end-use applications relative to other options. With all low carbon energy vectors still undergoing rapid technology advancement and cost reduction, it is impossible to predict definitive scenarios. The cases presented should therefore not be viewed as forecasts or predictions, but rather as a set of two potential bookend scenarios. The Transformative Scenario is meant to represent the potential size of Canada's hydrogen opportunity if bold action is taken in the near term, whereas the Incremental scenario is based on a business as usual approach with lighter policy measures and a slower start to adoption.

Ultimately the timing and regionality of hydrogen's adoption in Canada is in the nascent stages, and all stakeholders can help influence what path we set ourselves on through strong leadership and initiative, and through a collaborative approach to development of the sector.

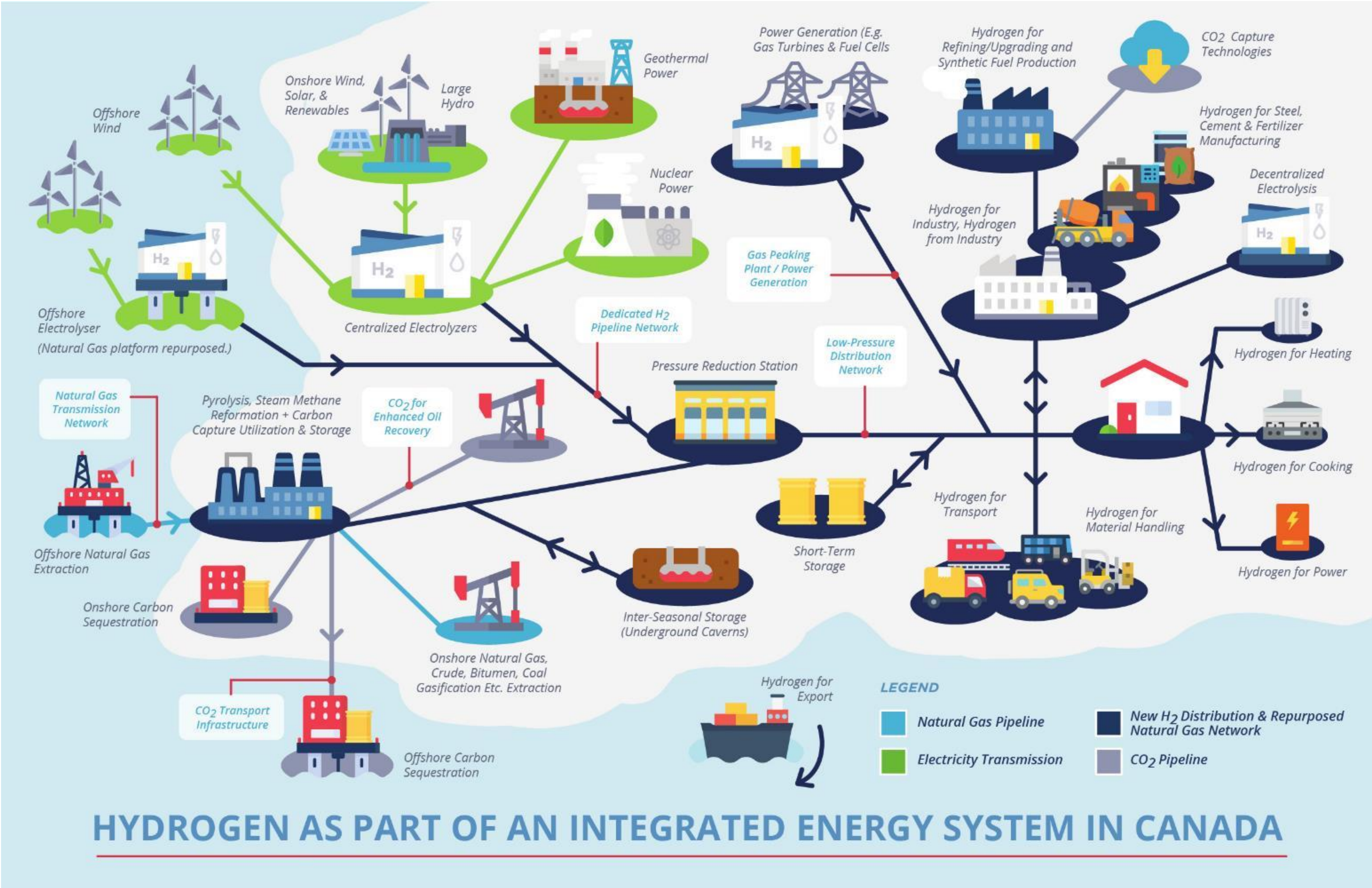


Figure 33 – Hydrogen as Part of an Integrated Energy System in Canada

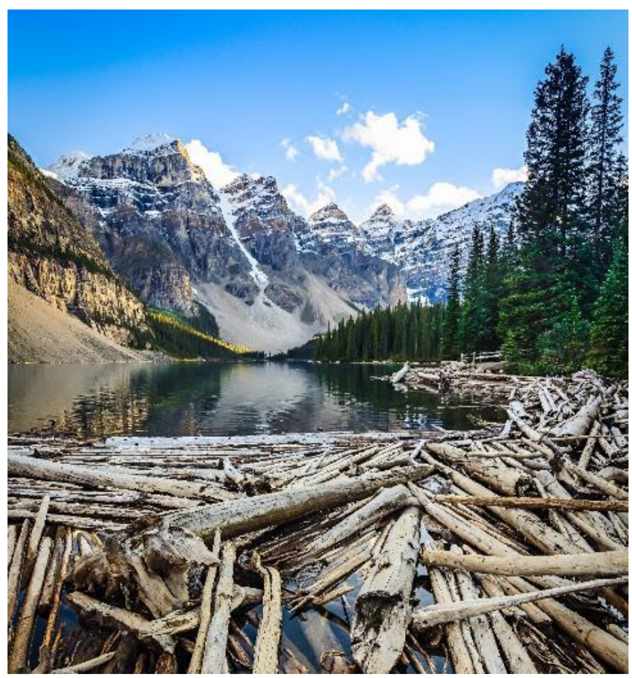
ROLLOUT TIMING & REGIONALITY

Timing

Implementation in the Near-Term (2020 – 2025)

Hydrogen use in the near-term will be dominated by relatively mature market applications at or near the commercial market Technology Readiness Level (TRL) including FCEVs and FCEBs for transit operation. Pre-commercial applications such as heavy-duty trucks, seaport goods movement equipment, power generation, heat for industry and the built environment, and industrial feedstock applications will be introduced as pilot projects in regional HUBs. These regional HUBs will be strongly influenced by:

- ZEV mandates for passenger vehicles such as the existing legislation in Quebec and British Columbia;
- Carbon pricing and regulations like the Clean Fuel Standard driving low carbon hydrogen production for industrial applications including conversion of CO_2 into renewable methane at ethanol plants and biogas-to-RNG upgraders, production of renewable diesel and upgrading of transportation fuel products;
- Existing hydrogen generation, distribution and dispensing infrastructure that can be leveraged;
- Pilot results, codes, stands and regulatory approvals for blending hydrogen and natural gas to decarbonize the utility distribution system;
- Renewable gas targets for natural gas utilities where hydrogen qualifies as a pathway.

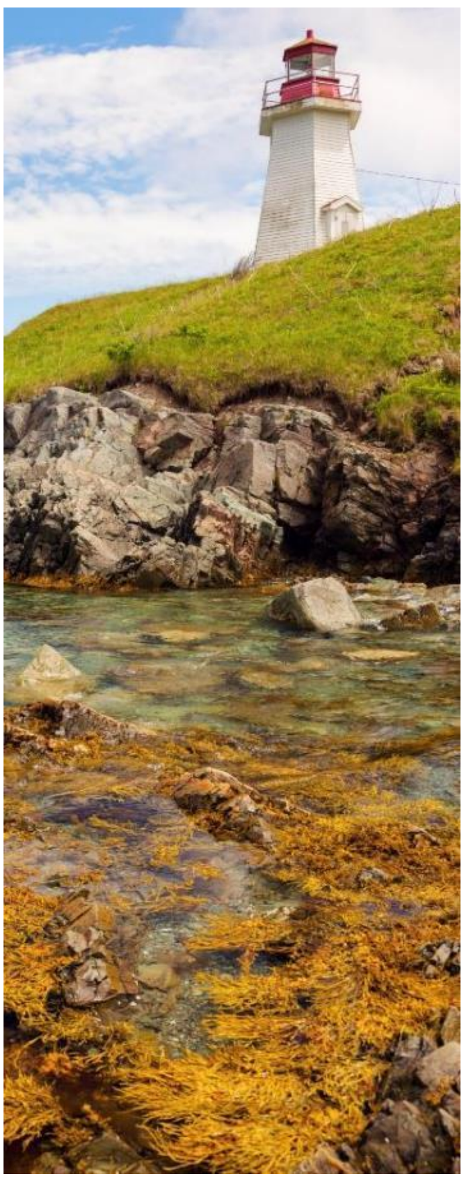


Local hydrogen production must be built concurrently with demand through end-use deployments within sub-regional HUBs in each province or region. Growing supply and demand in HUBs will bring down the cost of low-carbon intensity hydrogen pathways and spur the development of new sources of demand in several important ways. First, hydrogen production facilities can be built at scale capturing cost savings and using the diversity and longevity of demand to lower financing costs and improve project return on investment. Second, transmission and distribution costs are minimized as both supply and demand are co-located or in the same area. Finally, as many of Canada's industrial HUBs are already established users of hydrogen for refining, ammonia, and methanol, new low-volume buyers of hydrogen can scale their demand according to the timing of their needs.

There are several high potential areas to build out HUBs that have the potential to create self sustaining hydrogen economies more quickly, taking a holistic, energy system approach. These deployment HUBS bring supply and demand together but also bringing all key players together, to develop and implement regional plans that build on specific strengths and opportunities, while identifying the unique barriers and challenges, thereby improving the overall business case of each project. Specific projects and areas for early adoption include:

- The Alberta Industrial Heartland, near Edmonton, has several advantages to become one of the first hydrogen HUBs in Canada. It has access to plentiful natural gas and CCUS sites, an existing hydrogen pipeline and two CO_2 pipelines. This existing infrastructure would reduce the cost of new low-carbon hydrogen projects. It is also adjacent to the City of Edmonton, which has large potential demand for hydrogen in the transportation, space heating and electricity generation sectors.

- Coastal ports in BC, Ontario, Quebec, Manitoba and the Atlantic region are also high potential sites for hydrogen HUBs. Ports are concentrated centres of energy consumption for transportation and could also serve as the exit points for exported hydrogen.
- The transportation corridor between Montreal and Detroit is another high potential area as it connects demand for transportation with industrial and manufacturing centres. A regional hydrogen HUB along this corridor would allow supply and demand from multiple sources to be aggregated unlocking massive economies of scope and scale.
- Ethanol plants and landfill gas/biogas-to-RNG upgraders in provinces with access to hydroelectricity, such as B.C., Manitoba and Quebec, are potential sites for electrolyzers that can produce green hydrogen that can be combined with available CO_2 and produce RNG, and methanol.



Implementation in the Mid-Term (2025 – 2030)

In the mid-term, industrial clusters will serve as the starting points for expanding hydrogen use into other sectors and regions. For example, the production facilities and infrastructure built for industrial applications can be extended to supply hydrogen for residential heating, hydrogen refuelling stations or dispatchable power generation. Similarly, industrial clusters can be connected along corridors such as highways, railways, and pipelines to create larger and larger integrated networks.

As the technology matures and the full suite of end-use applications is at or near commercial TRL levels, hydrogen use in the mid-term will be focused on applications that provide the best value proposition relative to other zero-emission technologies. For example, FCEVs and FCEBs will enter the rapid expansion phase as the market for fuel cell and battery technology becomes more defined, for example where factors like range, gradeability, and fast fill times offer advantages for FCEBs.

Class 8 heavy-duty trucking in corridors that require heavy payloads and seaport goods movement equipment in regions with regulated airsheds will move into the commercial phase of deployment. New, larger scale hydrogen production in the mid-term will allow direct H_2 or H_2/NG blending for industry, the built environment and as a feedstock for chemical production and hydrocarbon upgrading to be commercialized in regional HUBs during this period.

Pre-commercial applications like Class 5-7 delivery trucks operating in urban zero-emission zones, passenger and freight rail where electrification of the line is prohibitively expensive, mining vehicles and marine vessels that require the energy density advantages that hydrogen offers, will all be piloted during this period.

Implementation in the Long-Term (2030 – 2050)

In the long-term, it is anticipated that with advances in battery and charging technology, there will be a more defined division between battery and fuel cell utilization in Canada. This is expected to result in the higher power demand applications (utility biased) predisposed toward hydrogen energy storage and the lower power demand applications (efficiency biased) using batteries for energy storage. New transportation applications will move into the commercial and rapid expansion phases during this period.

In parallel, economies of scale in the production of hydrogen and regulatory pressures could lead to accelerating growth in the blending of hydrogen in the natural gas distribution system while the Clean Fuel Standard will drive synthetic liquid fuel production for both the domestic and export markets. Power generation applications will continue to grow, albeit incrementally, lagging the transportation and industrial markets.

Regionality

Provincial regulations and policies, resource availability, geography and climate, infrastructure, and technology maturity will shape the timing and scale for hydrogen deployment across Canada. Figure 34 is a consolidated view of the most promising production and end-use applications in each Province in the mid-term. In the long-term, it is expected that most end-uses will be deployed across Canada.

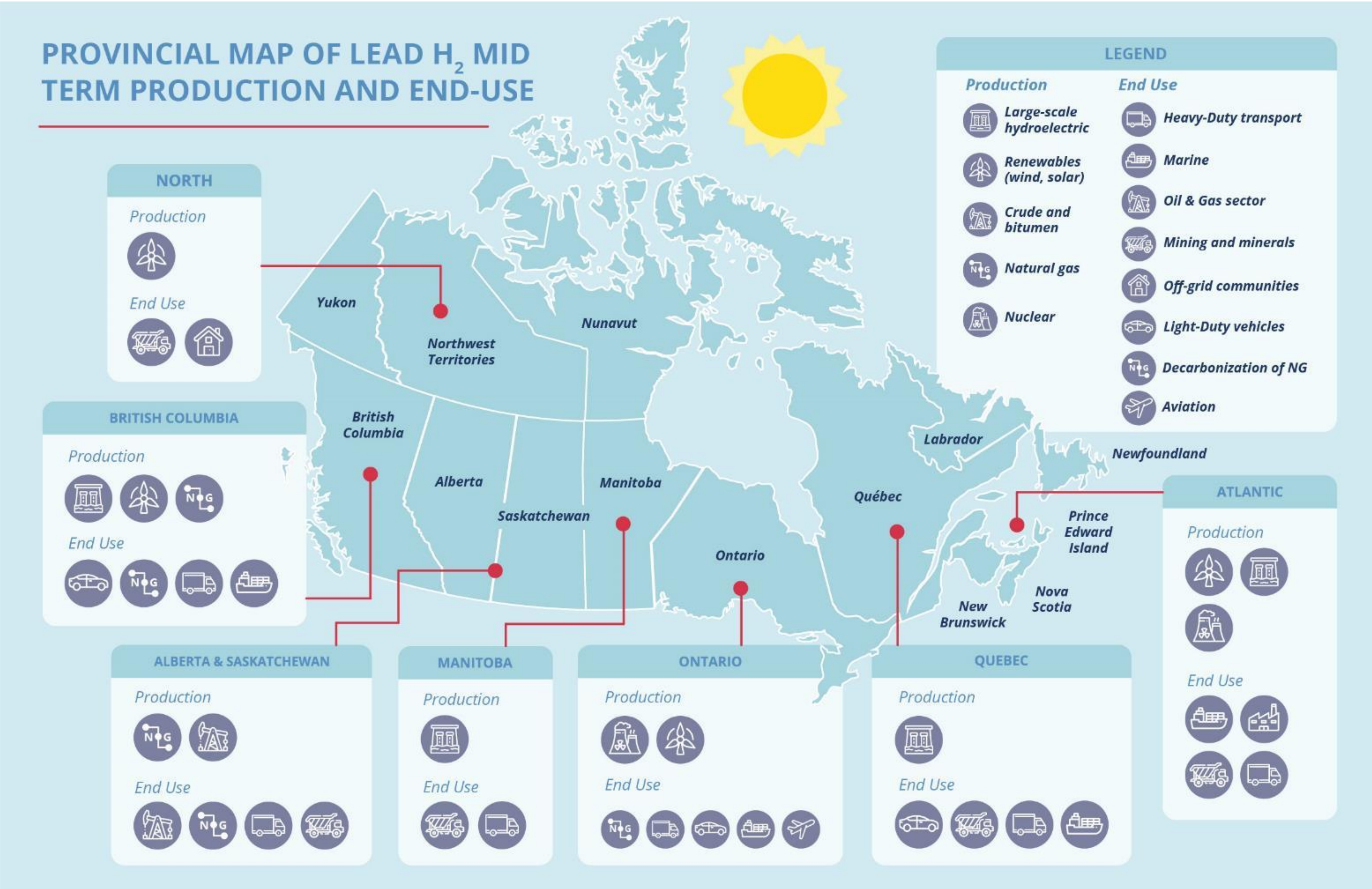


Figure 34 – Lead Mid Term Regional Production and End-Use Adoption Potential of Hydrogen Across Canada

QUANTIFYING THE OPPORTUNITY

The total primary energy supply in 2050 is expected to be delivered through several low carbon energy carriers including electrification, biofuels, hydrogen, and fossil fuels with carbon abatement. Modelling has been done to estimate potential adoption rates of hydrogen under 'Incremental' and 'Transformative' scenarios. The 'Transformative' scenario provides a directional estimate of the market size for hydrogen in key applications in achieving net-zero by 2050. In this 'Transformative' scenario, hydrogen could make up 31% of delivered energy, i.e., secondary energy use, in Canada by 2050 assuming economic and population growth are offset by efficiency improvements resulting in consistent energy consumption over time. This represents just over 20Mt of hydrogen demand per year in 2050, which is close to 3000 PJ of delivered energy. A more conservative Incremental scenario based on less aggressive policy assumptions shows opportunity for 8.3 Mt of hydrogen demand per year by 2050. Note that the Incremental scenario is not consistent with meeting net-zero targets in 2050. The demand by projected end-use application is shown in Figure 35.

