July 2022

CHALLENGES AND OPPORTUNITIES IN SCALING CANADA'S CLEAN HYDROGEN ECONOMY:

Drawing attention to the potential of nuclear energy

Authors: Umer Farooq, Montajima Tasnim, Muhammad Hamza Abbas, Jaclyn Victor

Policy Lab Project, Max Bell School of Public Policy, McGill University

COACH: JONATHAN ARNOLD

SPONSOR: CANADIAN NUCLEAR ASSOCIATION

COURSE INSTRUCTOR: NATHALIE MARIE J. DUCHESNAY

Acknowledgments

Many thanks to the Canadian Nuclear Association for providing us with such a topical policy question and for the guidance provided by John Stewart and Victoria Christie. We are deeply indebted to our wonderful coach, Jonathan Arnold, for his continued support and feedback throughout the entire process – this would not have been possible without him. Thank you as well to the federal and provincial governments, academics, research organizations, industry experts, and climate organizations who generously made time to speak with us to share many emerging insights – a complete list of experts can be found in Annex 4. Finally, we feel incredibly fortunate to have received ongoing support from our families, friends, and colleagues over the last several months.

We extend our sincere gratitude to you all for your support, expertise, and willingness to inform our work.

This work is produced by a group of students at McGill University's Max Bell School of Public Policy as part of their program requirements. The following opinions do not reflect those of McGill University, the Max Bell School of Public Policy, the Canadian Nuclear Association, or any affiliated individuals.

Executive Summary

The signatories of the Paris Agreement committed to achieving net-zero carbon emissions by 2050. To reach this goal, the global energy transition away from fossil fuels is essential. Hydrogen will play a crucial role in this transition and in the associated diversification of energy resources – particularly in sectors where reducing emissions is difficult and expensive.

Canada is among the first countries to strategize its priorities for producing and utilizing low carbon-intensity hydrogen as a key enabler for energy diversification. The federal government recently pledged to accelerate its emissions reductions, now targeting a 40-45% reduction by 2030. Canada is well-placed in this transition because, due to their technical and human resource capacity, natural resource feedstocks, political will, and well-established fuel cell production technology, the country has a comparative advantage.

This policy brief considers various competitive production pathways to make hydrogen. It focuses particularly on nuclear-to-hydrogen pathways, recognizing a general lack of discussion within the hydrogen industry and federal government about its potential.

Scope of this report: This policy brief explores various hydrogen production pathways, Canada's comparative advantage, the role of nuclear energy, necessary market mechanisms for upscaling, end-use demand for hydrogen, and some challenges associated with the emerging hydrogen economy. It ultimately provides recommendations for both federal and provincial governments regarding the measures needed for realizing the potential of clean hydrogen in Canada.

Methodology: As part of this report the team conducted a thorough literature review, analyzed relevant data, and conducted key informant interviews. Limitations are discussed in section 3.3.

Key Insights

Production pathways

Hydrogen is a versatile energy carrier in that it can be produced from various feedstocks and with several different processes. Primary pathways to produce low-carbon hydrogen include fossil fuels via steam methane reforming, with the option of using carbon capture and storage (CCS) or renewable and nuclear energy resources via electrolysis. Canada has an advantage in producing hydrogen with these feedstock and processes, as it has abundant hydrocarbon resources and low-cost clean electricity. The diverse geography of Canada extends distinct opportunities for regions to each devise their production policies based on the resources available to them, while also considering the cost and carbon-intensity of different hydrogen production processes.

Hydrogen production via steam methane reforming is one of the most cost-effective processes, however, since the feedstock is fossil fuels, it produces significant carbon dioxide (CO_2) emissions and the need to capture up to 90% of these increases cost and complexity, making is less favourable. Nonetheless, this pathway is well-established in resource-rich jurisdictions like Alberta and Saskatchewan and can play a transitory role on the path to net-zero if coupled with CCS. Since large industrial clusters already need and use hydrogen, the demand market could be further realized through this pathway.

This could pave the path for clean hydrogen production via electrolysis in the medium- to long-term, where the hydro, wind, solar, or nuclear energy resources could be deployed to further reduce emissions. Electrolysis uses electricity to separate hydrogen and oxygen atoms from water, however, it is electricity-intensive, thus it is best to use clean electricity to power the production.

Nuclear energy extends a significant opportunity to the net-zero transition by being a low-emission, high-density feedstock. Nuclear energy can also be used to power electrolysis in a clean manner, with the electricity being generated in either large nuclear generating stations or small modular reactors (SMRs).

End-use demand for hydrogen

The transition to net-zero requires both higher supply and demand of hydrogen so that economies of scale can be developed. Today's high hydrogen production costs lead to low end-use demand. Without higher demand, Canada will not achieve economies of scale, thus production costs will remain high. To address this circular causality problem, the federal government must encourage and support the development of both the demand and supply sides of the hydrogen economy.

Hydrogen does have a substantial market in industrial applications such as oil refining, ammonia production, methanol production, and steel production. Hydrogen demand in the transportation sector is also expected to rise in the medium- to long-term. Given that transportation is Canada's second-largest contributor to national carbon emissions, it would benefit from a full transition to net-zero fuel sources. Although hydrogen is not expected to have market demand for use in light-duty vehicles in the short- to medium term, however, it has enormous potential in heavy-duty vehicles in the medium to long-term. Canadian heavy-duty fuel cell vehicles are more economically efficient than many other low-carbon alternatives; however, these vehicles are limited in supply and the fueling station network is currently insufficient to accommodate a greater supply of vehicles. Hydrogen could also become a promising fuel for long-distance marine vessels, although further research is required to demonstrate the safety of storing hydrogen fuel on ships.

Market barriers to scaling hydrogen production

There are certain market barriers making it difficult to scale and balance supply and demand. Key ones include the high production costs, high-risk investments, and a lack of storage and transportation infrastructure.

Because transportation infrastructure is limited, most of the hydrogen produced in Canada is used on site at various types of industrial locations including petrochemical, fertilizer, and steel complexes. Hydrogen can be transported by vehicles, pipelines, trains, or ships; however, the required infrastructure technologies are costly and therefore difficult to scale. Thus, transporting hydrogen remains a major barrier to being able to achieve scale by using hydrogen off-site. Nevertheless, technological progress in compressor designs has shown promise to cater to the challenges associated with its transportation.

Hydrogen storage poses a major challenge. Hydrogen transporting requires compression which is quite costly and poses safety concerns. Canada is fortunate to have geological formations in the Canadian Shield where hydrogen can be stored in a safe and cost-effective manner, however given the transportation challenges, hydrogen cannot be transported to these regions and their use is therefore limited. Canadian industries that have the potential to use hydrogen could, while transportation is further developed, benefit from hydrogen hubs which enable the widespread use of hydrogen in a condensed geographical area.

Policy recommendations

Overarching Recommendation #1: The CNA advocates for policies that support nuclear-based pathways for clean hydrogen production in the medium to long-term, while supporting other (non-nuclear) production pathways in the short-term to help build robust hydrogen supply chains.

1a. CNA to advocate and support for the dedicated use of nuclear energy (including SMRs) for clean hydrogen production

1b. CNA to encourage the federal government to systematically phase out high carbon-emitting hydrogen production by supporting and requiring CCS to abate CO_2 emissions in the short-term as a bridge until hydrogen production using clean electricity—solar, wind, hydro, and nuclear can be fully established.

1c. CNA should engage with governments at all levels to abandon the use of color schemes that are used for hydrogen production pathways.

1d. Thorough engagement and benefit sharing by CNA members with affected Indigenous communities.

1e. The CNA should engage more with the nuclear industry and federal and provincial governments to improve nuclear waste treatment technology and improve the waste minimization strategy, with a particular focus on SMR technology and the challenges around safe transportation and storage.

Overarching Recommendation #2: The CNA should advocate for policies that increase end-use demand for clean hydrogen while also mitigating investment risks.

2a. CNA to encourage and lobby with the government to allow tax credits for companies using electrolysis to produce hydrogen

2b. CNA to engage with all tiers of government to explore opportunities for developing SMRs near industrial complexes

2c. CNA to engage with members and other stakeholders for ensuring market certainty for fuel cell electric vehicles by supporting private sector for building hydrogen refueling infrastructure

2d. CNA to advocate for clear municipal policies to expand fuel cell electric buses as means of public transportation

2e. The CNA should influence the federal and provincial governments to develop a roadmap for expanding fuel cells for long-distance ships and to implement pilot projects to help develop safety protocols.

Overarching recommendation #3: Promote research and development, and evidence-based policy advocacy.

3a. In collaboration with the nuclear industry, the CNA should design a government relations campaign to urge the government for more R&D expenditures for clean, nuclear-based hydrogen production and for the timely allocation of current resources allocated in the 2022 federal budget

3b. CNA should collaborate with the Canadian Hydrogen and Fuel Cell Association for advocacy and communication campaigns to promote sustained support for R&D for innovative technologies, subsidies and cost reduction of fuel cell technologies to support the sector.

3c. CNA to collaborate with think tanks, academia, and other research institutions to conduct research to better understand public and industrial perception, knowledge, and willingness about moving towards a hydrogen-based economy, particularly one that emphasizes nuclear-based production

3d. CNA to develop a communications plan for the financial sector that focuses on the financial needs of nuclear hydrogen producers

Overarching recommendation #4: Advocating for removing market barriers for hydrogen producers through infrastructure development.

4a. CNA to engage with players in all parts of the value chain to gather an understanding of key legislative and regulatory gaps so that they can be addressed appropriately

4b. CNA to assist with and learn from the ongoing technical assessment that evaluates hydrogen export from Canada

4c. CNA and members to work with other stakeholder to provide technical expertise to improve the storage and transportation component of hydrogen and conduct mapping of regions where hydrogen can be stored underground

4d. CNA to conduct mapping of existing and potential infrastructure for hydrogen hubs and work with the nuclear industry to establish SMRs in regions where hydrogen deployment hubs are feasible

Table of Contents

Introduction

Countries around the world – including Canada – are increasing actions to address climate change and reduce greenhouse gas emissions. Canada's 2030 Emissions Reductions Plan strives to reduce emissions by 40-45% by 2030 from 2005 levels and then to net-zero by 2050.[1] A net-zero economy is one that either emits no carbon emissions or offsets any that are produced.[2] Although Canada already has an extensive network of low-carbon energy sources generated from hydroelectric stations, other renewable generators, and nuclear plants, the high-emitting oil and gas industry remains a big player when it comes to supplying Canada's significant energy demands.