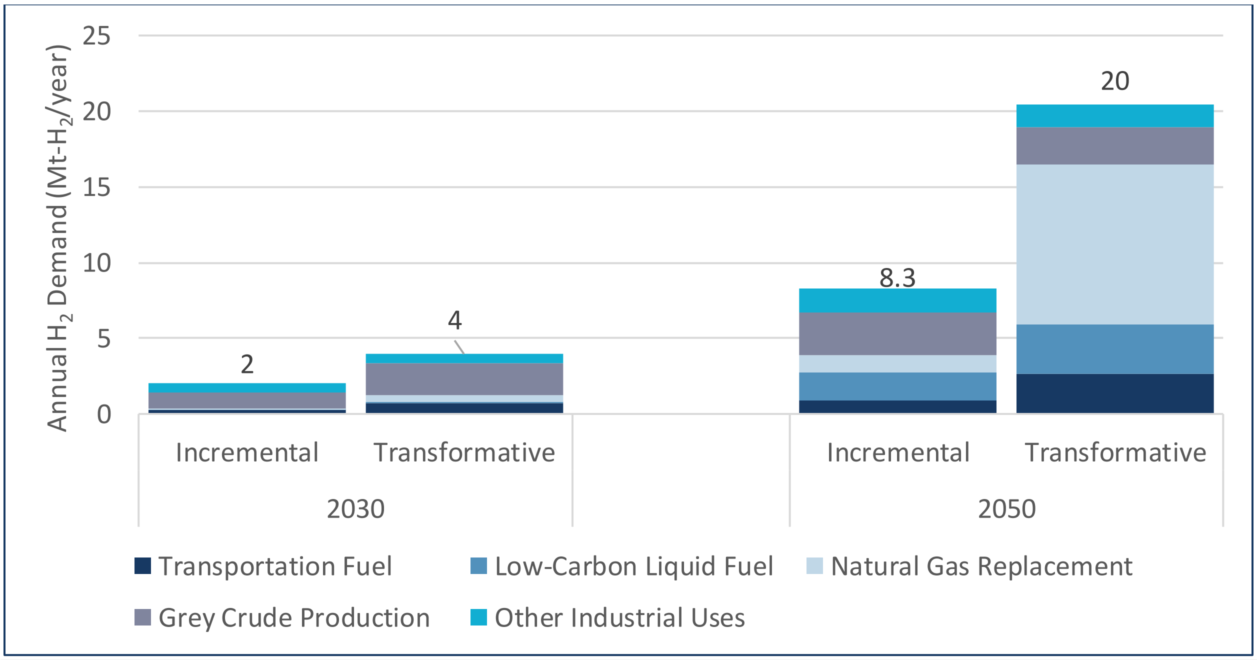
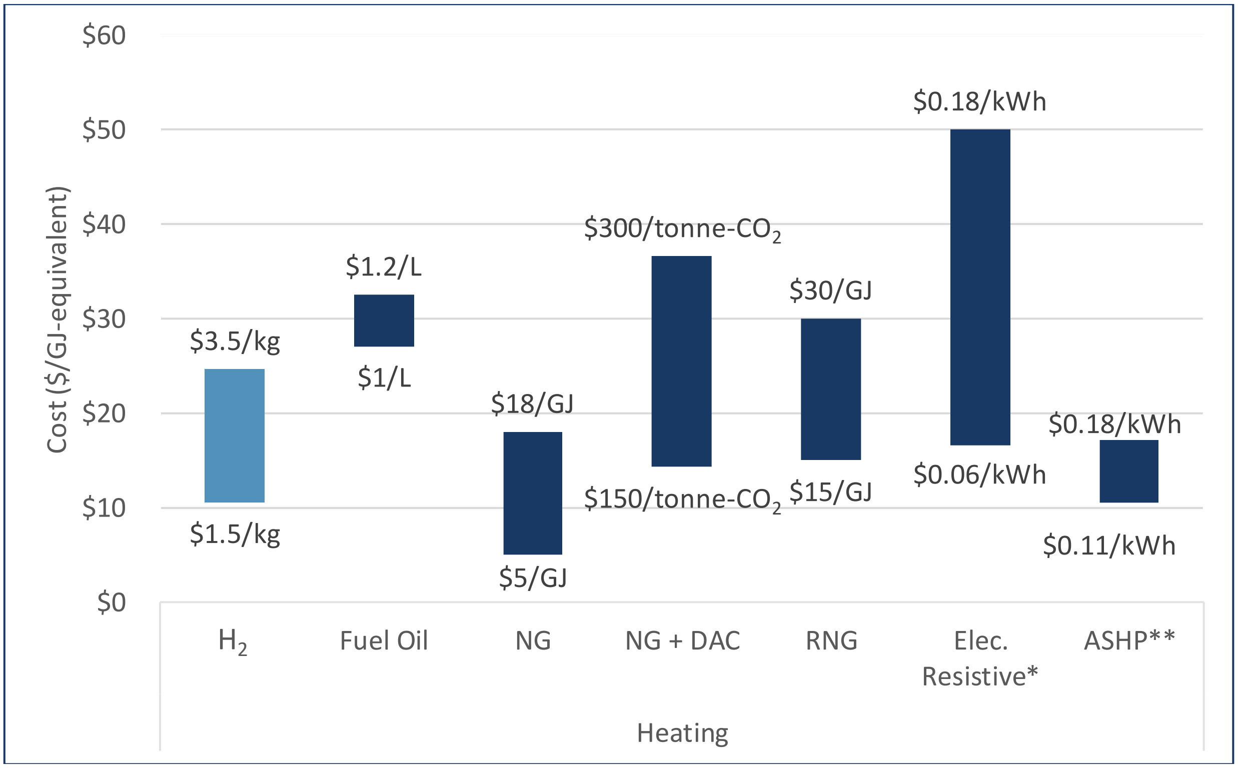


Figure 35 – Aggregate Demand Opportunity for Hydrogen in Canada

Ultimately the market will decide where best to deploy hydrogen once greater supply becomes available in Canada. The two big drivers will be cost competitiveness compared to alternative energy sources that can serve each end-use, and decarbonization potential which will ultimately be linked to the economics as carbon pollution pricing reflects the true price of emissions.

When comparing the cost of hydrogen to an incumbent fuel, it is important to consider the end-use application. For example, when used as a transportation fuel, hydrogen will be consumed in a fuel cell, which is significantly more efficient than a gasoline or diesel internal combustion engine (ICE). Therefore, the relative costs of the fuels cannot be compared on a simple $/GJ basis.

Figure 36 and Figure 37 shows the estimated cost of hydrogen relative to other fuels for heating and transportation applications. For both hydrogen and the alternative fuels, the costs shown reflect the total cost to the customer including production and distribution. The values are presented in $/GJ-equivalent, which takes into account the efficiencies of FCEVs and BEVs relative to ICE vehicles and air source heat pumps (ASHP) relative to electric resistive. As a heating fuel, hydrogen is more expensive than natural gas, but this value does not account for the increased costs of natural gas due to carbon. Over time, the delivered costs of all of the available fuels are likely to change. As a point of comparison, the figure shows the expected cost of natural gas used for heating for which the carbon emissions have been offset through direct air capture (DAC). Hydrogen for transport is cost competitive with gasoline and diesel, but will typically cost more than battery electric vehicles. Despite the additional cost, fuel cell vehicles will still be attractive in vehicle segments where operational requirements like longer range, improved performance in cold climates, and faster fueling are important.

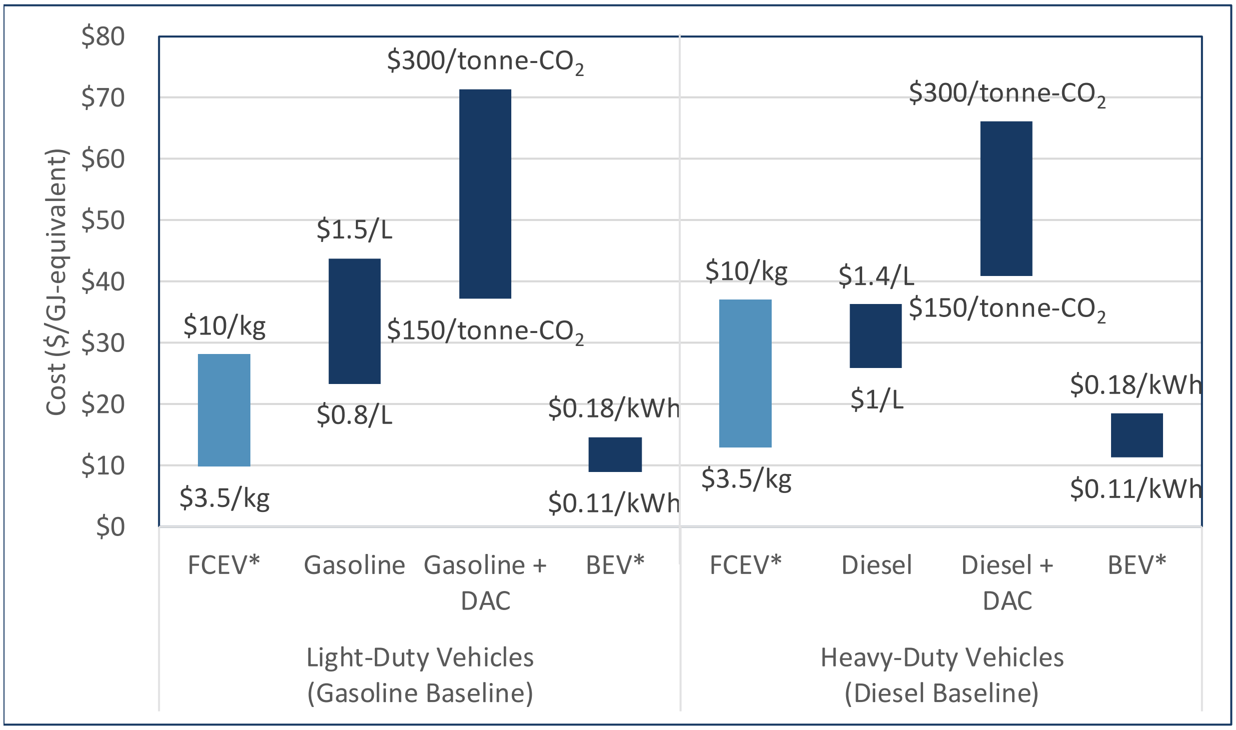


*The low price range for electric resistive heaters is less than for ASHP because resistive heaters may be used in industrial applications and therefore would be subject to rates for large scale industrial customers whereas ASHPs are typically in residential and commercial applications

**Coefficient of performance for ASHP = 2.92

Figure 36 – Hydrogen Cost Comparison as a Heating Fuel

The expected cost of hydrogen is dependent on the end-use application. As a heating fuel, it is assumed that the hydrogen will be produced in bulk and injected into the natural gas pipeline network in the short- to medium-term. The production takes place at or near the site of injection, so distribution costs are comparable to natural gas today, and the gas is only compressed to 100 bar, limiting compression costs. In the light- and heavy-duty vehicle sectors, it is assumed the fuel will be distributed via truck and compressed to 700 bar and 350 bar respectively. Comparable costs have been achieved in California for public transit applications.



*Energy efficiency ratio for light-duty vehicles: FCEV = 2.5, BEV = 3.4, energy efficiency ratio for heavy-duty vehicles: FCEV = 1.9, BEV = 2.7

Figure 37 – Hydrogen Cost Comparison as a Transportation Fuel

The emissions reduction potential of hydrogen is also dependent on the end-use application. Figure 38 and Figure 39 show the relative emissions reduction of hydrogen and electricity when used as a heating fuel or in a transportation application. The emissions reductions are compared to a natural gas baseline for the heating application, gasoline for light-duty vehicles, and diesel for heavy-duty vehicles. Negative numbers in these graphs indicate scenarios where emissions are increased relative to the baseline fuel.

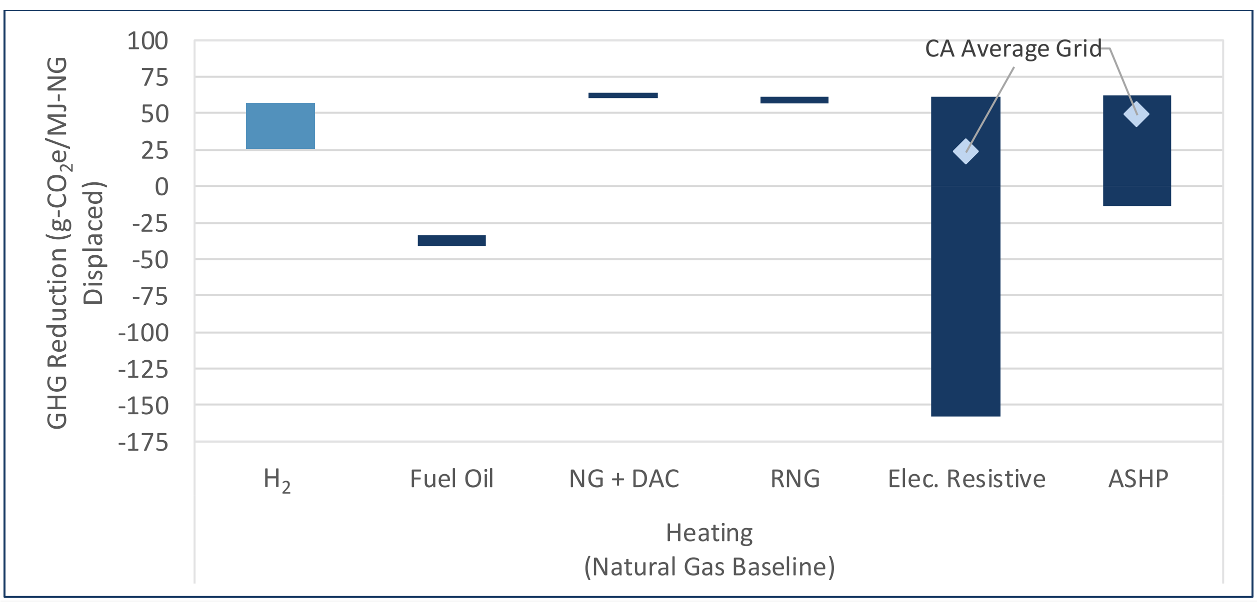


Figure 38 – GHG Emissions Reduction Potential of Hydrogen as a Heating Fuel

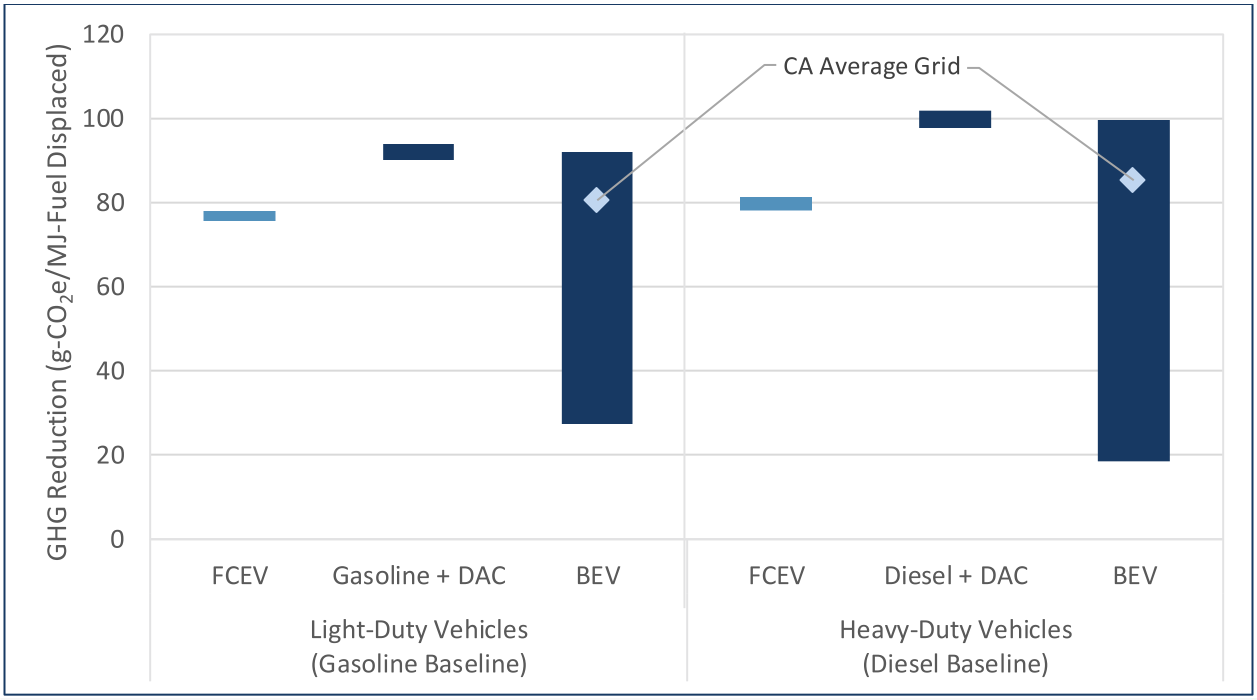


Figure 39 – GHG Emissions Reduction Potential of Hydrogen as a Transportation Fuel

The emissions reductions are dependent on the carbon intensity of the various energy sources. For hydrogen, the carbon intensity was assumed to be between 10.3-16.2 g-CO_2e/MJ when used as a heating fuel and 35.0-40.9 g-CO_2e/MJ when used as a transportation fuel to account for the additional energy required to liquify, compress, and distribute the hydrogen. These carbon intensities are consistent with large scale electrolysis and SMR with CCUS facilities, as described in the *Production Pathways' Cost & Carbon Intensity* section of this report.

The electrical emissions reduction potential is based on a carbon intensity of 140 g-CO_2e/kWh, which is the Canadian average. The lower bound (worst performing) shows the reduction potential based on Alberta's electric grid (790 g-CO_2e/kWh), which is the highest carbon intensity grid of any province in the country. The upper bound (best performing) represents Quebec's electricity grid (1.2 g-CO_2e/kWh), which is the lowest carbon intensity grid in the country.[1] In areas where the grid is particularly high-emitting, electrification will actually emit more than using natural gas or fuel oil. However, as the grid gets greener over time, the emissions reduction potential will improve.

[1] Canada Energy Regulator. (2020). Canada's Renewable Power Landscape 2017 – Energy Market Analysis. Retrieved from https://www.cer-rec.gc.ca/nrg/sttstc/lctrct/rprt/2017cndrnwblpwr/ghgmssn-eng.html

Cost and carbon intensity of each fuel are important factors that will drive adoption of the low carbon options for heating and transportation. A useful metric for comparison of different technologies is the incremental cost of hydrogen or other low carbon energy sources to the incumbent fossil fuel divided by the emissions reduction. This is often expressed in dollars per tonne of CO_2e abated ($/tonne-$CO_2e$). In transportation applications that employ fuel cells, hydrogen will cost less than gasoline or diesel resulting in a negative $/tonne-$CO_2e$ value. This provides a strong economic driver for adoption if capital costs are comparable. As a heating fuel, the cost of abatement in Canada is approximately $100-300/tonne-$CO_2e$, which is comparable to other low carbon options. While costs and carbon intensity are important factors, they are not the only limiting factors, there is also the operational differences, higher upfront capital costs and overall risk aversion (especially to new technologies). Further study is required to fully understand the costs of the entire value chain of each low carbon technology to assess the strength of each option.