Hydrogen as a low carbon-emitting energy source could play a major role in this decarbonized future. Hydrogen can be produced from multiple feedstocks and pathways where Canada already has competitive strengths, including clean electricity, nuclear energy, and natural gas.

Canada's hydrogen economy is still undeveloped; however, a circular causality problem is a primary barrier to developing the hydrogen economy, whereby the cost of low-carbon hydrogen production remains high, and the demand is low. Driving up demand will help to achieve economies of scale and hopefully lower costs of production. Government policies could be used to stimulate both the supply and demand sides of the hydrogen economy so that Canada can pursue the hydrogen path as they strive towards net-zero. Not only this, but the hydrogen economy can generate significant economic benefits as well.

Canada's Hydrogen Strategy was developed in 2020 as a call to action intended to spur investment in the industry to reduce greenhouse gas emissions, seize economic opportunities, and create new jobs. While the strategy places an emphasis on renewable energy sources as feedstocks for hydrogen, nuclear pathways to producing hydrogen receive less attention. Nuclear energy is a low-carbon feedstock that is abundant and scalable and can be used to produce low-carbon hydrogen through electrolysis. Such a capacity could be developed across Canada; however, costs of hydrogen production remain high, particularly with a nuclear feedstock. Using nuclear energy as a hydrogen feedstock is not currently being considered seriously in Canada. As the hydrogen economy continues to develop, however, the nuclear industry may be able to contribute to it in the long-term.

This report intends to look at the role that nuclear-based hydrogen could play in Canada's net-zero future. By using expert interviews and detailed criteria and measures throughout its research, the report will first examine the feasibility of using the most common feedstocks to determine what Canada's best options are for increasing hydrogen supply. It will then look at demand-side use options and existing barriers to hydrogen production as a means of complementing the feedstock criteria/measures analysis. A particular focus on the feasibility of coupling nuclear energy with hydrogen production is adopted throughout. Doing so will likely be best achieved in the long-term, therefore short- and medium-term options are considered as well as intermediary steps. The recommendations that conclude this report provide a path forward that the Canadian Nuclear Association (CNA) should pursue so their partners can contribute to the emerging hydrogen economy.

Policy questions

This report is guided by the questions that are provided by the Max Bell School of Public Policy (McGill University) and the CNA.

Challenge question: What types of government policy are needed (if any) to scale up the production of clean hydrogen in Canada?

Opportunities and challenges to be considered:

1. Given the Transition Accelerator's and the federal government's emerging visions for a hydrogen economy, what policy measures, federal and provincial, are needed to realize the potential while optimizing the balance of benefits and costs?
2. What market mechanisms would likely relate to producing hydrogen flexibly, versus continuously?
3. To what extent should these policies focus on a particular fuel source/technology to produce hydrogen?
4. What is the potential scope for these various fuel sources to supply hydrogen, and how carbon-intensive would these processes be?

Outline

Section two of this report begins by introducing hydrogen as an energy carrier with the potential to decrease Canada's CO_2 emissions and generate specific economic opportunities while continuing to meet Canadian energy demands. Canada has a comparative advantage in hydrogen production due to its abundance of energy resources and political will to support the net-zero transition. Section three will briefly discuss the report's methodology, describing the key informant interviews and search strategy. Section four begins the analysis by taking a closer look at the various production pathways through the lens of a criteria/measures analysis. End-use demand options are then analyzed through the lens of hydrogen potential role in reducing their carbon emissions. The analysis ends with a discussion about various market barriers to the realization of these pathways. The report concludes in section five with four key recommendations for the CNA to pursue to help develop the economy and ultimately increase the demand for nuclear technologies.

Background

Hydrogen in a net-zero world

Hydrogen is not only the first and simplest element on the periodic table, but it is also an alternative energy carrier that can be produced and consumed in a net-zero way to help accelerate the momentum of the energy transition away from fossil fuels. The complete hydrogen energy industry chain includes: i) hydrogen production ii) storage and transportation, and iii) downstream applications.[3] Most of the current hydrogen production comes from natural gas which has high emissions, but low-carbon hydrogen is a viable pathway.

Hydrogen can be stored as a liquid or gas, and can be utilized with various technologies, most notably fuel cell technology. Fuel cell technology transform chemical energy into electrical energy with the only by-product being water.[4] Significant progress has been made in recent years in developing hydrogen storage and fuel cell technologies. Some fuel cells have recently been commercialized, differing in terms of the materials used in their fabrication.

Hydrogen has a high specific energy density meaning that it contains about three times more energy than gasoline does per unit mass.[5] In other words, 1 kg of hydrogen possesses the same energy as approximately 2.8 kg of gasoline.[6] Hydrogen's comparatively low volumetric energy density, however, translates into a significant challenge regarding its storage and transportation. Despite these, hydrogen can be readily available for sustainable production in regions with excess freshwater reserves, such as Canada. Although it is challenging at this stage, splitting water via electrolysis has shown great potential for clean hydrogen production. Additional research is required to identify other economic and environmentally friendly methods of hydrogen production and its downstream uses.

Color codification

Hydrogen is produced from many different renewable and non-renewable sources, with variable costs and CO_2 emission intensities. The various processes of producing hydrogen are often codified with colors that are associated with the raw material used as feedstock, which also gives insight into the carbon intensity of each feedstock. For example, hydrogen produced from fossil fuels coupled with CCS is categorized as blue hydrogen, whereas hydrogen produced by using renewable electricity and electrolysis is distinguished as green hydrogen since there are lower or zero carbon emissions.

While the color-coding system for the different types of hydrogen is widely used, many key informants (KIs) agree that using it is overly simplistic and can even jeopardize accurate economic projections and global acceptability since there are no clear defining standards for the carbon intensity of each "color". The critical parameter in analyzing hydrogen production and its environmental impact should instead be based on the life-cycle carbon intensity of the primary feedstock. Therefore, this report focuses on the carbon intensities of hydrogen pathways rather than on the color codification scheme. This report uses the term clean hydrogen in reference to hydrogen that is produced with low or zero emissions.

Global demand

Global hydrogen demand is rising. Goldman Sachs estimates show that the global market for using low-carbon hydrogen can reach $12 trillion (USD) by 2050.[7] Another study by the Hydrogen Council (2017) provides relatively lower estimates of $2.5 trillion (USD) in global sales for hydrogen and its technology.[8] Qualitative data analysis supports the argument that Canada has a comparative advantage in hydrogen production and exports because of the low costs of hydroelectricity, nuclear, solar, and wind energy, suggesting that Canada could be well-placed to supply future demand.

Canada's Hydrogen Opportunity

Canada's comparative advantage in producing clean hydrogen

With regards to economic benefits, jobs, and export potential, Canada has a comparative advantage in producing clean hydrogen. The hydrogen strategy provides very ambitious targets for the hydrogen-based economy. When combined, the hydrogen and fuel cell sectors have the potential to generate $25 billion in revenue by 2030 and $47 billion by 2050.[9] These estimates are only based on local demand for hydrogen and do not include the spillover effects of the economic benefits from building hydrogen production facilities, constructing hydrogen pipelines, and end-use manufacturing.[10]

Energy resource availability

Canada is a resource-rich country with its energy resources adding 8.1% to the nominal GDP in 2020.[11] Canada is even ranked 6th globally for primary total energy production.[12] Total energy production in Canada is 25,979 petajoules (PJ); of this, 41% comes from crude oil, 26% from natural gas, 16% from uranium, 5% from coal, 5% from hydro, 4% from natural gas liquids, and 3% from other renewables.[13] Canada exports a lot of its uranium, thus only 2% of Canada's total energy demands are met by nuclear energy.[14] Canada has one of the world's largest uranium reserves and could take advantage of this for increased nuclear power generation in the country, particularly seeing that the majority of Canada's energy is produced from fossil fuel products and nuclear power offers clean energy.

Available pathways: general overview

Hydrogen can be used as a primary and secondary energy source.[15] The carbon intensity of the various primary energy sources (e.g., fossil fuels, nuclear, and renewables) and pathways of producing hydrogen should be a major consideration given Canada's goal of net-zero carbon emissions by 2050. Canada must consider hydrogen production that can satisfy low-cost and low-carbon-intensity requirements. There are several feedstock options available in Canada that can offer competitive costs and emission levels, however, tradeoffs will likely be required in choosing a primary feedstock.

Fossil fuels can offer a proven short-term solution for low-cost hydrogen production. When this is coupled with carbon, capture, and storage (CCS), some of the carbon generated in the process can be abated.[16] Alberta and Saskatchewan have significant reserves of natural gas, the required processing and transportation infrastructure, and proper geology for storing the sequestered carbon emissions. This capacity could be transferred to natural gas steam methane reforming with CCS as a means of producing low-cost hydrogen. Steam methane reforming is a well-established production process in which high-temperature steam (H_2O) is utilized to generate hydrogen from a methane source such as natural gas. Alberta is currently using their steam methane reformers for this purpose, [17] however, the hydrogen produced is used as an industrial feedstock and the resulting emissions are not being sequestered.[18] Expanding the use of steam methane reformers for hydrogen production is certainly feasible, however, given its use of natural gas, in order to meet net-zero targets, CCS will have to become cheaper, more efficient, and more broadly used so that the technology can remain viable. This dilemma highlights the importance of continuing to seek out clean hydrogen production options.