The scale of aggregate demand in the 2050 Transformative scenario is significant and highlights the need for Canada to explore all low carbon intensity hydrogen production pathways. When considering pathways to satisfy future potential demand and optimize the potential for hydrogen, it is important to also consider the other changes that will be happening in the energy mix as Canada transforms all carbon emitting energy sources to carbon neutral sources . It is anticipated that direct electrification will play a significant role in reducing emissions in many sectors, from battery electric vehicles to heat pump adoption for building heat. Demand for electricity as an energy vector is expected to grow by at least 57%, and will be met through the deployment of additional renewable energy sources such as hydro, wind, and solar. Demand for bio-based liquid and gaseous fuels is also expected to grow. Natural gas on the other hand will have declining demand if not used to produce hydrogen, as any combustion related emissions in a net-zero energy system would need to be offset, for example through direct air capture. Figure 40 shows how much additional electricity generation or natural gas with CCUS capacity would be needed if all hydrogen is made though each of the pathways. The magnitude of energy feedstock needed highlights that a production strategy must be diverse, and that Canada will need to rely on fossil fuel pathways as well as the electrolysis pathway to meet decarbonization objectives.

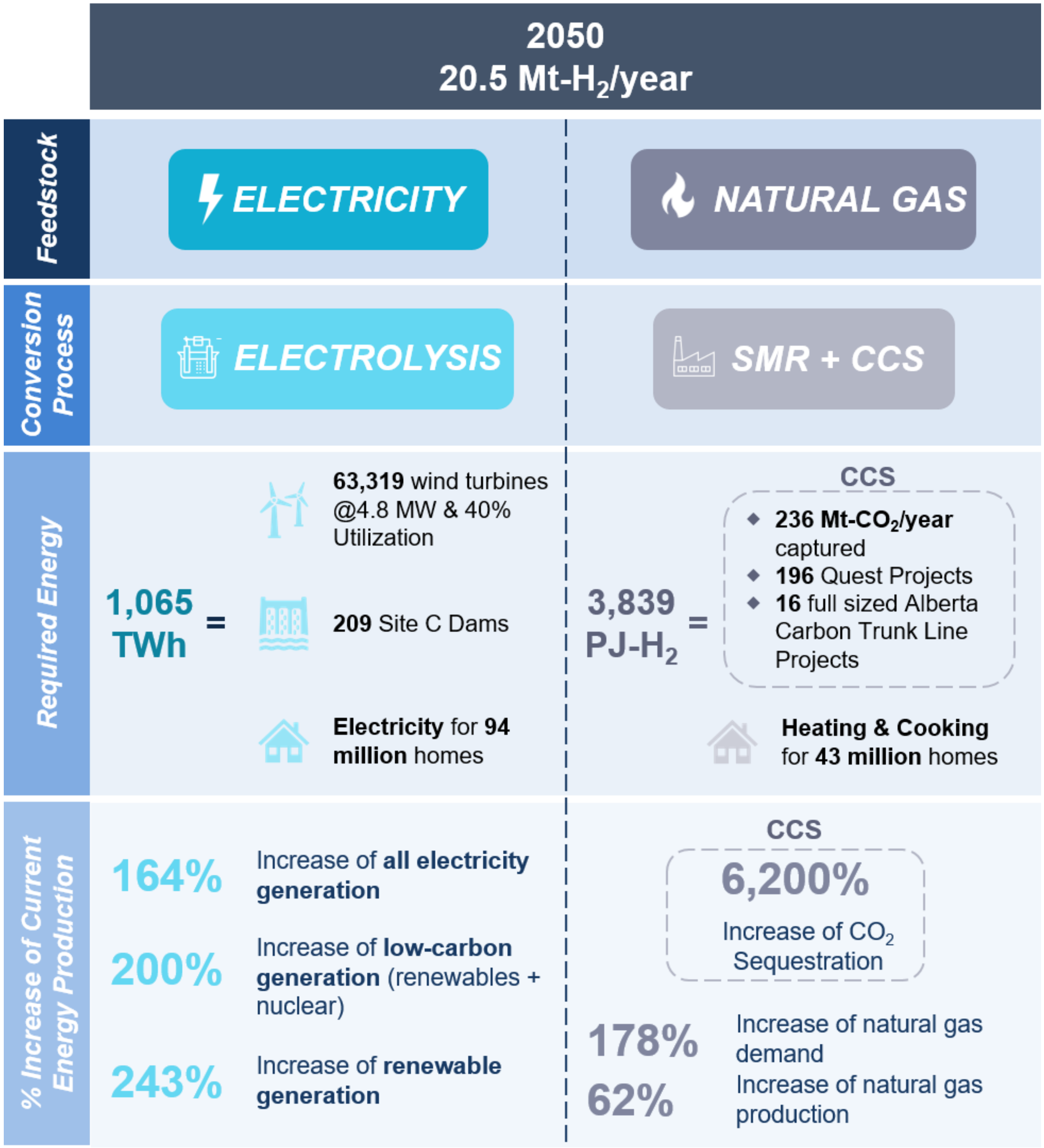


Figure 40 – 2050 Fossil Fuel vs Electrolysis Based Hydrogen Production

HYDROGEN'S DECARBONIZATION POTENTIAL

To evaluate the role hydrogen can play in reaching Canada's goal of becoming net-zero by 2050, modelling analysis was undertaken for an incremental scenario and a transformative scenario, to understand hydrogen's potential in the broader energy system, alongside electrification and other low-carbon fuels. These scenarios are more likely to be achieved with strong pricing and regulatory incentives to drive hydrogen adoption, and alignment action across government and industry.

Increased electrification with renewable and low CI power sources will play a large role in reducing emissions. It is well suited to many applications including light-duty BEVs and to provide heating when the use of heat pumps is cost effective. However, it will be impossible to grow clean electrical generation fast enough to meet demand if entire energy sectors electrify to meet climate targets. Hydrogen produced from natural gas and crude oil incorporating CCUS enables Canada to utilize its natural resources while limiting emissions as deployment of low CI electricity generating infrastructure grows. There are also end-use applications where electrification is challenging, including heavy-duty vehicles where the low energy density of batteries limits carrying capacity and where continuous operation of vehicles makes fueling time critical. In cases such as these, hydrogen is likely to become an important low CI option.

Similarly, low CI crude production, which includes traditional crude combined with indirect CCUS or enhanced oil recovery such that the net CO_2 emissions are near zero, and liquid and gaseous biofuels, will be an important part of the energy mix. These fuels serve effective substitutes for traditional crude and natural gas respectively as they can be incorporated into the current energy system without the need to replace or upgrade existing distribution and end-use infrastructure. The use of low CI crude and biofuels will be primarily limited by feedstock supply and economics. The cost to produce them will increase as the lowest hanging fruit opportunities for production are exhausted.

EVOLUTION OF THE ENERGY SECTOR

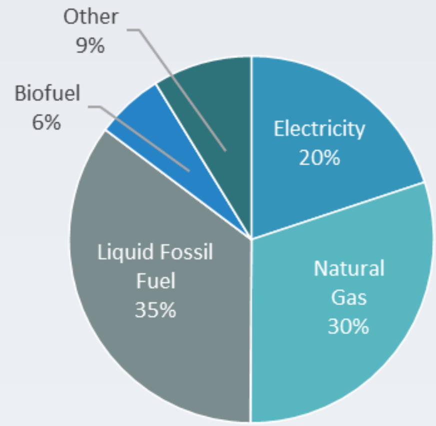


Figure 41 – Canada's 2017 Secondary Energy Demand

As demand for hydrogen grows, so will the need for other low-carbon energy sources.

Between now and 2050, high-emitting fuel sources will replaced by a combination of increased electrification, biofuels, low-carbon liquid fuels – including synthetic fuels and traditional crude offset through CCUS – and hydrogen.

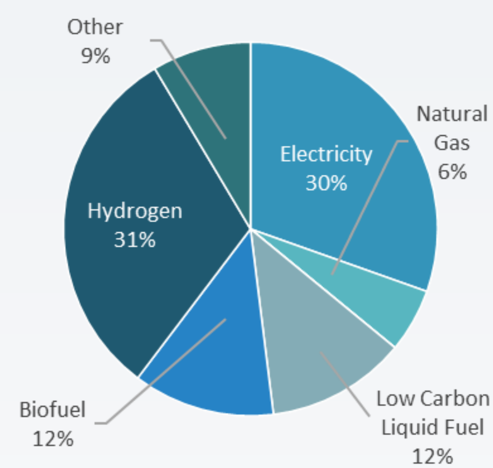


Figure 42 – Canada's 2050 Secondary Energy Demand Scenario

There are limited opportunities for cost-effective RNG production, which are likely to be maxed out on the path to net carbon neutrality. However, all low carbon fuels, including RNG will have a role in Canada's future.

Hydrogen demand was forecasted to essentially fill the gaps that electrification, and other low CI energy sources cannot reach or where they would be cost prohibitive. The analysis took into account the expected relative costs of each low CI energy source as well as the ability of technologies to meet end-use demand requirements.

The GHG emissions abatement potential was estimated by comparing hydrogen consumption to the incumbent energy source for each sector. In transportation applications, hydrogen is considered as a substitute for diesel and gasoline derived from crude oil; in the natural gas grid, hydrogen replaces natural gas; and in industrial uses, low CI hydrogen replaces either natural gas or grey hydrogen produced via SMR without CCUS depending on the specific application.

When applicable, the calculated emissions reductions account for the improved energy efficiency of fuel cells compared to internal combustion engines. In transportation applications, it was assumed that hydrogen would be used in fuel cells with energy effectiveness ratios (EER) of 1.9 for light-duty vehicles and 2.5 for medium- and heavy-duty vehicles. When used as a substitute for natural gas or as a feedstock for industrial processes, there is no efficiency gain relative to the incumbent fuel.

Figure 43 shows the transformational and incremental decarbonization potential from hydrogen in 2030 and 2050 by sector. In the Transformative case, hydrogen can reduce emissions by up to 45 Mt-CO_2e/year by 2030. In 2050, the emissions reduction increases up to 190 Mt-CO_2e /year. This simplified analysis assumes energy demand remains flat between now and 2050, with increased energy demand offset by energy efficiency improvements.

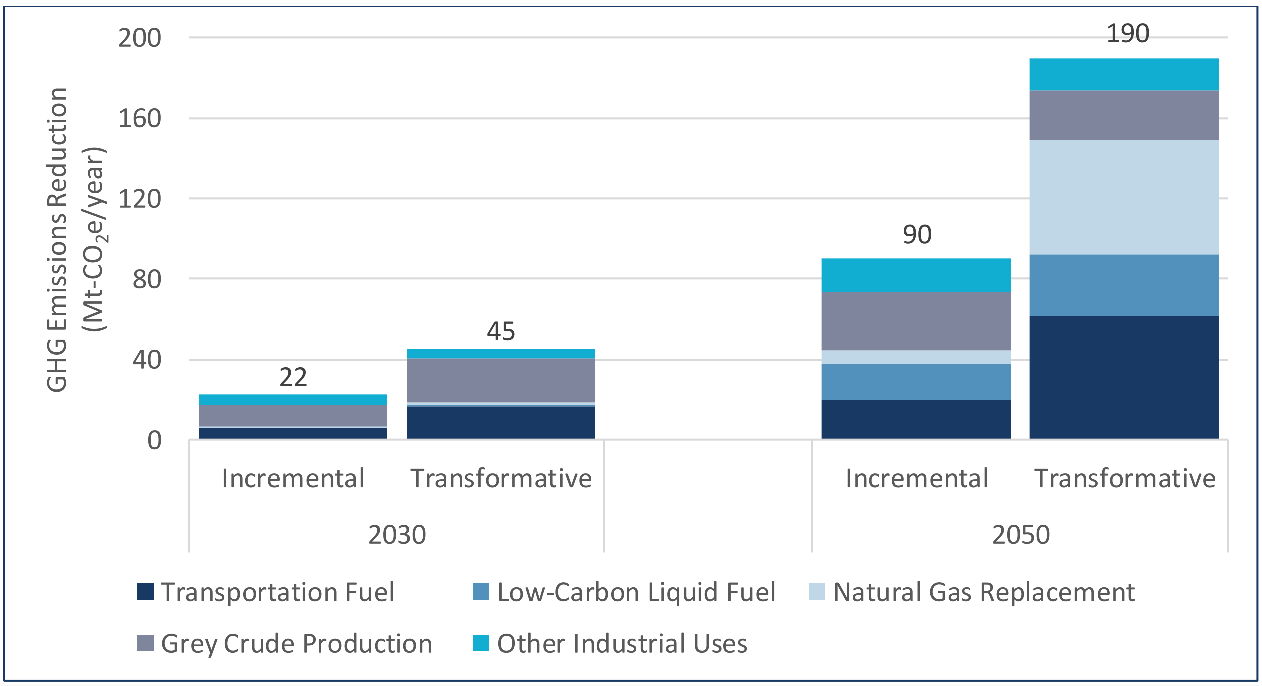


Figure 43 – Hydrogen Decarbonization Potential

Figure 44 shows the magnitude of emissions reduction from hydrogen relative to Canada's 2030 and 2050 targets.

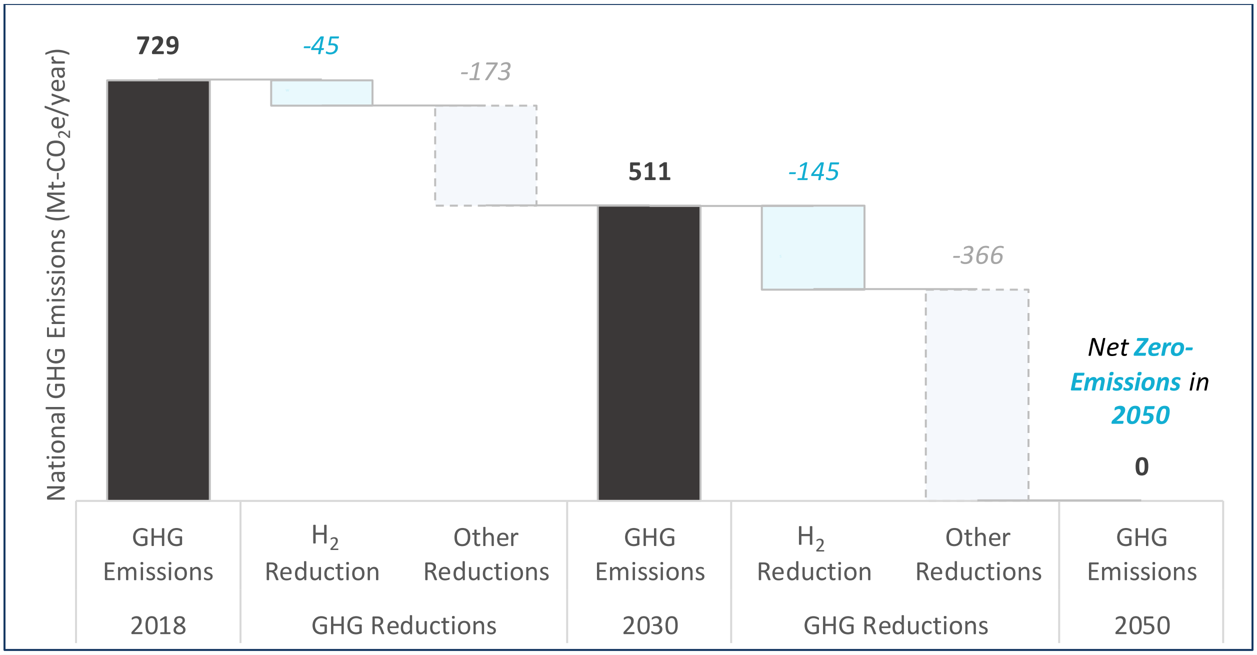
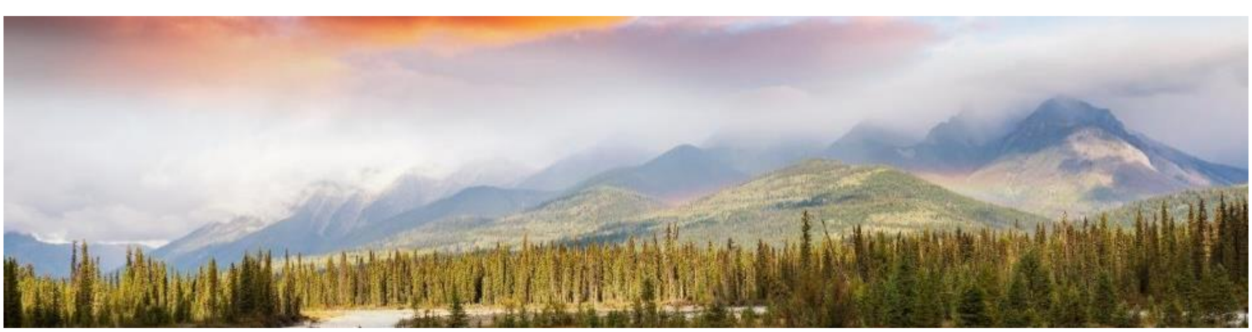


Figure 44 – Potential Role of Hydrogen in Reaching Canadian Decarbonization Targets – Transformative Scenario

ECONOMIC OPPORTUNITY

Domestic Market

Considering only the domestic demand for hydrogen production and revenues from the local manufacturing and services, the hydrogen and fuel cell sector has the potential to generate almost $50 billion in sector revenue in 2050 under the Transformative scenario (Figure 45). This figure is based on the estimated demand for hydrogen in 2030 and 2050 under the Incremental and Transformative modelling scenarios and assuming an average hydrogen sales price of CAD$2/kg. In addition, revenues from the manufacturing of electrolyzer equipment, fuel cell stacks and engineering and consulting services are estimated based on a conservative market share of 5% of the domestic market. The estimated value of the domestic market is expected to be almost **$50 billion per year** by 2050. This does not take in to account how the hydrogen market will indirectly benefit several other adjacent industries that would also contribute to economic growth and could lead to manufacturing opportunities in Canada, including SMR and CCUS facilities and equipment, H_2 pipeline development, and end-use applications in buildings, industry, and the natural gas grid.