Electrolysis is the process by which electricity is used to split water into its two elements: hydrogen and oxygen. The option of using low-carbon-intensity electricity in electrolysis to produce hydrogen is promising and consistent with Canada's decarbonization goals. The Yukon, British Columbia, Manitoba, Ontario, Québec, New Brunswick, and Newfoundland and Labrador all have significant hydropower systems and robust electricity grids. Québec also has some of the lowest electricity rates in North America, along with capabilities to export hydrogen to other jurisdictions.[19] Saskatchewan, Alberta, and the Maritimes are also well-placed to produce excess electricity from wind and solar, however, such supply is not steady. When used alongside a reliable source like hydro, other renewables can be used to produce hydrogen on a large scale via electrolysis. Although the costs of electrolyzers continue to decrease and efficiency continues to improve, electrolyzers still come with a significant capital cost.[20] Costs of electrolyzer technologies are expected to fall in the future with wider adoption.[21]

While a recent report by the David Suzuki Foundation believes it will be possible to meet future energy needs using only renewable resources, this would only be possible with concerted planning and execution efforts – something unlikely to happen.[22] It is generally agreed amongst key informants (KIs) that it will be difficult to meet future energy needs by exclusively using renewables. Wind and solar are not consistent energy sources and hydroelectric is not available in all regions, therefore, renewables will likely have to be supplemented using steadier and more accessible energy sources. Nuclear energy is a low-emission, high-density feedstock that has demonstrated its success as an energy source in Canada. Canada's first nuclear generating station – the Pickering 1 reactor – was established in Ontario and connected to the power grid in 1971.[23] Since then, Ontario's nuclear capacity has increased to the point where 60% of its electricity now comes from nuclear sources.[24] In 1983, New Brunswick power also commissioned their first nuclear generating station – the Point Lepreau Generating Station – which in 2019/2020 comprised 35% of New Brunswick's electricity sales.[25, 26] Nuclear energy can produce electricity for electrolysis either through large nuclear-generating stations, as proven in Ontario, or via small modular reactors (SMRs,) which are smaller nuclear reactor facilities compared to traditional nuclear power plants.[27] As smaller units, SMRs can be easily placed near demand sources such as industrial facilities or off-grid communities, and at maximum capacity, they can generate up to 300 MW of electricity.[28] SMRs come with high upfront capital costs however, and while a few jurisdictions in Canada now have solid plans in place to build units, but the technologies are yet to be commercialized.

Canada's hydrogen production

Clean hydrogen has the potential to cover up to 30% of Canada's energy demand by 2050.[29] If hydrogen could be used to this potential, it would help Canada reduce 45 Mt of CO_2 by 2030 and 190 Mt-CO_2e emissions annually by 2050. Canada's natural resource reserves, its energy supply infrastructure, highly skilled labor in the energy sector, and strong commitments toward innovation and environmental sustainability could enable Canada to become a top producer of hydrogen. In 2018, Canada produced about four million tonnes of hydrogen, most of which was produced in Alberta using steam methane reforming of natural gas.[30,31] This process is carbon-intensive and if not paired with a CCS facility, it works counter to decarbonization efforts. Recent technological advances in CCS, however, can reduce the carbon emissions of natural gas and improve the desirability of this pathway.

The federal government's proposed CCS tax credit is a major push in this direction.[32] It is estimated that by 2050, Canada could have the capability to increase less carbon-intensive hydrogen production by seven times to help meet the global energy demand for clean hydrogen.[33]

Technical and human resource capacity

The hydrogen sector in Canada has the potential to meet the domestic energy demand and thereafter export internationally.[34] In 2020, there were 845,000 jobs in the Canadian energy sector – 4.7% of Canada's total employment.[35] The transition from hydrocarbon-based energy resources to hydrogen could help generate 350,000 new high-paying jobs by 2050.[36] These jobs would be able to employ some workers from the fossil fuel industry should the industry decline in scale. This would require the retraining of workers and perhaps even relocation resulting from a geographical mismatch of skills.[37] It should be noted that the KIs are skeptical of these new job figures – the creation of these jobs would largely depend on the end-use demand and uptake of hydrogen. It is unclear what the occupations and skill sets required would look like.

Canada spends significant resources on energy sector research and development (R&D), with total government expenditures in 2019-2020 reaching $1.07 billion ($758 million by the federal government and $316 million by the provincial governments).[38] Canadian industries have also invested in R&D; with 2020 investments totaling nearly $1.6 billion.[39] If Canada plans to develop a hydrogen-based economy, the country needs sustained investment from the government and private sector over the next three decades in hydrogen development, but particularly in the nuclear-to-hydrogen pathway.

Role of Indigenous communities

The energy sector of Canada is one of the largest employers of Indigenous people in Canada.[40] The energy transition towards hydrogen affirms even more opportunities for Indigenous people through new employment and business development. Since hydrogen is produced via various pathways based on the geographical and resources availability, there exists an immense opportunity for Indigenous participation across Canada.

It was a 2015 campaign promise of the federal government to affirm a nation-to-nation relationship with Indigenous peoples. Canada's ratification of the United Nations Declaration on the Rights of Indigenous Peoples further reinforces the need to affirm such a relationship. The emerging hydrogen economy can be seen as an opportunity to demonstrate commitment to the promise, particularly with regards to articles 18 (participation in decision-making), 19 (good faith consultations), 26 (traditional land rights), and 29 (environmental protection) of UNDRIP.[41] Doing so can offer opportunities to break from colonial ties, move towards energy autonomy, and reap financial benefits from energy development projects (like SMRs deployment).[42]

Policy momentum

The hydrogen strategy was developed by Natural Resources Canada (NRCan) after consultation with multiple stakeholders from the public and private sectors. Canada's federal and provincial governments are already providing public policy support on the common themes of boosting overall hydrogen demand and supply, while allowing each jurisdiction to pursue its own comparative advantage. Canada has also strengthened its energy partnership with Germany, showing Canada's long-term commitment to reducing carbon emissions and towards renewable energy.[43] With regards to nuclear, the federal government's 2018 SMR Roadmap connects partners from different industries across the country as they work to introduce SMRs into Canada's hydrogen future.

Examples of the efforts made by different jurisdictions in the last few years to promote hydrogen supply and demand include: 1) the federal government allocated $8 billion for projects to support decarbonization of large-emitters, of which $425 million are allocated explicitly for low-carbon steel and cement production with hydrogen,[44] 2) The provincial governments of British Columbia, Alberta, Ontario, and Québec released hydrogen strategies. While these measures are a start, they are likely insufficient. Not only do the existing policy supports not consider the entire hydrogen value chain, but they also do not explicitly support the nuclear pathway, thereby making it difficult to scale the economy.

Methodology

This report uses a mixed approach, involving a literature review with a detailed search strategy, selection criteria, and a set of informant interviews. Each are described briefly in turn.

Key informant interviews and Canadian Hydrogen Convention

The team conducted semi-structured key informant interviews for this policy lab. The KIs were carefully selected from different fields based on their previous or current experience and knowledge of the hydrogen-based economy, hydrogen production pathways, supply, storage, costing, government regulations, and transportation. Given the complexity of the topic and limited information on the government policies for a hydrogen-based economy, it was challenging finding a variety of experts on the topic. The team received a ~50% response rate to interview requests and completed 15 key informant interviews.

Two questionnaires were developed based on thorough research of the national and international hydrogen and environmental strategies, and the related literature. The first questionnaire (non-scientific) was for KIs belonging to academia, civil society organizations, think tanks, the private sector, and non-technical staff in government institution. This questionnaire addressed different aspects of the economic outcomes, the role of nuclear energy, comparative advantage, policies, production, transportation, and supply challenges for hydrogen. The second questionnaire was used for experts that had scientific and technical expertise in the field of hydrogen production, supply, and transportation. The team also made slight modifications to each questionnaire intending to make it relevant for more technical stakeholders. A member of the team attended the Canadian Hydrogen Convention in April 2022 to visit different private sector booths and talk to expert presenters. A detailed list of organizations consulted is listed in Annex 4.

Search strategy and literature review

The team shortlisted key databases that would be relevant for the policy lab project. The following general databases were selected from which to identify key reports and peer-reviewed articles for literature review: McGill Library, Google Scholar, Elsevier-Science Direct, Springer, SAGE, Jstor, Taylor and Francis, and subject-specific journals covering hydrogen. The team also reviewed federal and provincial government environmental regulations and hydrogen strategies. Federal and provincial government publications provided a thorough understanding of the role of hydrogen in Canada's net-zero emissions strategy and the government's efforts to boost hydrogen demand and production. [45] Recent news articles and reviews by experts were also researched.

More information on search restrictions and criteria-measures analysis is provided in Annex 1.

Limitations of this research

The researchers attempted to connect with over 30 experts, yet with a 50% interview success rate, they were not able to talk to as many experts as would have been ideal. Regarding data collection, it was difficult to quantify the benefits of hydrogen production, given that the hydrogen economy is still in its infancy. For this reason, as well, it was challenging to collect data for certain indicators, and the true economic projects are difficult to predict. Although they made a concerted effort to be impartial, the researchers would also like to acknowledge their personal limitations and biases.

Analysis

This section discusses the main production pathway options of fossil fuels (with CCS) and renewable and nuclear electricity sources. We developed a criteria/measures framework to easily compare the different production pathways. This framework uses six criteria, including: economic efficiency (cost per kilogram of producing hydrogen), practicality (current capacity), environmental sustainability (climate related and non-climate related), safety (of the different production pathways), scalability, ease of implementation, and net benefits.

These pathways will determine Canada’s future hydrogen supply; however, supply should be considered alongside demand as well. As such, the section discusses potential end-use demand options and the impact they could have on reducing carbon emissions, as well as the ease of implementing hydrogen into their operations. Important sectors include transportation, heating, and industrial use.

The last section analyses key market barriers to scaling up the production of clean hydrogen including high investment risks, outdated legislation, barriers, and opportunities related to transportation and storage infrastructure, and hydrogen hubs.

Production pathways

It is imperative to understand the fundamental working principles of each of the production pathways through lifecycle carbon emission studies. Each pathway uses a different feedstock, so, their costs and carbon emissions are different. To find the net-benefits, particularly in terms of economic and environmental impacts, governments will first have to decide on their short- and long-term strategies of introducing hydrogen into the energy mix. This will allow the understand of net-benefits to be well-informed and specific to each province's unique approach.