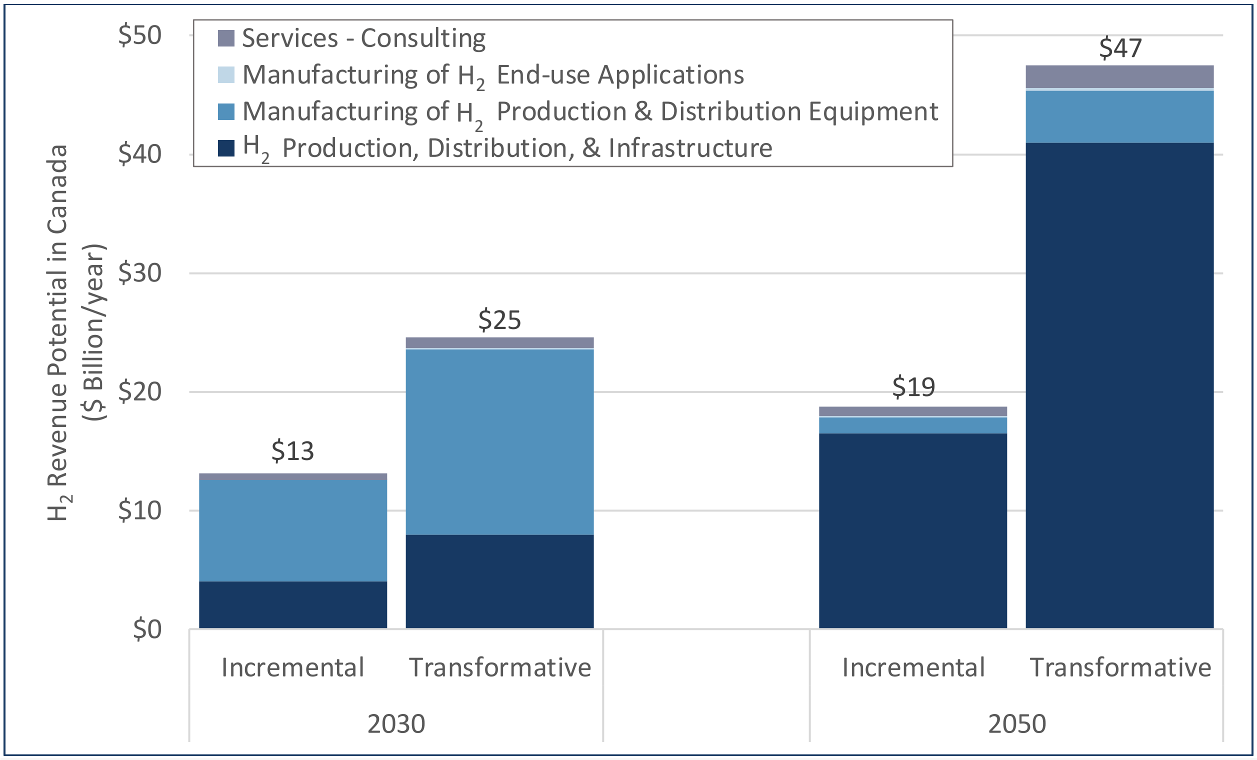


Figure 45 – Hydrogen Revenue Potential in Canada in 2030 & 2050

Based on the direct sector revenue estimates, the job creation potential for hydrogen in 2050, under the Transformation Scenario is more than **350,000** (Figure 46). This was calculated by multiplying the annual revenue for each subsector by a job multiplier based in similar industries (Table 2). For example, the number of jobs for the hydrogen production industry is based on the multiplier from the industrial gases industry. This number represents a combination of new job growth and retrained and reskilled labour.

Table 2 – Job Multipliers

Jobs per $M (jobs created each $M in revenue) [1,2]	
Jobs per revenue created in the machinery and equipment industry	12.2
Jobs per revenue created in the automotive industry	10.2
Jobs per revenue created in industrial gases	6.7
Jobs per revenue created in manufacturing of other transport equipment	14.5
Jobs multiplier –hydrogen	**6.7**
Jobs multiplier –equipment	12.3
Jobs multiplier –aftermarket	14.3

[1] These job multipliers are based on numbers from the US Fuel Cell & Hydrogen Energy Association's Road Map to a US Hydrogen Economy report (2019), adjusted to Canadian dollars. These projections should be seen as indicative of the order of magnitude of the number of jobs in the hydrogen industry and are subject to many uncertainties and unpredictable changes in economics and technologies.

[2] Source: McKinsey Global Institute Economics Research, GTAP input-output data

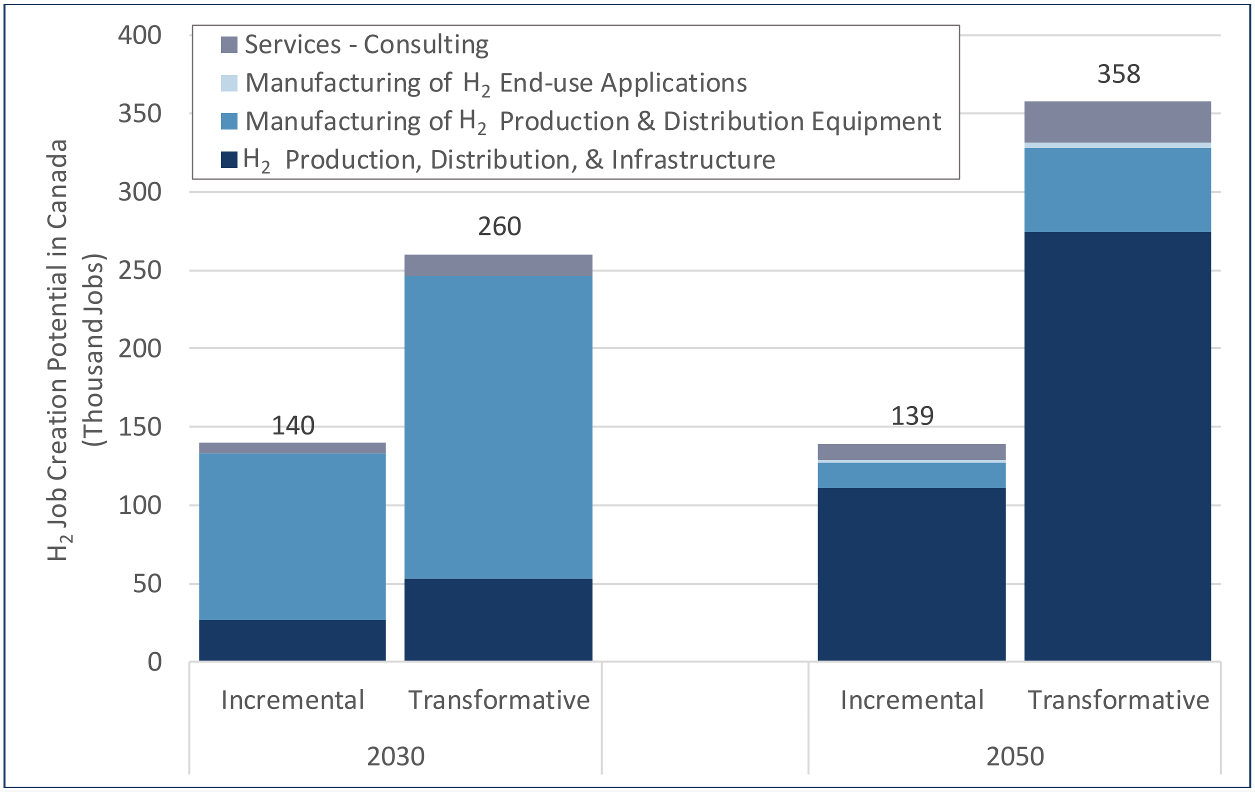


Figure 46 - Hydrogen Sector Job Creation Potential in Canada in 2030 & 2050

The energy transition will fundamentally shift the Canadian economy and alter value chains in many related sectors. One shift of particular importance is the transition away from the direct burning of fossil fuels without carbon abatement. Canada's energy sector accounted for 900,000 direct and indirect jobs as of 2017, with assets valued at $596 billion[1]. This industry's significant energy expertise and infrastructure can be leveraged to support the development of the future hydrogen economy in Canada. Hydrogen will be critical to achieving a net-zero transformation for oil and natural gas industries. It provides an opportunity to leverage our valuable energy and infrastructure assets, including fossil fuel reserves and natural gas pipelines, providing a pathway to avoid underutilizing or stranding these assets in a 2050 carbon neutral future. Leveraging these valuable assets will not only be instrumental in achieving the projected economic growth for the domestic market, but also presents the opportunity for Canada to position to become a leading global clean fuels exporter.

Opportunities for Indigenous Communities and Businesses

The energy sector is one of the largest employers of Indigenous peoples in Canada. As the energy sector transforms to adopt low carbon fuels, the emerging hydrogen economy will offer new opportunities for Indigenous communities through employment and new business creation.

The versatile production pathways of hydrogen and potential for scalable and distributed production facilities offers the potential for greater participation and ownership in the value chain than has been possible in the oil and gas and power sectors.

Hydrogen presents unique business opportunities for Indigenous communities with the capacity to take advantage of existing infrastructure, including renewable electricity, to produce, distribute and use hydrogen. These opportunities could outside of local communities as well. For example, Indigenous

[1] https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/10-Key-Facts-on-Canada_s-Energy-Sector-2018-en%20.pdf

communities and businesses could participate in early deployment HUBS whereby they could become fuel producers and distributors both for nearby communities and adjacent industry.

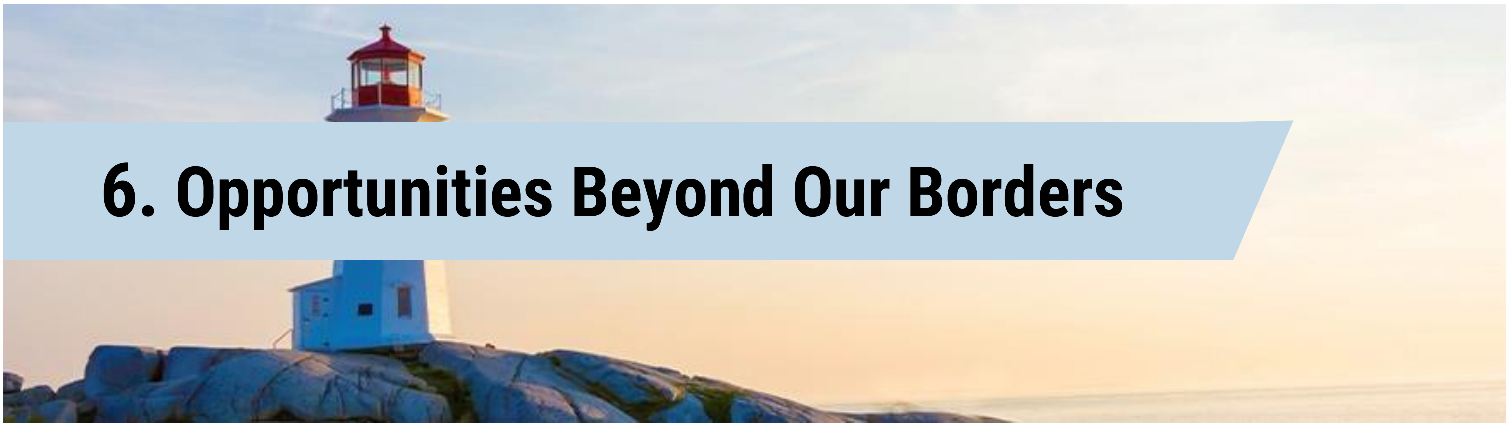
Many of Canada's remote communities house Indigenous peoples, and a large proportion of these communities are reliant on imported diesel for power generation. This leads to high operating costs and poor air quality. In the medium to longer term hydrogen can offer an opportunity for greater energy independence, as it can be made from local biomass and/or hydroelectric resources. Displacement of high-emitting diesel with hydrogen will result in improved local air quality and better health outcomes for community members.

As Canada invests in hydrogen infrastructure build-out, there is an opportunity for Indigenous peoples to participate. Some of the anticipated distribution corridors to move hydrogen from production to end-use locations will likely run through Indigenous lands. As such, skilled construction labour will be needed for build-out of production and distribution infrastructure assets, including future potential hydrogen pipelines. While there has been mixed support for traditional pipelines, hydrogen pipelines may offer a unique low environmental risk alternative to move energy within Canada, though local land disruptions through Indigenous territories will still need to be considered. Early and meaningful engagement on all aspects of hydrogen production, distribution and deployment will be essential.

Indigenous communities and businesses across Canada are already identifying hydrogen as a new opportunity for economic development, with environmental benefits. By leveraging the natural resources under their stewardship, as well as existing commercial facilities owned and operated by Indigenous-led businesses, new hydrogen opportunities are emerging. For example, the Penticton Indian Band is considering the development of a hydrogen-powered passenger railway service in the Okanagan Valley – a potential first in North America – mobilizing partners and experts throughout the region to advance a holistic vision of sustainable transport. In northeastern BC, Renewable Hydrogen Canada (RH_2C) is developing the Sundance Hydrogen project that includes Indigenous participation through operation of co-located greenhouses utilizing waste heat from electrolyzer plants that will provide fresh, local produce for the region. In Ontario, the Saugeen First Nation has formed a partnership with Bruce County to advance foundational hydrogen infrastructure, noting that the local geology can serve as a vast reservoir capable of storing hydrogen produced from local renewable resources and nuclear power. Once stored, the hydrogen can be supplied to markets as a low CI gaseous fuel; it can also be converted back to electricity to power the regional transmission grid. Similarly, Des Nedhe Development sees opportunities to include hydrogen refueling and EV chargers their existing conventional gas stations within Saskatchewan, as the next step in the transition to a lower carbon economy. They also see strong synergies between Canada's uranium mines, path to small modular reactors, and hydrogen as providing economic opportunities in the medium term.

The scale of Indigenous clean energy leadership and ownership has the capability to grow over the short and long-term. Going forward a holistic approach, to understand the potential role of hydrogen as part of broader energy pathways, in support of reconciliation, will be critical. Hydrogen deployment initiatives can be most effectively advanced through early and meaningful dialogue with Indigenous peoples.

As the Hydrogen Strategy emphasizes, collaborative, strategic partnerships are essential for growing the production and use of hydrogen across Canada. Partnerships that emphasize environmental protection, cultural recognition, community energy planning aligned with traditional values, economic development, and project participation, will be essential to maximize benefits for Indigenous peoples in the hydrogen economy.



6. Opportunities Beyond Our Borders

Momentum on hydrogen and fuel cell technology is growing globally, with market estimates ranging from $2.5-$11.7 trillion by 2050. Canada has the potential to produce large amounts of low-cost, clean hydrogen in excess of its domestic demand, creating an opportunity for Canada to become a supplier of choice of a new carbon-free energy export commodity. Canada, known for its leading hydrogen and fuel cell technology companies, is also well positioned to attract direct foreign investment, and continue to grow as a word-leading exporter of technology, products, and services.

EXPORT MARKET

Canadian governments, industry and academia have a long history of international collaboration to advance hydrogen production and use. These collaborations have included fundamental research, commercialization, deployment, and policy development. As a result, Canada is well positioned to continue as a global leader in both technology innovation and commercial developments. International collaborations accelerate advancements in R&D and product development, ensure codes and standards necessary for commercial rollout are harmonized, and build on policies and best-practises. They also position Canadian companies to showcase their products and expertise in international markets for export and to attract additional direct foreign investment.

With worldwide demand for hydrogen increasing, there is a significant opportunity for Canada to become a supplier of low CI hydrogen as a new carbon-free energy export commodity complementing Canada's energy exports of crude oil, natural gas, and transportation fuels. Canadian oil and natural gas exports alone totaled $119 billion in 2019, and, with import countries looking to decarbonize their energy systems, hydrogen could take a significant portion of this share in the coming decades.[1] There is also potential to grow the export market for Canadian products, services, and intellectual property. A recent study indicated that hydrogen exports could reach $50 billion by 2050, doubling the overall economic potential of the market projected for Canada in the same timeframe.[2] In November 2017, the Hydrogen Council estimated that the global annual sales for hydrogen and related equipment could be 2.5 trillion by 2050.[3] More recently in September 2020, the global investment bank Goldman Sachs estimated that the addressable market for hydrogen could be worth $11.7 trillion by 2050, split between Asia, Europe and the U.S.[4]

[1] Natural Resources Canada. (2020). *Energy and the Economy*. Retrieved from: https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/energy-facts/energy-and-economy/20062#L4

[2] The Transition Accelerator. (2020). *Towards Net-Zero Energy Systems in Canada: A Key Role for Hydrogen*. Retrieved from https://transitionaccelerator.ca/wp-content/uploads/2020/09/Net-zero-energy-systems_role-for-hydrogen_200909-Final-print-1.pdf

[3] Hydrogen Council. (2017). *Hydrogen Scaling Up*. Retrieved from https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf

[4] Barron's. (2020). *'Green Hydrogen' Could Become a $12 Trillion Market. Here's How to Play It.* Retrieved from https://www.barrons.com/articles/goldman-sachs-says-so-called-green-hydrogen-will-become-a-12-trillion-market-heres-how-to-play-it-51600860476

Canada has the potential to produce large amounts of low-cost, low CI hydrogen in excess of its domestic demand. Leveraging the country's diverse range of hydrogen production feedstocks to create hydrogen for export could create substantial economic value. Canada has several strategic advantanges for producing hydrogen for export including:

- Deepwater harbours and port infrastructure along both coasts, Hudson's Bay and the Great Lakes providing access to key markets in Asia, Europe and North America
- Abundant low carbon electricity, biomass, natural gas, and CCUS potential
- Integrated, country-wide natural gas and pipeline network
- Connected energy systems integrated with the large US markets, especially California and the East Coast
- A well-trained workforce with deep technical experience in the energy sector

A full analysis of the export potential for hydrogen is beyond the scope of the strategy in the near-term, but several key markets, technologies, and policies are recommended as a foundation. It is recommended that export opportunities be studied in depth following release of this *Hydrogen Strategy for Canada*, with the goal to create a specific action plan related to pursuing opportunities for export in parallel to the focus on establishing a vibrant domestic market.

TARGET MARKETS

Five key markets have been identified as potential export markets for Canada: The USA (particularly California and the Eastern US), Japan, South Korea, China, and the European Union. These have been identified based on their stated strategies, demand potential and proximity to Canada. As the global demand for hydrogen continues to evolve, new export markets in South America may also develop.

In the USA, the two main markets for hydrogen are expected to be in California and in the densely populated North Eastern states. California's estimated demand for hydrogen could be as large as 1 to 4 million tonnes by 2050. The state has strong governmental regulations and supportive funding for hydrogen infrastructure and fuel cell vehicles. The Innovative Clean Transit Regulation and Zero Emission Vehicle Mandates are expected to create significant demand for hydrogen in the transportation sector. The state also has significant renewable natural gas and energy storage requirements which could be partially addressed with imported hydrogen. For the market in the Northeastern US, there are potential opportunities to reuse elements of the LNG and other infrastructure already in place in Atlantic Canada. The ports, rail, highway and pipeline interconnections between the Maritimes and the Eastern US could provide a route to market for hydrogen generated in Central Canada and Quebec.