Hydrogen production via fossil fuels could be the most cost-effective process, however, its negative environmental impacts make it unfavorable. Nonetheless, this pathway is well-established in jurisdictions with significant natural gas reserves and can play a transitory role on the path to clean hydrogen. In provinces without large natural gas reserves like Ontario, Québec, and British Columbia, hydrogen production via electrolysis could be the most favorable pathway owing to the availability of clean electricity. The deployment of efficient electrolyzers could set the stage for the use of nuclear energy as a source of clean and reliable electricity to power electrolyzers.

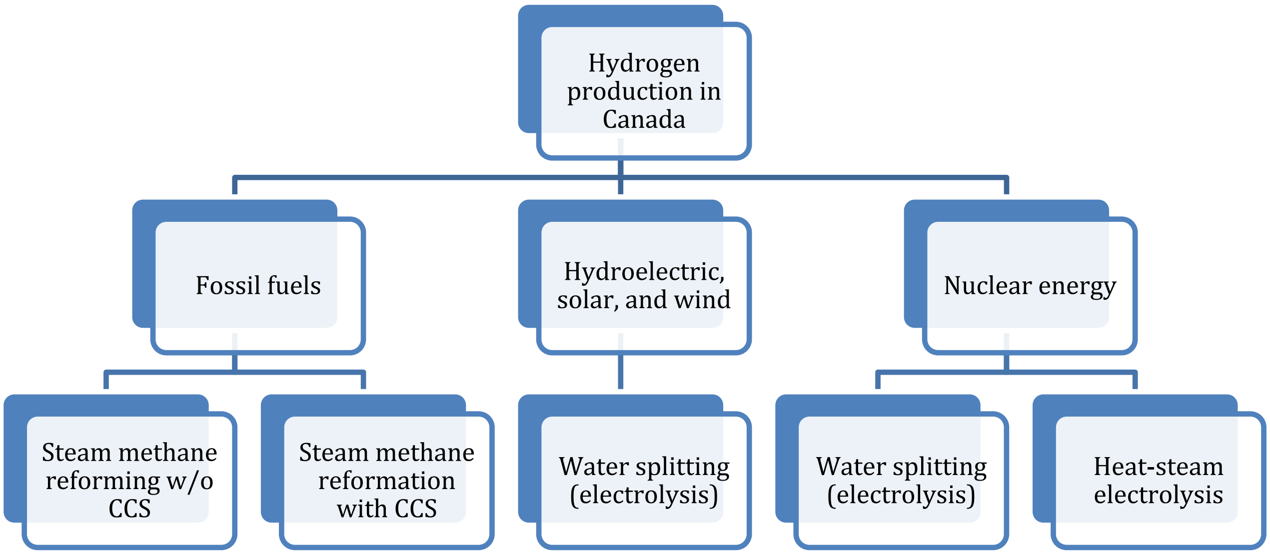
The table below (Table 1) presents the summary of the costs associated with different pathways and their lifecycle carbon emissions.

Table 1: Cost by feedstock of producing hydrogen and CO_2 emissions per kg hydrogen

Feedstock	Cost estimates per kg (USD)	CO_2 emissions (kg CO_2 / kg H_2)	Merits and demerits
Fossil fuels w/o CCS (for reference only)	0.5 to 1.7	9	Lowest cost and highest carbon intensity
Fossil fuels with CCS	1 to 2	1	Low cost and low CO_2 emissions
Hydro, solar, and wind	3 to 8	0	High cost, high intermittence, and lowest carbon intensity
Nuclear energy	5	0	Highest cost and lowest CO_2 intensity, smaller space requirements, high capacity and efficiency.

Note: These estimates come from different sources. Source: International Energy Agency, 2021,[46] Transition Accelerator, 2020 [47] and authors' own calculations from IAEA calculators.

Figure 1: Available hydrogen production pathways in Canada



Fossil fuels

In Canada, Alberta and Saskatchewan have significant reserves of natural gas, along with the associated processing and transportation infrastructure and a skilled workforce. The Canada Energy Regulator predicted that despite the decline in global demand for petroleum as the world shifts to net-zero, Alberta will continue exporting the oil for several more decades. Because of the abundance of these resources, an industry around hydrogen production from oil and gas has arisen. Hydrogen production in Alberta is mainly done using steam methane reforming. It is important to mention that Alberta's natural gas prices are among the lowest in the world, making this a very cost-effective option. Unless coupled with CCS, however, this process is carbon-intensive and therefore faces significant resistance globally.

When coupled with CCS, however, this capacity and expertise could be used to produce low-cost hydrogen. Alberta has two commercial-scale pilot CCS pilot projects in place, currently used by the oil sands and fertilizer sectors. There is potential for these to be used by steam methane reforming processes used to produce hydrogen. The federal government's recent tax credit initiatives for CCS technologies and the Alberta government's $50 million investment to establish a Hydrogen Center of Excellence. Alberta has several steam methane reformers, and the hydrogen being produced by them is currently being used directly as industrial feedstock.[48, 49] Such technologies could be deployed and used until the hydrogen ecosystem is further established such that lower carbon-emission pathways and transportation and storage of hydrogen can be realized.