In Asia, Japan, South Korea, and China have ambitious hydrogen strategies. Japan and South Korea will need to rely on imports to meet the bulk of their demand. The estimated demand for hydrogen in Japan could be between 5-35 million tonnes per year in 2050 according to the Ministry of Economy, Trade and Industry. The country has already begun investigating supply options with Australia, who have, in turn, developed an aggressive and ambitious hydrogen export strategy. In South Korea's National Hydrogen Economy Roadmap, the estimated demand in 2050 is between 4 and 20 million tonnes per year, with limited domestic production potential similar to Japan. China has plans to make significant investments in hydrogen and fuel cell vehicles. The demand is expected to be between 18 to 160 million tonnes per year by 2050. China may eventually be able to become self-sufficient in its production when coupled with the large renewable and nuclear energy systems it is developing.

In Europe, Germany is leading the development of its hydrogen economy based on renewable energy and electrolysis. The German Government expects that around 2.7 to 3.3 million tonnes (90 to 110 TWh) of hydrogen will be needed by 2030, with significant upside growth in the 2030 – 2050 timeframe. To cover part of this demand, Germany plans to establish up to 5 GW of generation capacity including the offshore and onshore energy generation facilities[1]. They will also likely rely on imports of hydrogen to complement domestic production. In the rest of Europe, there are several hydrogen hubs being developed in the Netherlands, the UK, and Portugal. The Port of Rotterdam in the Netherlands is working to introduce a large-scale hydrogen network across the port complex, with the goal to make Rotterdam an international hub for hydrogen production, import, application and transport to other countries in Northwest Europe[2]. The hub will also enable Rotterdam to maintain its position as important energy port for Northwest Europe in the future, anticipating that demand for hydrogen will be growing.

British Columbia, with its proximity to East Asia, could be an export hub for Canadian hydrogen, leveraging local and Alberta production capacity provided transportation infrastructure is established to connect the two provinces. The British Columbia Hydrogen Study completed in 2019 shows export potential of $15 billion by 2050 from that province.[3] Atlantic Canada could be a potential export hub for Canadian hydrogen to serve the European market. The following image (Figure 47) highlights the international landscape for hydrogen production and demand, and identifies at a high level how Canada could explore serving these markets through export channels. Provincial and local leadership will be needed to develop identify and invest in developing strategy export hubs for Canadian hydrogen.

[1] The Federal Ministry for Economic Affairs and Energy, Germany. The National Hydrogen Strategy. June 2020.

[2] https://www.portofrotterdam.com/en/doing-business/port-of-the-future/energy-transition/hydrogen-in-rotterdam

[3] BC Hydrogen Study, Zen and the Art of Clean Energy Solutions Inc., 2019

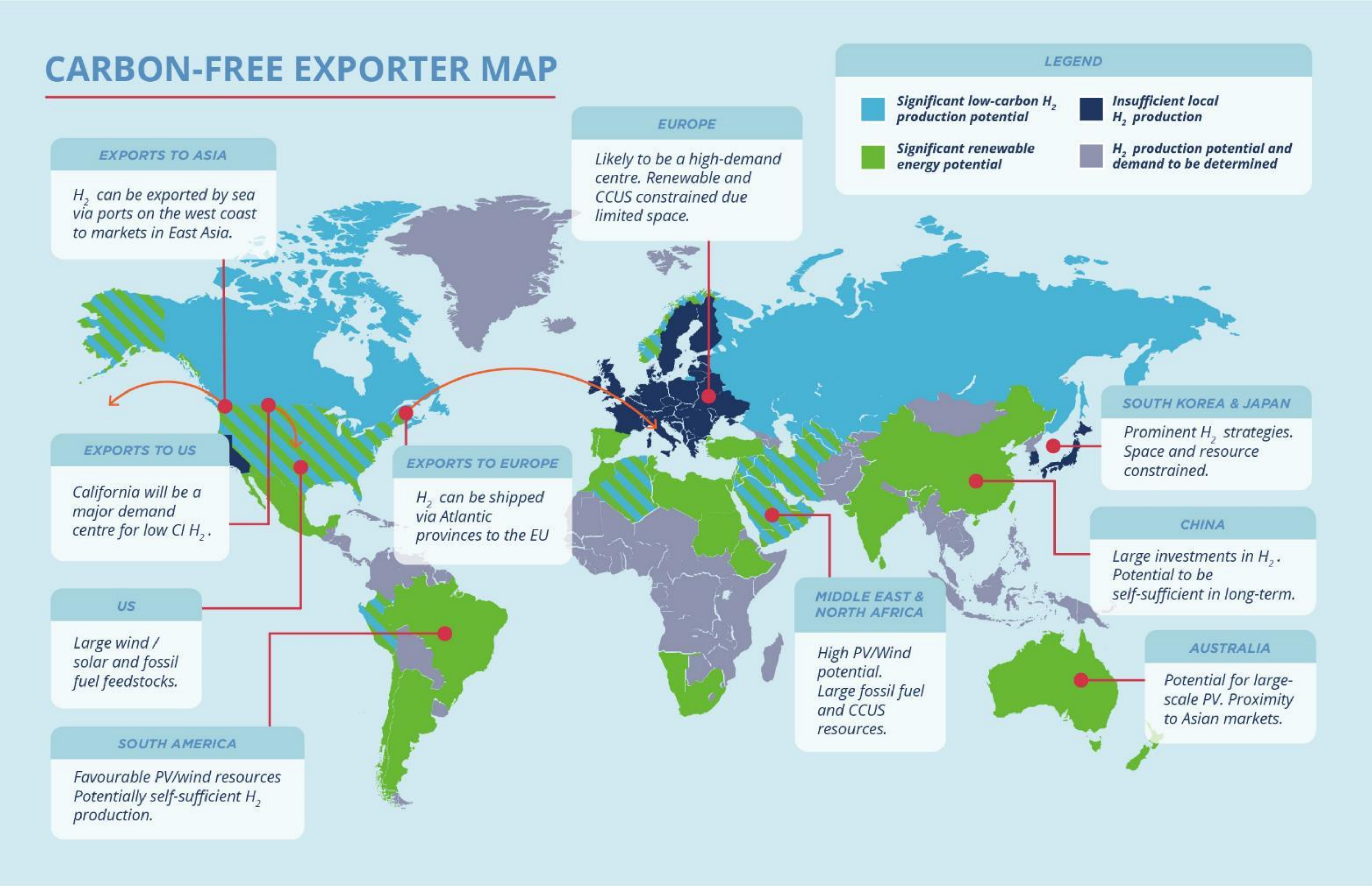


Figure 47 – Canada's Potential as Hydrogen Exporter[1]

[1] Based on data and maps from BloombergNEF Hydrogen Economy Outlook. March 2020

ENABLERS

Innovation and Intellectual Property Leadership

Canada is recognized as a global leader in the hydrogen and fuel cell sector, seen as a hub for technical expertise, intellectual property, and leading products and services. In 2018, the industry generated revenue of $207 million and was responsible for 2,177 jobs[1]. According to a survey conducted by the Canadian Hydrogen and Fuel Cell Association in 2017, 86% of respondents' hydrogen and fuel cell facilities were located in Canada with BC, Ontario, Quebec and Alberta home to some of the largest industry clusters as shown in Figure 48.

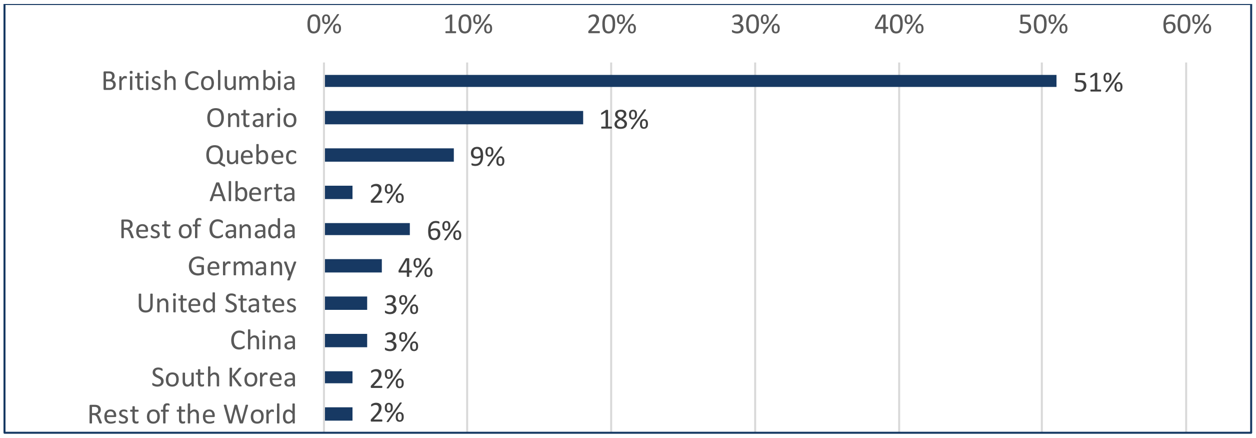


Figure 48 – Hydrogen and fuel cell facilities by region

Canadian companies, educational institutes, government agencies, and NGOs are involved with hydrogen and fuel cells across a range of sectors and areas of expertise from fundamental scientific research through to aftermarket sales and services. Many of these organizations have been involved with hydrogen and fuel cells for multiple decades and have strong interconnections and shared talent pools.

Domestic deployments will help Canadian companies across the value chain, both in providing a local market for their goods and services, and also by serving as local reference projects opportunities for Canadian companies looking to export products, services, or IP into international markets. A common theme heard from cleantech stakeholders is that international partners ask to see local reference projects to validate technology readiness and the business case.

Canadian companies in the sector are today generally relying on export markets to grow their business, given the relatively small Canadian market to date. Due to Canada's technology leadership, lead companies have attracted significant foreign investment, and international companies have set up shop in Canada to be able to leverage the local trained talent pool. This sector will continue to grow economic value for Canada, provide jobs, and attract foreign investment provided technology and innovation leadership is maintained.

Canadian companies in the hydrogen and fuel cell space are currently recognized as technology and product leaders, and today heavily rely on international sales of services and products to regions leading in hydrogen adoption. These companies will benefit from a growing domestic hydrogen economy, and can also grow from increased international sales as Canada builds on the opportunities outside our

[1] CHFCA. (2018). Canadian Hydrogen and Fuel Cell Sector Profile. Retrieved from http://www.chfca.ca/wp-content/uploads/2019/10/CHFC-Sector-Profile-2018-Final-Report.pdf

borders for the growing hydrogen sector. Canadian reference projects will validate the strengths and business case for Canadian products, facilitating international sales.

Staying at the forefront of innovation is critical to sustaining Canada's competitive advantages, and Canada is at risk of losing ground. Other countries have been heavily rapidly increasing investment in the sector whereas Canada has, in recent years, slowed investment in fundamental research. As a result, there have been examples of Canadian companies moving operations to other countries where there is more support for technology advancement. It is important for Canada to act now to prevent loss of critical IP.

Stakeholder engagement highlighted areas in which Canada can excel in hydrogen innovation. Canada already has a leading fuel cell sector with expertise ranging from fundamental materials to complete systems and vehicles. Building on these strengths to maintain leadership should be a key area of focus. As Canada transitions to deployment, there are opportunities for innovative solutions in hydrogen production technologies, as well as important complementary technologies such as CCUS and hydrogen storage unique to Canada's geology, such as use of depleted wells for both carbon storage and hydrogen storage either as a blend or pure fuel. Canada can also develop expertise in engineering and integration using deployment HUBs to strengthen local skills. Deployment HUBs also present an opportunity to nurture skills development and training, to ensure workers and communities are equipped with the skills needed to succeed in a clean energy future. In this way, Canada can showcase how, youth, women, Indigenous peoples, and other underrepresented Canadians can become the backbone of a low-carbon economy, through focused efforts from industry and governments.

Storage Technologies

Hydrogen storage and transport from production hubs to users' sites will be one of the more challenging obstacles for the large-scale global adoption of hydrogen. Liquefaction and chemical storage, in the form of chemical carriers such as ammonia or liquid organic hydrogen carriers, in particular will need to be developed to enable the safe and cost-effective transport of hydrogen from Canada to export markets around the world. Canada is currently investing in large scale Liquefied Natural Gas (LNG) infrastructure including seaports and liquefaction facilities that could potentially be adapted for hydrogen.

As countries develop hydrogen import strategies, it is expected that emissions from both production and transportation will be considered in the overall lifecycle analysis to determine decarbonization potential as an important decision metric. Canada will need to participate in international R&D related to transportation technologies if bulk export is deemed to be a strategic priority in the export roadmap.

Standards and Regulations

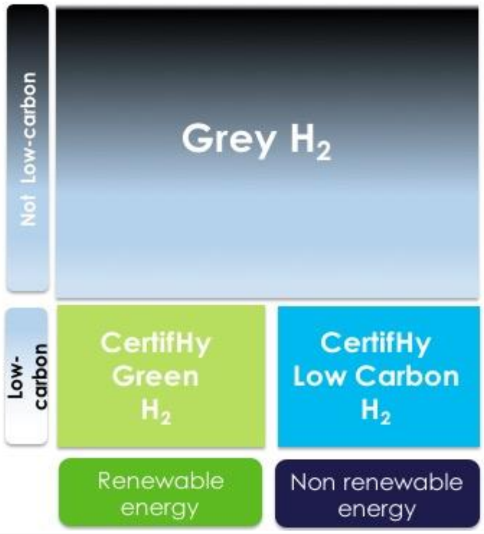


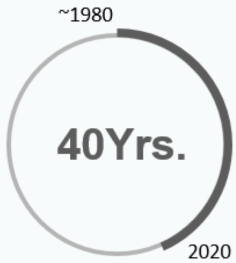
Figure 49 – CertifHy Green and Low Carbon Hydrogen Definitions

Other countries are also pursuing the same export markets and Canada will need strong policies and investments to remain competitive. The Canadian hydrogen industry will need to be integrated with export markets in terms of codes and standards, carbon intensity tracking, and renewable gas standards. Of particular importance is how other countries will value hydrogen produced from fossil fuel and non-renewable feedstocks. For example, the European CerifHy[1] Guarantee of Origin initiative label both the carbon intensity and the source of the hydrogen, distinguishing between renewable energy origins and non-renewable energy. Given Canada is focusing on all sources of low CI hydrogen, it will be important for Canada to participate in these types of activities. Branding and promoting Canada's low carbon fuels will be important to gain market acceptance. Branding and claims will need to be backed by certified lifecycle analysis.

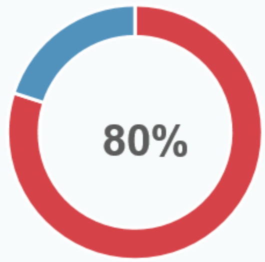
[1] https://www.certifhy.eu/project-description/certifhy-1.html

STAKEHOLDER INPUT: CLEANTECH & INNOVATION

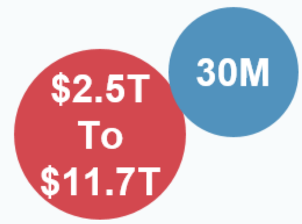
Opportunities



- *Canada has been a pioneer in fuel cell technology for more than 40 years and is home to some the world's leading hydrogen companies*



- *Canadian fuel cell technology is used in over 80% of applications worldwide and Canada has a global IP leadership*



- *The global market for hydrogen could be worth between $2.5T and $11.7 in 2050 and employ 30M people*

Challenges

Decline in research and development has impacted Canada's early lead in innovation

Larger countries investing heavily in national research programs has pulled talent and IP away from Canada

Lack of domestic deployments means no local market and no 'living labs' to spur collaboration & innovation

Investors in Canadian companies need to be able to see examples of technology deployments domestically

Findings

- *Establish domestic deployment hubs that highlight local technology, and encourage cross sector and international collaborations*
- *Time is of the essence. Need to quickly accelerate development and support multi-year research priorities or Canada will lose innovation edge*
- *Targeted technical research in strategic areas is needed in near term to inform the development of codes and standards and commercialization of cross-cutting H_2 technology applications.*
- *Encourage mission-oriented approaches to focus research, development and demonstration (RD&D).*

7. Remaining Challenges

Canada has a strong head start in hydrogen and fuel cells and is well positioned to realize the opportunities offered by a vibrant domestic and export hydrogen economy. However, there are challenges we must work to overcome. With global competition increasing, targeted actions across the hydrogen value chain are needed to overcome these challenges and position Canada for success.

ECONOMIC & INVESTMENT

The factors limiting hydrogen use in many applications today are economic rather technological, as hydrogen is not yet cost competitive compared to conventional fuel options. For example, hydrogen used as a carbon-free heating fuel is ~5X more expensive than natural gas. While hydrogen can be cost competitive with some RNG sources, conventional natural gas is typically used as the benchmark. Hydrogen can be among the lowest cost alternatives for reducing carbon emissions on a dollar-per-tonne-abated basis. A challenge today is that GHG emissions are not always adequately reflected in the market cost of baseline fuels. Implementation of the federal Clean Fuel Standard as well as carbon pricing, will be important steps forward.

Achieving scale is also critical to economic competitiveness of the sector and to ensuring access to an affordable and abundant source of clean hydrogen. The market for low CI hydrogen in Canada is in the very early stages, and the large capital investment to scale production requires that demand grow concurrently with supply. Predictable, long-term demand is therefore critical before industry can invest in large-scale projects.

Costs of end-use applications are also a barrier to adoption, which can limit demand and associated scale. In transportation applications, FCEVs are more expensive than BEVs and PHEVs, due to low production volumes. Further work is also needed to drive down core fuel cell stack, balance-of-plant, material and manufacturing costs, as well as other vehicle speciality component costs such as hydrogen storage tanks. Investment in R&D is needed to achieve cost parity with alternatives, as is investment in manufacturing processes and facilities to achieve scale. Build out of refueling infrastructure also requires high upfront capital investment. For light duty FCEVs, multi-station refuelling networks providing accessibility and redundancy must be established before OEMs will deploy larger numbers (100s) of vehicles. This is an economic challenge for station developers who are required to make significant capital investments with uncertainty in fueling demand growth over time. For transit agencies looking to deploy FCEBs, the upfront infrastructure costs are high, and makes running early pilot deployments a challenge. While at-scale hydrogen infrastructure has been proven to be very cost effective, getting to scale is a challenge for transit agencies that are cash constrained and risk adverse.

Some applications, such as using hydrogen blended with natural gas as a heating fuel, do not require new or retrofit end-use equipment. However, the economic challenge is that, as described above, the incumbent fuel is very low cost. In addition, utilities will need to make investments in pilot projects and codes and standards development to develop this market.

While the sector must ultimately be self-sustaining, temporary support is needed in the next 5-10 years to attract and de-risk industry investment. This includes through investments in foundational infrastructure and subsidies to encourage end-use adoption and drive to scale up. Attracting investment from international sources will also be important..

TECHNOLOGY & INNOVATION

While some hydrogen and fuel cell technologies are at a level of commercial readiness, sustained support for R&D is needed to further reduce costs, develop solutions in the less mature applications, and discover new breakthrough technologies to benefit the sector. Current short term funding cycles in R&D may limit private sector investment in Canadian innovation. Commitment to support long term R&D for advanced technologies is therefore a current policy gap. Continuing to stay at the forefront of innovation is critical to sustaining Canada's competitive advantages.

Other countries have been rapidly increasing investment in the sector whereas Canada has, in recent years, slowed investment in fundamental research. Canada is also lagging other countries in starting hydrogen pilot projects. As a result, there have been examples of Canadian companies developing research centres and/or moving parts of their operations to other countries where there is more support for technology advancement. It is important for Canada to take action now to prevent loss of critical IP.

Technology development and innovation are needed for core materials, end-use products, as well as in the hydrogen production, storage and distribution value chains. Adjacent and complementary areas such as CCUS will also be critical to Canada's leadership in the sector. Technology development and innovation require local deployments to foster collaboration between industry, academia and international partners. Critical hands on experience can be gained to understand market needs and develop practical and commercially ready solutions. Canada's lack of domestic deployments is currently hampering innovation in the sector.

POLICY & REGULATION

Clean hydrogen projects around the world have primarily been in regions with a combination of supporting policies, regulations, and GHG reduction targets.

There is currently a lack of comprehensive, long-term policy and regulatory frameworks that include hydrogen in Canada. Where policies are in place they, are not consistent across regions resulting in a 'patch-work' approach that slows adoption. Achieving long-term 2050 targets represents a radical transformation of the energy sector and requires clear, coordinated efforts.

Policies and regulations that encourage the use of hydrogen technologies include low carbon fuel regulations, carbon pollution pricing, vehicle emissions regulations, zero emission vehicle mandates, creation of emission-free zones, and renewable gas mandates in natural gas networks. Mechanisms to help de-risk investments for end-users to adapt to regulations are also needed.

A more cohesive national framework with a common vision could provide a clear signal of the importance of hydrogen and avoid a patchwork of policies and regulations across jurisdictions.

HYDROGEN & INFRASTRUCTURE

Domestic supply of low CI hydrogen is limited in many parts of Canada today, and this is preventing both commercial and pilot rollout of end-use applications. For some applications, there is also a need to transport and store hydrogen from the site of production to the end-user. This includes refueling infrastructure for transportation applications. Build out of supply and distribution infrastructure must be timed concurrently with growth in demand, and this can be difficult to coordinate and requires a regionally focused development approach.

Other challenges related to infrastructure include the significant carbon storage requirements for long-term transition of the petroleum and low carbon fuels sectors, as well as the storage of high volumes of hydrogen for integration at existing nuclear sites. Geological storage, such as in depleted wells and salt caverns, will be limited to certain regions, and also require high up-front investment to be validated for hydrogen storage.

Over time, as domestic production and demand grow, there will be a need for dedicated infrastructure such as hydrogen pipelines and liquefaction plants. Ensuring that these crucial assets can be built, in a coordinated and timely manner, will be essential to ensuring low cost, low CI hydrogen can be delivered to both domestic and international markets.

CODES & STANDARDS

The deployment of hydrogen is in the early stages across many jurisdictions and sectors in Canada, and there are some gaps in existing codes & standards that need to be addressed to enable adoption.

Complex local and regional issues related to the certification of new hydrogen deployments may take significant time and effort to resolve. Harmonizing codes and standards across jurisdictions (provincial and international) will ensure that best practices are applied across the domestic and international hydrogen economy to facilitate the growth of trade and export markets.

Applications that have not yet been piloted in Canada and are in the precommercial stage represent important areas of focus. For example, blending of hydrogen into natural gas systems has been demonstrated around the world in numerous power-to-gas projects. Lack of developed and adopted codes and standards in Canada related to this end-use application is currently one of the main rate limiting steps.

Canada is also working with countries around the world to develop and align codes and standards, through efforts like the Canada/US Regulatory Cooperation Council. These efforts also include developing and aligning common methodology to determine the CI of hydrogen production pathways.

AWARENESS

There is currently a lack of awareness about the opportunities for hydrogen and around safety issues, both by the public, as well as within industry and government.

Limited domestic hydrogen deployments have further resulted in a lack of tangible case studies to increase awareness and support long-term planning and buildout. For example, mine safety and reliability must be successfully proven in the pilot stage before technology can be fully adopted.

Increased awareness about hydrogen as a viable decarbonization pathway that is safe and provides economic benefits is critical to establishing a vibrant hydrogen sector. Targeted awareness campaigns in certain industry sectors, including providing easy tools for end-users to evaluate hydrogen options, will be an important step in supporting adoption.

There is currently a lack of awareness regarding how hydrogen fits with other decarbonizing energy vectors in a net-zero future. While deployment of hydrogen and increasing electrification are in fact highly complimentary, perceived competition may limit adoption. This must be addressed with a targeted awareness campaign to show how these applications can work together.

In addition to the need for awareness of the opportunities for hydrogen and around safety issues, there is also the need for targeted awareness of the career opportunities for talented and skilled labour in the hydrogen economy. This includes the transition of mid-career workers and the training of the next generation of workers to the low carbon technology sector.

8. Seizing Canada’s Hydrogen Opportunity

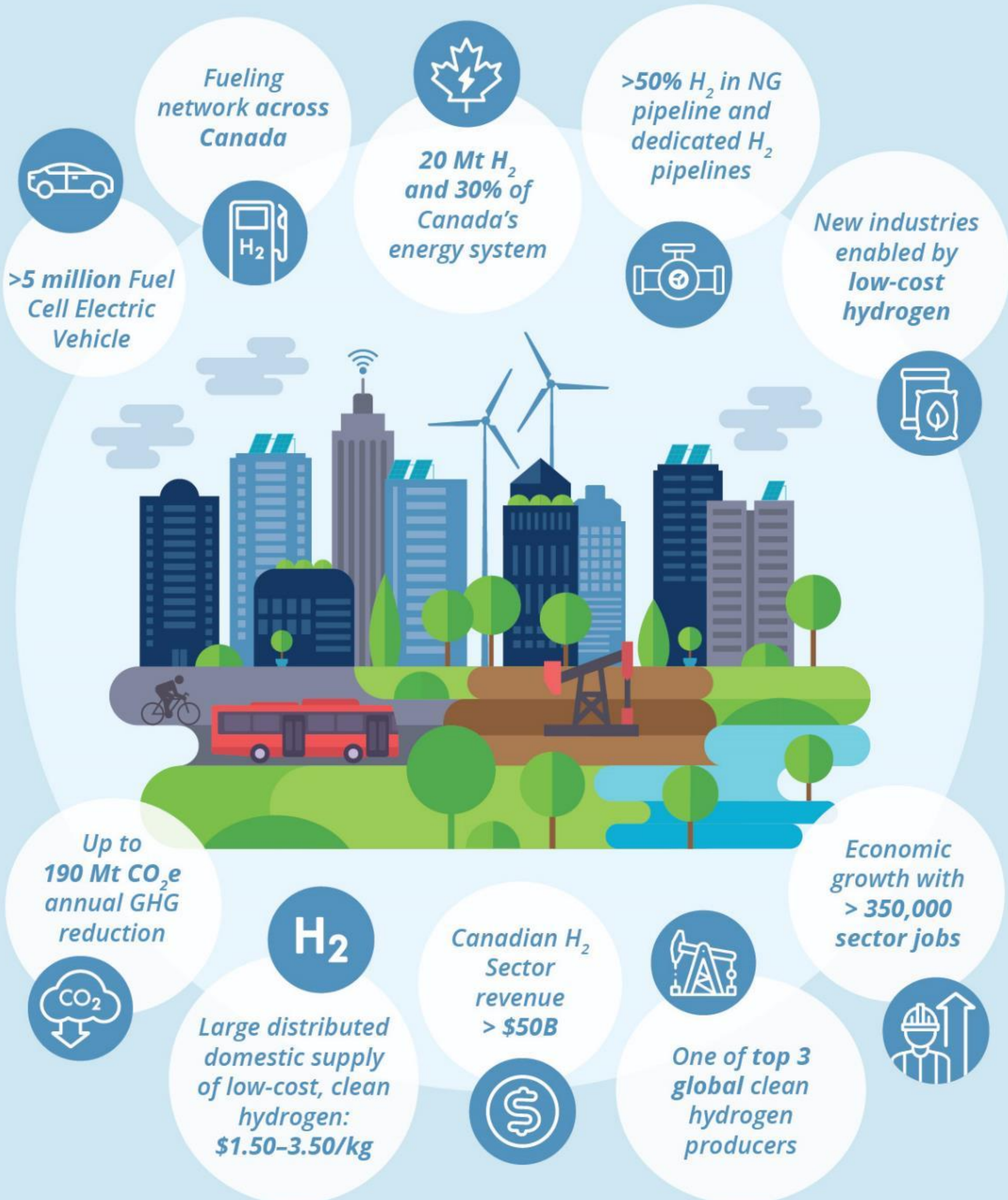
Canada’s hydrogen opportunity is substantial. Canada has all the right ingredients and comparative advantages to develop a robust and thriving domestic hydrogen market. Canada’s resources are suited to producing vast amounts of clean, cost competitive hydrogen that can decarbonize our hard-to-abate end-use sectors from coast to coast. Deployment of hydrogen will lead to economic, environmental, and health benefits for Canadians, and will support Canadian companies at the forefront of the hydrogen and fuel cell sectors. While the immediate priority is on establishing at-scale domestic rollout of hydrogen, the opportunities for export of Canadian hydrogen, as well as products, services, and intellectual property also shows strong potential driven by growth in the worldwide demand for hydrogen.

The *Vision for Hydrogen in Canada in 2050* shows the magnitude of the hydrogen opportunity in Canada. If we embrace hydrogen as a strategic and necessary element of Canada's transition to a more inclusive and equitable clean energy future it can play a pivotal role in helping us achieve net zero by 2050 while maintaining the affordability, reliability and sustainability of Canada's energy supply. Aligning around a common vision is critical to setting us on the right path now.

The *Roadmap to 2050* outlines actions in the next 5 years to lay the foundation for the domestic hydrogen rollout in Canada, grow and diversify the sector in the mid-term, and achieve rapid market expansion in the long-term.

The time to act is now, and the release of this strategy is just the starting point. A set of eight recommendation pillars with specific actions are outlined as guidance for the various committees, working groups, and government and industry players who will together move this forward through the implementation plan.

VISION FOR HYDROGEN IN CANADA IN 2050



ROADMAP TO 2050

Near-Term: Laying the Foundation

The focus of the next 5 years will be on laying the foundation for the hydrogen economy in Canada. This includes developing new hydrogen supply and distribution infrastructure to support early deployment HUBs in mature applications while supporting Canadian demonstrations in emerging applications. Early actions are fundamental to driving investment in the sector, as is the introduction of policies, such as carbon pricing and regulatory measures needed to move Canada forward on a path to achieve net zero targets. Regulations such as the Clean Fuel Standard will be fundamental to driving near-term investment in the sector, in addition to introducing new policy and regulatory measures that will advance Canada to achieve net-zero emissions by 2050. To achieve medium- and long-term goals, innovation investment must be made early. Early stage, 'breakthrough' R&D can take 5-10 years to realize and may require additional work to fully mature. Even later stage support for process efficiency or cost reduction can take several years, followed more time for piloting and demonstration.

Canada's petroleum sector is a major driver of investment, with $52 billion in 2019. Despite the oil price downturn and uncertainty over the COVID-19 recovery, an opportunity exists for government to partner with industry to drive commercial hydrogen projects as part of the sector's net-zero agenda. Similarly, the chemical industry can move to adopt clean hydrogen as a feedstock with government involvement.

Emerging hydrogen use in the near-term will be dominated by mature market applications at or near commercial market readiness including oil and gas upgrading, ethanol plants and landfill gas/biogas-to-RNG upgraders, forklifts, light-duty FCEVs, and FCEBs for transit operation. Pre-commercial applications such as heavy-duty trucks, seaport goods movement equipment, power generation, heat for the built environment, and industrial feedstock applications will be introduced as pilot projects in regional HUBs.

These regional HUBS will be strongly influenced by:

- Regulatory approvals for blending hydrogen and natural gas to decarbonize the utility distribution system.
- Availability of technical evidence from pilots to inform the safe integration of fuel cells into domestic regulatory regimes, i.e. Railway Safety Act, Motor Vehicle Safety Act.
- The best form of renewable gas in a regional context, i.e. the best use for hydrogen, RNG and biogas.
- Zero-Emission Vehicle mandates for passenger vehicles such as the existing legislation in Quebec and British Columbia.
- Variances in CFS compliance plans that will drive low carbon hydrogen generation for industrial applications including the upgrading of transportation fuel products.
- Existing hydrogen generation, distribution and dispensing infrastructure that can be leveraged e.g. liquefaction capacity in Quebec, or steam methane reforming with carbon sequestration in Alberta.

Mid-Term: Growth and Diversification

Activities to stimulate the sector in the next 5 years will be followed by growth and diversification of the sector in the 2025 – 2030 timeframe. Early deployment HUBs will grow and new ones will be initiated, connected by corridor infrastructure. In order to reach the opportunities outlined in the 2050 Transformative scenario, Canada should aim to be 10-20% of the way there by 2030 in terms of deployment volumes and GHG abatement.

As the technology matures and the full suite of end-use applications is at or near commercial technology readiness levels, hydrogen use in the mid-term will be focused on applications that provide the best value proposition relative to other zero-emission technologies. For example, fuel cell electric vehicles and transit buses will enter the rapid expansion phase as the market for fuel cell and battery technology becomes more defined. Fuel cells will gain traction where charging times, energy requirements, range, grade ability, and operation in extreme climates make battery technology technically challenging for specific market segments. Class 8 heavy-duty trucking in corridors that require heavy payloads and drayage equipment in regions with regulated air sheds will be commercially deploy.

New, larger scale hydrogen production in the mid-term will allow hydrogen/natural gas blending for industry, the built environment and as a feedstock for chemical production and hydrocarbon upgrading to be commercialized in regional HUBs. Clean large-scale hydrogen production in the upstream segment of the oil and gas sector will provide low cost hydrogen at volumes that can benefit other sectors.

Deployment in pre-commercial applications like Class 5-7 delivery trucks, operating in urban zero-emission zones, passenger and freight rail where gantry infrastructure needed to electrify the line is prohibitively expensive, mining vehicles and smaller domestics marine vessels continues to grow. Similarly advancement and growth in liquid synthetic fuel and methanol production, can be expected.

A regulatory framework and market ready technologies are expected to enable deployment of hydrogen in mining operations in a variety of good movement and stationary power applications. As increasing renewables are introduced into electricity grids, pilots to explore hydrogen as a utility scale energy storage medium will be required.

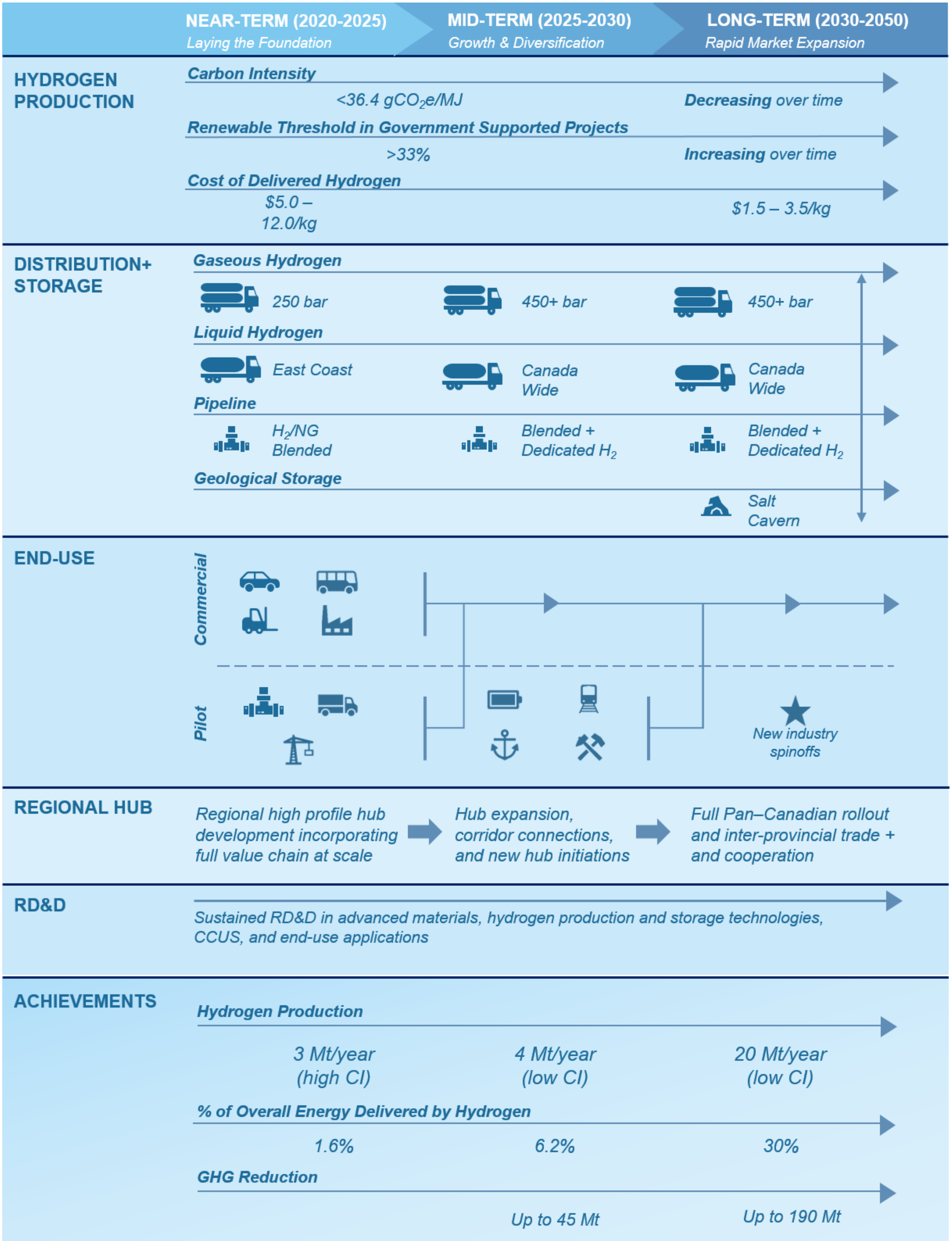
Long-Term: Rapid Market Expansion

In the 2030-2050 timeframe, Canada will start to realize the full benefits of a hydrogen economy as the scale of deployments increase and number of new commercial applications grows, supported by Canada's foundational backbone supply and distribution infrastructure.

In the long-term, it is anticipated that with advances in battery and charging technology there will be a more defined division between battery and fuel cell utilization in Canada for transportation purposes. This will result in the higher power demand applications (utility biased) predisposed toward hydrogen energy storage and the lower power demand applications (efficiency biased) using batteries for energy storage. New transportation applications will move into the commercial and rapid expansion phases during this period.

As the percent of hydrogen in NG systems increases, dedicated hydrogen pipelines will become an attractive alternative.

As low CI hydrogen is more widely available throughout Canada, existing heavy emitting industries will be able to adapt their operations, including, ammonia and nitrogen fertilizers, and low carbon steel.


NEAR-TERM (2020-2025)
Laying the Foundation
MID-TERM (2025-2030)
Growth & Diversification
LONG-TERM (2030-2050)
Rapid Market Expansion
HYDROGEN PRODUCTION
Carbon Intensity
<36.4 gCO2e/MJ
Decreasing over time
Renewable Threshold in Government Supported Projects
>33%
Increasing over time
Cost of Delivered Hydrogen
$5.0 – 12.0/kg
$1.5 – 3.5/kg
DISTRIBUTION+ STORAGE
Gaseous Hydrogen
250 bar
450+ bar
450+ bar
Liquid Hydrogen
East Coast
Canada Wide
Canada Wide
Pipeline
H2/NG Blended
Blended + Dedicated H2
Blended + Dedicated H2
Geological Storage
Salt Cavern
END-USE
Commercial
Pilot
New industry spinoffs
REGIONAL HUB
Regional high profile hub development incorporating full value chain at scale
Hub expansion, corridor connections, and new hub initiations
Full Pan–Canadian rollout and inter-provincial trade + and cooperation
RD&D
Sustained RD&D in advanced materials, hydrogen production and storage technologies, CCUS, and end-use applications
ACHIEVEMENTS
Hydrogen Production
3 Mt/year (high CI)
4 Mt/year (low CI)
20 Mt/year (low CI)
% of Overall Energy Delivered by Hydrogen
1.6%
6.2%
30%
GHG Reduction
Up to 45 Mt
Up to 190 Mt

TIME TO ACT

The time for Canada to act is now. Governments around the world are developing plans for green and inclusive energy recoveries while releasing and executing hydrogen strategies that are building global momentum. In 2019 Canada seized this momentum by developing and launching a new Hydrogen Initiative under the Clean Energy Ministerial, designed to be the cornerstone for global hydrogen deployment. Now, one year later, Canada is poised to again leverage this momentum to grow the domestic opportunity for hydrogen production and end-use, while also benefitting from growth in global demand.

Although the COVID-19 pandemic has shaken all sectors of the economy, the recovery also presents a unique opportunity to build back better to advance a greener and more equitable energy future. The International Energy Agency has recommended that governments put clean energy solutions such as hydrogen at the heart of stimulus plans. Green infrastructure investments are key to achieving the post-pandemic economic recovery, clean growth, and climate change commitments of the Canadian Federal Government. Recovery from the economic impacts of COVID-19 will take many years. Stimulus funding may represent a unique and critical investment opportunity for the foundational infrastructure and skills need to support the sector. If the opportunity is wasted, Canada risks losing its competitive head start as austerity measures kick in during the anticipated recovery period.

Recommendations

Recommendations have been developed in consultation with stakeholders and represent actions needed to lay the foundation for maximizing the benefits of hydrogen in Canada's future energy system mix. These recommendations will inform development of concrete action plans in the implementation phase immediately following the release of this strategy. The recommendations in this section represent sector-wide themes. Recommendations have been proposed in eight pillar areas:

- ***Pillar 1: Strategic Partnerships*** *- Strategically use existing and new partnerships to collaborate and map out the future of hydrogen in Canada.*

- ***Pillar 2: De-Risking of Investments*** *- Establish funding programs, long-term policies, and business models to encourage industry and governments to invest in growing the hydrogen economy.*

- ***Pillar 3: Innovation*** *- Take action to support further R&D, develop research priorities, and foster collaboration between stakeholders to ensure Canada maintains its competitive edge and global leadership in hydrogen and fuel cell technologies.*

- ***Pillar 4: Codes and Standards*** *- Modernize existing and develop new codes and standards to keep pace with this rapidly changing industry and remove barriers to deployment, domestically and internationally.*

- ***Pillar 5: Enabling Policies and Regulation*** *- Ensure hydrogen is integrated into clean energy roadmaps and strategies at all levels of government and incentivise its application.*

- ***Pillar 6: Awareness*** *- Lead at the national level to ensure individuals, communities, and the private sector are aware of hydrogen's safety, uses, and benefits during a time of rapidly developing technologies.*

- ***Pillar 7: Regional Blueprints*** *- Implement a collaborative, multi-level, collaborative government effort to facilitate the development of regional hydrogen blueprints to identify specific opportunities and plans for hydrogen production and end use.*

- ***Pillar 8: International Markets*** *- Work with our international partners to ensure the global push for clean fuels includes hydrogen so Canadian industries thrive at home and abroad.*

A series of four concrete actions and rationale are provided for each of the eight pillars in the following section.

Pillar 1: Strategic Partnerships

1. *Collaborate across multiple levels of government and with Indigenous groups through Intergovernmental Working Groups to establish priority areas for deployment and to share knowledge, best practices, and lessons learned through early deployments.*

2. *Expand public/private partnerships leveraging Canada's innovative clean technology companies and world-leading hydrogen and fuel cell expertise to accelerate deployment projects across the value-chain.*

3. *Foster cross-sector collaborations within regional deployment HUBs to show the economic and operational benefits of multiple applications operating as part of an integrated ecosystem.*

4. *Leverage international collaborations and pursue synergistic international initiatives to attract direct foreign investment and to accelerate opportunities for Canada in global markets.*

Rationale

Hydrogen is an energy vector that crosses geographical boundaries, ties energy systems such as the electricity and natural gas grids together, and whose benefits are best demonstrated in integrated deployments that span multiple end-use applications. Stakeholders identified that better information sharing and collaboration across regions and sectors is needed to develop Canada's hydrogen economy. Strategic partnerships are needed across levels of government and regions, between the public and private sector, with Indigenous groups, across industry sectors and academia, and with international partners.

Coordination across all levels of government will be essential to align policies and programs and identify areas for collaboration. Coordination of this type is best carried out through an intergovernmental working group. Similarly, to ensure the unique perspectives, needs, and priorities of Indigenous groups are fully represented, a dedicated Indigenous working group could be considered.

Government and industry must work closely together, with each playing important but distinct roles and each bringing resources, expertise, and perspectives to the table. Strategic partnerships between governments and industry are also essential in successfully growing domestic hydrogen deployment. Early adoption is likely to occur in areas which bring together governments, fuel producers, end-users, and other key players, in a HUB concept, which ensures supply and demand grow together.

High profile domestic deployment HUBs or 'lighthouse projects' will be important to show the business case for hydrogen at scale. These early domestic deployment HUBs should be encouraged to include pan-Canadian participation where practical, and to include targeted outreach activities and information sharing. Initiation of these projects has already started with many 'shovel-ready' projects proposed as green stimulus recovery initiatives.

Canada cannot do this alone. While Canada demonstrated early leadership in both hydrogen and fuel cells, activity and investment in hydrogen has been accelerating around the world with other nations developing comprehensive plans for their own domestic and export markets. Canada can learn from international partners as well as help grow international trade opportunities by sharing learnings from domestic activities. International partnerships will range from government collaborations on policy approaches, to research collaborations in shared areas of interest, to participation in international codes and standards development, to the development of trade opportunities. International partnerships can be facilitated through the Hydrogen Initiative with International Energy Agency as Operating Agent, as well as Canadian Trade and Investment support channels.

Pillar 2: De-Risking Investments

5 *Implement long-term policies that create hydrogen demand certainty and de-risk the private sector investments needed to establish supply and distribution infrastructure.*

6 *Establish multi-year programming as well as a clear and long-term regulatory environment to support early production and end-use projects, including support to assess the feasibility of projects.*

7 *Develop regional deployment HUBs to demonstrate, validate, and implement business cases across the full value chain, from production and distribution to end-use.*

8 *Facilitate co-funding opportunities, leveraging multiple levels of government and the private sector.*

Rationale

It is estimated that $5B - $7B of combined public and private investment will be needed in the five years to lay the foundation of a strong national hydrogen economy that will maximize emissions reductions and provide long-term economic growth for the sector. Attracting this magnitude of investment from domestic and international sources requires actions across several fronts to de-risk investments.

Governments at all levels, as well as private sector stakeholders will all have a role to play in de-risking these investments.

Long-term policies such as the federal Clean Fuel Standard (CFS) and carbon pricing are important steps toward creating an environment of higher certainty for investors. The CFS could recognize hydrogen as a pathway to reduce the CI and resulting credit burdens on conventional fuels. The CFS could also provide credit generation and financing opportunities for projects that generate clean hydrogen. While the CFS does not preclude these pathways, there is an opportunity to be more explicit in how hydrogen can be considered as a compliance mechanism.

Long-term government climate policies like carbon pricing that reflect the externalities of climate change, air pollution, related health issues, and energy security can also provide a signal to stimulate investments. Governments can also provide market certainty by leading through example with strong procurement policies. This has been successful in Quebec where the provincial government's procurement of FCEVs in Quebec City spurred the buildout of fuelling infrastructure by industry.

Tax deductions to corporate, institutional, and individual investors made in the cleantech space is another mechanism to de-risk and attract investments, as is expanding the 100% accelerated capital cost allowance to all cleantech investments including those in hydrogen.

The market for low CI hydrogen in Canada is in the very early stages. While the sector must ultimately be self-sustaining, temporary fiscal support to de-risk investments across the value chain is needed in the next 5-10 years, while the market matures.

Canada can learn from other regions like California, where established multi-year funding commitments have been effective. For example, the California Energy Commission provides funding for hydrogen infrastructure build-out in conjunction with a Low Carbon Fuels Standard program that offers capacity payments to provide revenue certainty while demand for hydrogen grows.

Funding models should evolve over time. In the early stages resources could support projects that span the entire value-chain, both through regional deployment HUBs and large-scale projects. Considerable up-front work is required to develop complex projects of this nature, from a technical and economic perspective, before domestic projects can move into the implementation phase. Support for feasibility studies should be considered as an essential first step in project development.

Pillar 3: Innovation

9 *Develop strategic fundamental research priorities where Canada can sustainably excel and provide economic value; set technology performance and cost goals.*

10 *Establish dedicated funding for sustained RD&D to ensure Canada retains its leadership position in hydrogen and fuel cell technologies.*

11 *Leverage expertise in academia, government labs, and private sector labs to create regional research hubs and to encourage mission-oriented approaches to research, development, and pilot deployments.*

12 *Foster collaboration between Federal labs, industry, and academia as well as international partners, by supporting consortium-based projects for fundamental research and by coordinating reviews and information sharing.*

Rationale

Canada was an early leader in the hydrogen and fuel cell sector and is recognized worldwide as a region for technical expertise, intellectual property, and leading products and services. While some hydrogen and fuel cell technologies are at a level of commercial readiness, support for RD&D is needed to further reduce costs, develop solutions in the less mature applications, and discover new breakthrough technologies. Continuing to stay at the forefront of innovation is critical for sustaining Canada's competitive advantage. Other countries have been rapidly increasing investment in the sector, and Canada's leadership role is in jeopardy. As a result, there have been examples of Canadian companies developing research centres and/or moving parts of their operations to other countries where there is more support for technology advancement. It is important for Canada to act now to prevent loss of critical IP and cleantech jobs.

Canada already has a leading fuel cell sector with expertise ranging from fundamental materials to complete systems and vehicles. Building on these strengths by identifying priority areas, in consultation with industry and academic stakeholders, where Canadian researchers can excel will be essential to maintain leadership. Canada also has complementary technologies such as CCUS and hydrogen storage which are unique to Canada's geology. Canada can also leverage existing expertise in engineering and systems integration using deployment HUBs to strengthen local skills and knowledge while promoting a more diverse and inclusive workforce.

A mission-oriented approach would set a clear direction and align the efforts of participants across the energy ecosystem, while using the full range of government instruments to generate investments and innovation across the economy.

Funding for advanced research and development must come from both the public and private sector. Stakeholders identified gaps and limitations such as how much Canadian government funding can be used as "match funding" on international collaboration projects.

Collaboration across federal labs, industry, and academia is ultimately needed to both drive innovation and to develop the next generation talent pool in the sector. Canada has seen talent being recruited by other regions and efforts are needed to fight the "brain drain". Without top talent, innovation will slow. To attract new young talent to the sector, students must be able to see a linkage to industry opportunities and this can be facilitated through industry/academia collaborations, through industry sponsored student competitions, as well through internships and co-op placements. A Canadian mechanism to establish targets and priority areas modelled after the U.S. DOE's Multi-Year Research, Development, and Demonstration Plan could be used to provide guideposts to drive towards common goals. Reviews to track progress and share information could be coordinated in an annual merit review type format.

Canadian expertise in hydrogen technology development, both within academia, and in the private sector, is recognized around the world. Sustained resources to support innovation will also enable Canadian researchers to build and strengthen collaboration internationally. International collaborations will ultimately accelerate hydrogen deployment both at home and abroad.

Pillar 4: Codes and Standards

13 *Update, harmonize and recognize codes and standards (including the Canadian Hydrogen Installation Code) to enable deployments and to facilitate new technology and infrastructure adoption in early markets.*

14 *Establish a codes and standards working group, which includes inter-provincial Authorities Having Jurisdiction representatives, to share lessons learned and identify gaps in codes and standards.*

15 *Develop standards that are performance based versus prescriptive, and ensure hydrogen is not excluded from broader codes, standards, and regulations due to restrictive language.*

16 *Facilitate Canadian leadership and participation on international standard and certification efforts (e.g. development of global carbon intensity metrics, blending levels for hydrogen in natural gas systems), simplifying international trade.*

Rationale

Deployment of hydrogen technologies, including fuels cells, and refueling infrastructure, is in the early stages in many parts of Canada. It is important that codes & standards are in place that support deployment, and keep pace with new technology and innovation. Wherever possible, these standards should be performance-based rather than prescriptive to ensure that innovation is not restricted in this emerging sector.

Canada has a mature and effective standardization framework led by the Standards Council of Canada, and national standards development organizations (SDOs) like the Bureau de Normalization du Québec (BNQ) and CSA Group. However, these organizations are dependent on resources, and subject area expertise from industry and governments, to facilitate their work.

One of the foundational pieces in Canada is the Canadian Hydrogen Installation Code (CHIC) which sets the installation requirements for equipment that produces, uses or dispenses hydrogen. Although the CHIC was first of kind globally when it was developed in 2010, it has not been kept up to date, to include the most recent advancements and understanding. This has forced domestic hydrogen deployment activities to reference more recent codes from other jurisdictions internationally. This difference between established industry practices and the national code has led to inconsistencies in how Authorities Having Jurisdiction (AHJ's) recognize certify hydrogen projects across the country. While an updated version of CHIC is currently being finalized, going forward more timely updates to the code and recognition/implementation by the Provinces will be essential to facilitating the installation and operation of new hydrogen equipment in Canada.

As one of the key applications for hydrogen, the decarbonization of natural gas requires regulatory changes within the provinces to allow the use of hydrogen in natural gas distribution and transmission networks. These regulatory changes (e.g. expanding the definition of renewable gas) will be underpinned by detailed technical codes and standards, for example for material compatibility, design, testing, for key system components.

The revision, development, and adoption of key codes and standards is an essential component to enable Canada to seize the hydrogen opportunity. This work will require a coordinated effort between industry, the SDO's, national testing laboratories, and the Provincial and Federal governments, as well as Authorities Having Jurisdiction. As part of the implementation plan, it is recommended that a dedicated codes and standards working group be formed that includes industry across the value chain, SDO's, national testing laboratories, academia and the Provincial and Federal governments. Working group members should work through a Standardization Collaborative to clearly identify gaps in Canada's hydrogen codes and standards, and to develop a prioritized action plan to close gaps. As broader codes and standards are developed (e.g. definition of RNG in natural gas networks), it will be important to establish performance based standards that do not exclude hydrogen.

One of the most effective ways to accelerate domestic adoption of hydrogen is to focus on harmonizing Canadian standards with international requirements for safety, performance, and reliability, especially in jurisdictions where Canadian suppliers are working extensively. Harmonized standards allow Canadian companies to support multiple markets with the same equipment design, avoiding costly customization, unnecessary certification testing, and potential barriers to market entry.

Pillar 5: Enabling Policies and Regulations

17 *Ensure that governments at all levels consider hydrogen's essential role in Canada's energy future as they develop new policies, programs, and regulations.*

18 *Encourage governments to modernize and update existing policies, programs, and regulations to facilitate growth of domestic hydrogen production and end-use.*

19 *Ensure hydrogen is part of integrated clean energy roadmaps at national and provincial/ territorial levels.*

20 *Establish technology-neutral, performance-based standards to define a hydrogen carbon-intensity threshold. Establish tiered, time-based requirement for renewable hydrogen content in government supported projects.*

Rationale

Canada's net zero future will be powered by two things, electricity and low carbon fuels. Hydrogen shows the potential to make up to 30% of Canada's delivered energy in a net zero future, closing the gap in the toughest and most hard-to-abate energy intensive sectors. The critical role that hydrogen can play in our net-zero future should be considered as governments develop their own long-term climate policies, programs, and supporting regulation.

Similarly, there is an opportunity to lever existing policies, programs, and regulations to align with and support a path to being net-zero, which includes hydrogen.

The regions that have been most successful in stimulating the adoption of hydrogen have developed a combination of regulations and programs that work hand-in-hand, and stakeholders have indicated that this is what is needed as a cohesive pan-Canadian approach. Regulatory tools can either require adoption of alternative technologies or inhibit the use of conventional technologies. A zero-emission vehicle mandate and creation of emission-free zones or imposing high road taxes on internal combustion engine vehicles are all examples of policies which have been implemented in jurisdictions around the world. In Canada, both BC and Quebec have implemented ZEV mandates, and these are the provinces where FCEVs are being deployed and investments in infrastructure are being made.

Emissions standards are another mechanism to drive adoption of low- and zero- emission vehicles that are considered less prescriptive than ZEV mandates.

Canada has some existing policies, program, and regulations in place to drive towards decarbonization and sustainability goals. An important early activity will be to modernize and update existing policies, program, and regulations to ensure they are inclusive to hydrogen.

To meet long-term decarbonization goals, Canada will need to support all low carbon pathways, including electrification, low carbon fuels, and hydrogen. An overall integrated clean energy roadmap at the national level, and sub-national level could help identify the best role for each low carbon pathway and will identify how each pathway can be synergistic. For example, hydrogen is sometimes seen as competing with direct electrification. However, using hydrogen as a utility-scale energy storage medium can in fact enable higher penetration of variable renewables on the grid and aid in increased electrification. Roadmaps need to try to overshoot in all pathways to address the inherent uncertainty involved in the radical transformation that will need to occur in Canada's energy mix to meet carbon neutrality by 2050.

Ultimately both the CI and sustainability of feedstocks used to make hydrogen are important. In the near term, the focus needs to be on setting clear CI threshold for hydrogen. New policy should be considered to drive increasing non-emitting content in hydrogen supply to make sure that Canada develops energy sources that can be replenished in a reasonable timescale.

Pillar 6: Awareness

21 *Support community engagement and outreach where deployment HUBs are established.*

22 *Establish awareness and outreach campaigns to educate government, industry, the public, and other important influencers about hydrogen safety, uses, and benefits.*

23 *Develop a suite of tools and resources for early hydrogen markets to help end-users quantitatively evaluate hydrogen as an option for their operations. Host the tools and resources through a central, government-run website.*

24 *Support collaborations between industry and academia to develop hydrogen-specific curriculums to build awareness, interest, skills development, and training to develop the next generation talent pool and prepare the labour force for new opportunities.*

Rationale

Stakeholder engagement consistently highlighted a lack of awareness within the public, as well as within industry and government about hydrogen opportunities and safety issues. Increased awareness about hydrogen as a viable decarbonization pathway that is safe and provides economic benefits is critical to establishing a vibrant and inclusive hydrogen sector.

One of the best opportunities to drive awareness is to deploy hydrogen domestically in projects that are high profile and include awareness and outreach campaigns. Projects that provide an opportunity for the general public to interact with hydrogen as a fuel – for example fuel cell buses, hydrail or fleet vehicles such as car sharing services – provide a greater opportunity for outreach. Funded projects should require an element of outreach through program design.

A targeted hydrogen outreach campaign should be coordinated across the country and offered regionally to a range of stakeholders via different channels under a common brand and banner. This can include technical sessions and general campaigns to raise consumer awareness about hydrogen.

Governments, industry, academia, Indigenous organizations, and non-Government Organizations all can play an important role in supporting the development of tools that enable end-users to evaluate hydrogen as an alternative fuel in their operations, ensuring these materials meet their needs, and that of the general public. Examples include an online total cost of ownership tool for transit agencies, to compare lifecycle costs of a fuel cell bus to alternatives.

Sectors that are heavy users of diesel, such as the mining sector where there are multiple potential uses of hydrogen and each operation is unique, could benefit from a publicly available online tool that provides directional cost and business case assessment. There is a need for other basic tools, such as conversion factor tools and case study information, that could be shared in a centralized portal such as regularly maintained website.

As the hydrogen economy grows in Canada, the availability of a diverse and skilled workforce is essential. To attract the next generation of talent to the industry and/or encourage retraining from adjacent sectors with complementary skillsets, there needs to be a clear linkage to the growth in well-paid employment opportunities. This includes reflecting these emerging opportunities in labour market information available to Canadians to support their education and career choices. Industry/academia collaborations can support training, provide important new IP to benefit industry, and show students that there is a growing industry open to participation from all corners of society. Together, we must work to increase workforce participation from marginalized and underrepresented populations—including but not limited to women, youth, people with disabilities, and Indigenous peoples—to build a more inclusive and equitable low carbon energy sector. Early education outreach in elementary and high schools that includes hydrogen as part of Canada's overall clean energy future is also important.

Pillar 7: Regional Blueprints

25 *Facilitate the development of regional hydrogen blueprints, as a multi-level government collaborative effort, to identify specific opportunities and plans for hydrogen production and end-use. Ensure federal participation to capture synergies with the Hydrogen Strategy for Canada.*

26 *Identify opportunities for the establishment of regional HUBs, comprised of projects along the entire value-chain*

27 *Include utilities, major industry from adjacent sectors, and cleantech companies in development and implementation of blueprints.*

28 *Identify areas for alignment and replication with other provinces/regions to facilitate and accelerate overall adoption.*

Rationale

Hydrogen represents a truly pan-Canadian opportunity: from Western Canada with its abundant natural gas resources and carbon capture expertise, to Eastern Canada with its vast hydroelectricity resources. Hydrogen can be produced by a wide range of mature and emerging pathways. Local energy and feedstock resources as well as geological considerations will dictate the ultimate pathway(s) for producing hydrogen in each region. Most Canadian provinces can become producers of hydrogen for local use or export. Similarly, while there are opportunities to deploy hydrogen in a variety of end-uses across the country, these opportunities, particularly in the early deployment stages, depend on local industry interest, economic factors, as well as local policies and regulation.

For hydrogen to gain traction in Canada, projects which span the entire value chain from production, to distribution and storage, to end use will play a key role. This can be facilitated by the development of regional HUBs which can grow supply and demand concurrently. Governments at all levels will play important roles in supporting local deployment.

To seize these regionally diverse opportunities, the Hydrogen Strategy is complemented by a series of regional blueprints to guide the way. BC, Alberta, Quebec, and Atlantic Canada have already initiated activities to identify the opportunities and benefits hydrogen can offer their regions as a first step to releasing blueprints.

There is an opportunity to leverage local strengths, including research centres, major industries, and cleantech leaders, to contribute to the development and implementation of regional blueprints.

It is recommended that a diverse set of stakeholders be consulted in the development of these blueprints, including provincial and municipal governments, Indigenous groups, utilities and independent power producers, large established industrial players in adjacent sectors, end users, potential hosts for regional deployments including ports and industrial network clusters, as well as the cleantech sector and solution providers.

While local government and industry will take the lead in establishing these regional blueprints, there are benefits to having pan-Canadian coordination. This will help to avoid duplication and to identify areas for collaboration. Support will also be required to overcome common challenges across regions or for addressing issues that are critical to Canada developing and maintaining strategic advantages in the sector. There is a role for all levels of government to identify and enable the development of the pan-Canadian infrastructure assets which are needed to connect regional HUBs and support widespread adoption.

Pillar 8: International Market

29 *Develop a strong Canadian brand, positioning Canada to be a global supplier of choice for low carbon hydrogen, and the technologies to use it.*

30 *Invest in infrastructure to connect Canadian supply to international markets, such as liquefaction assets for energy dense hydrogen transport and hydrogen pipelines from western Canada to the US.*

31 *Establish domestic flagship projects that highlight Canada's expertise, attract investments into the domestic market, and that can be replicated internationally.*

32 *Leverage existing international fora (e.g. Clean Energy Ministerial Hydrogen Initiative, G20, IEA) to showcase Canada's leadership, and advance new market opportunities.*

Rationale

Momentum is growing globally, with countries around the world developing their own hydrogen strategies backed by significant investments, resulting in growing demand for hydrogen and the technologies to use it. Canada has advantages that position us to become a domestic producer and user of hydrogen as well as energy exporter, supplying clean hydrogen and hydrogen technologies into growing international markets. Important actions are required in the near term to secure the position of Canada's supply chain in global markets to fortify clean production, manufacturing, expert hydrogen sector services, and jobs in Canada.

Branding and promoting Canada's low carbon fuels, including hydrogen, will be important to gain market acceptance. This includes ensuring Canadian hydrogen production pathways are backed by certified lifecycle analysis. In considering the export of hydrogen, it is important to participate in international standards development activities underway to set thresholds and certify compliance with fuel standards.

For Canada to supply hydrogen to the European market, establishing aligned thresholds and ensuring third party certification systems are in place will be essential. Canadian natural gas pipelines cross borders into the US, and a top priority in anticipation of hydrogen blending into the pipeline is bilateral alignment on standards and certification with the US.

From the Canadian Pacific Railway to the St. Lawrence Seaway to the Trans-Canada Highway, the big projects that helped to build our country have always needed the vision and leadership of government. Now is the time to imagine a clean energy future enabled by new infrastructure assets such as hydrogen pipelines and hydrogen production and liquefaction plants that produce and move hydrogen within and across Canada and connect us to export markets. Development of infrastructure takes time, and Canada must identify enabling infrastructure for the sector.

Canadian technology is already powering a significant portion of hydrogen and fuel cell deployments globally. Over the next five years as domestic regional deployment HUBs grow and international markets develop, domestic deployments will provide reference projects that can highlight Canada's leadership. The experiences gained can be used to replicate similar projects in other countries using Canadian products, services, or intellectual property. A common theme heard from cleantech stakeholders is that international partners ask to see local reference projects to validate technology readiness and the business case.

Canada also leads and participates in several international partnerships, including the Clean Energy Ministerial, Mission Innovation, the IEA, and the International Partnership for Hydrogen and Fuel Cells in the Economy. These existing channels can be leveraged to showcase Canada's leadership in the hydrogen sector and advance new market opportunities.

Roles and Responsibilities

Development of a strong Canadian hydrogen economy requires a coordinated and collaborative effort between industry, governments, Indigenous organizations, utilities, academia, and non-government organizations driven by a common vision and strategy. The stakeholders in Table 3 were identified with roles and responsibilities in advancing he recommendations of this Strategy. For many of these activities, numerous stakeholders could play a role; however, the table aims to provide a general overview of the roles that key stakeholders could play during the early stages of hydrogen market development.

Table 3 – Stakeholder Roles and Responsibilities by Recommendation

● Responsible ◐ Informed/Consulted		Governments	Industry	Utilities	Academia	Indigenous	NGOs
Strategic Partnerships	Intergovernmental collaboration	●				●	
	Public/private partnerships	●	●	●		●	
	Cross-sector collaboration	●	●	●	●	●	●
	International collaboration	●	●	◐	●	◐	
De-Risking of Investments	Long-term policies	●					◐
	Multi-year programming	●					
	Domestic deployment HUBs	●	●	◐	◐	◐	◐
	Facilitate co-funding opportunities	●	◐	◐			
Innovation	Strategic research priorities	●	●	◐	●		
	Dedicated funding for RD&D	●	●	●	●	◐	◐
	Regional research HUBs	◐	●	◐	◐	◐	◐
	Consortium-based projects	◐	●	◐	●	◐	◐
Codes & Standards	Canadian Codes & Standards	●	◐	◐			◐
	Codes & Standards working group	●	●	●	◐		
	Performance based standards	●					◐
	International standards/certification	●	●	◐	◐		
Enabling Policies & Regulation	Hydrogen's role in new policies, programs, & regulations	●	◐	◐	◐	◐	◐
	Modernize existing policies, programs, regulations	●	◐	◐	◐	◐	◐
	Hydrogen in clean energy roadmaps	●				◐	◐
	Technology-neutral & performance-based	●					
Awareness	Awareness outreach in HUB regions	◐	●	◐	◐	●	◐
	Awareness on safety, uses, benefits	●	◐	◐	◐	◐	●
	Hydrogen tools and resources	●	●	◐	◐	◐	◐
	Industry/academia collaboration	◐	●	◐	●		
Regional Blueprints	Develop regional blueprints	●	●	●	◐	●	◐
	Identify regional HUBs	◐	◐		●	●	
	Diversify stakeholder input	●	●	●	●	●	●
	Alignment across regions/provinces	●	◐	◐	◐	●	◐
International Markets	Canadian brand	●	●	◐	◐	◐	
	Infrastructure Investments	●	●	●		◐	
	Domestic flagship projects	●	●	●	●	◐	●
	Leverage international relationships	●	●	◐	●	◐	◐

Implementation Plan

The release of this strategy is meant to serve as a catalyst for the next stages in Canada's hydrogen story. Following the release of this *Hydrogen Strategy for Canada*, there will be ongoing engagements with public, private, academia, and Indigenous partners. These engagements will be managed through a Strategic Steering Committee chaired by NRCan with committee members sourced from various sub-working groups (Figure 52). The Strategic Steering Committee and Working Groups will be tasked with building the momentum around the strategy, initiating and tracking activities related to the recommendations, following progress, and identifying new priority areas as the market evolves.

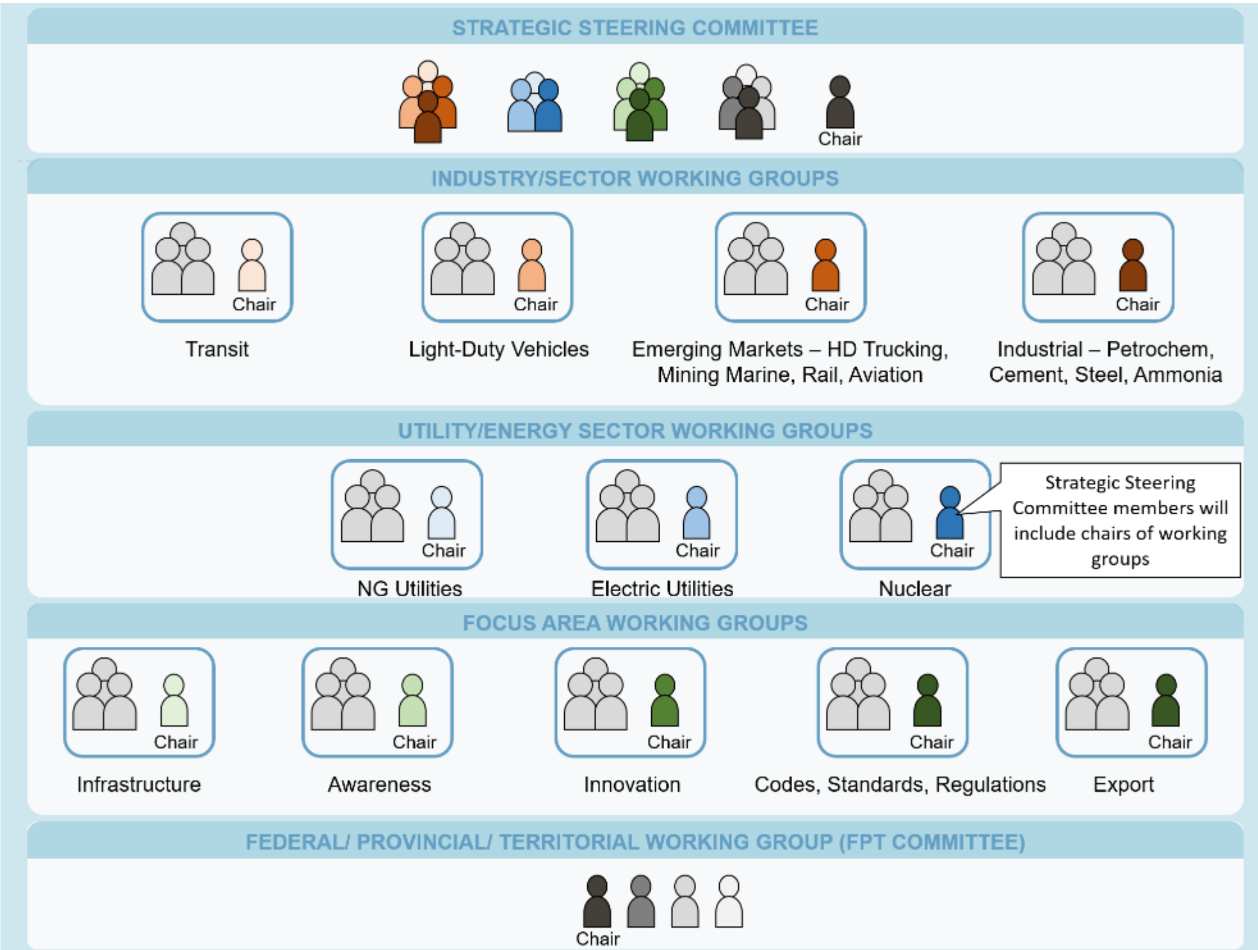


Figure 52 – Implementation Working Groups

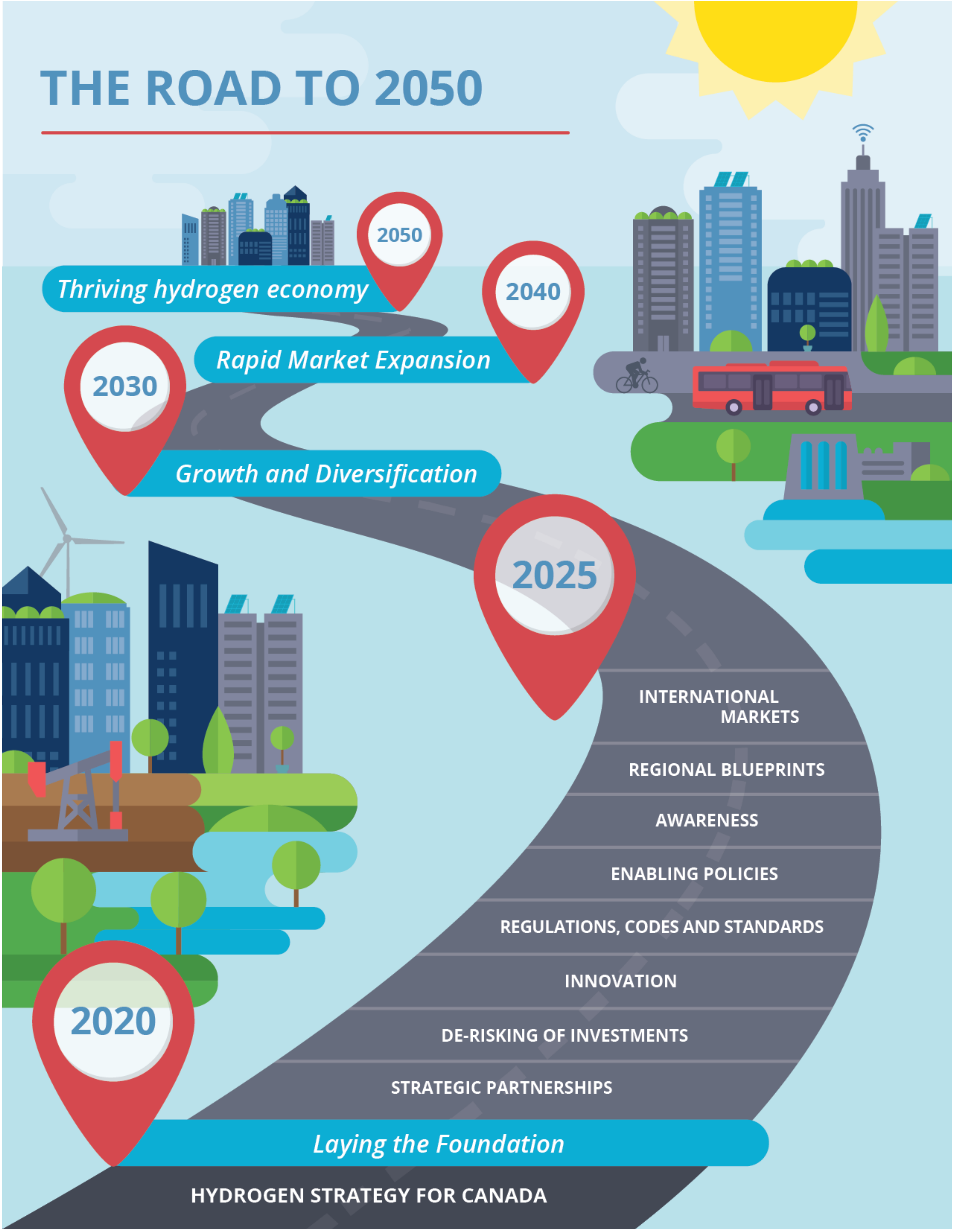


Figure 53 – Roadmap to 2050