As described below in table 2, despite the various possible production pathways, today's hydrogen production is mainly coming from fossil fuels via steam methane reforming. This hydrogen is mostly used in the oil refining process in Alberta. Although the low cost of $0.5 – 1.7/kg (USD) makes it the most economical pathway, the environmental impact of the steam methane reforming process is large, hence not suitable, even though its production viability and scalability stand highest (see table above). Since technology is yet to be coupled with CCS commercially, the government's support will accelerate scaling.

Hydroelectric, solar, and wind

Electricity generated by hydro, solar, and wind can be used to produce hydrogen by powering electrolyzers – significant potential exists to pursue this pathway. The Yukon, British Columbia, Manitoba, Ontario, Québec, New Brunswick, and Newfoundland and Labrador all have significant hydropower capacities and very robust electricity grids. Québec also has the lowest electricity rates in Canada, along with the capability of exporting it to other jurisdictions. Saskatchewan, Alberta, and the Maritimes are also well-placed to produce excess electricity from wind and solar which, alongside hydro, can then be used to produce hydrogen on a large scale via electrolysis. Although costs continue to decrease and efficiency continues to improve, electrolyzers, still come with a significant capital cost.[50] Significant potential exists in scaling up clean hydrogen production in Canada via renewable energy sources.

Table 2 in section 4.2.4 below shows that except for the safety aspect, no other selection criterion is satisfactory for hydrogen production from electrolysis using the clean electricity produced by solar, wind, and hydro in Canada. Hydro-Québec has several other commitments to export their clean and cheap surplus electricity and as they increase, the surplus will gradually decrease.[51] Therefore, the clean electricity supply required to produce the hydrogen through an energy-intensive electrolysis process is uncertain, hence the confidence level in practicality and scalability in Table 2 below for this source is marked as lowest.

Nuclear energy

Nuclear energy can produce hydrogen by using either cold water electrolysis, low-temperature steam electrolysis, high-temperature steam electrolysis, or thermochemical production with nuclear heat. Canada is the world's sixth-largest producer of electricity, with 67% coming from renewable resources and 15% coming from nuclear operations.[52] Industry professionals and the literature generally agree that it will be difficult to meet future energy needs using only renewables, thus creating a significant opportunity for low-cost, reliable, and publicly acceptable nuclear technology. Nuclear energy is a low-emission, high-density feedstock that has been successfully demonstrated in Ontario through their well-developed nuclear capacity, with 60% of its electricity coming from nuclear power.[53]

With recent progress in building SMRs, Canada has established its position to become an exporter of the technology after their success in Ontario. The estimated potential value for SMRs in Canada is $5.3 billion between 2025 and 2040.[54] The International Atomic Energy Agency (IAEA) and Bhabha Atomic Research Centre (BARC) collaborated to develop the Hydrogen Economic Evaluation Program (HEEP) which provides useful information about the utilization of nuclear energy for hydrogen production by conventional electrolysis, electrolysis at low and high temperatures, thermo-chemical processes, and steam reforming. The results from this program could be applied to conventional, new generation, and small modular nuclear reactors in Canada.[55]

SMRs offer a direct way of producing clean hydrogen with the added benefit of being placed where need exists. Although they have high upfront capital costs, energy generated would be affordable in the long-term. Some KIs recommend that should provinces decide to procure SMRs, they do so immediately to recover capital costs sooner. Using SMRs can provide a steady baseload of electricity thereby preventing the issue of generating electricity off-peak and selling at a loss.

A potential downfall of the use of nuclear power, particularly in SMRs, is the negative public perception of nuclear power. Over the years, considerable progress has been made internationally in developing next generation large reactors and SMRs for future use, they remain one of the most heavily regulated forms of energy production in the world, including Canada. Deploying wide-scale nuclear capabilities in Canada would require public buy-in, which could be achieved by building awareness and public confidence.

Safe and economic waste management of radioactive material from large nuclear power plants as well as SMRs is one of the key challenges associated with successful commercialization of this technology. Significant progress has been made in this area where the autonomous systems have the capability to make decisions to manage waste without direct human intervention.[56]

The Nuclear Waste Management Organization (NWMO) is responsible for designing and implementing Canada's plan for safe, long-term management of used nuclear fuel including waste from SMRs. Waste management is guided by the "polluter pays" principle where the nuclear operators are responsible for full life-cycle management of waste that they produce from SMRs and other technologies.[57] Canada's major nuclear operators fund the implementation of the waste management plan, and each waste producer pays an annual fee to the trust fund to ensure that there is enough fund for the project. When there are new nuclear operators, the NWMO determines the long-term costs and develops an appropriate funding mechanism for the resulting fuel wastes. The waste owners are required to convert their waste into durable waste form which is then accepted by the NWMO for management in the repository. According to NWMO the cost of developing a spent fuel repository is $1.3 billion (USD).[58] With increased SMR deployment there will be more waste, and more repositories will be required, therefore waste management will require additional funding.

The world is revisiting the plan to phase out nuclear-based energy production after the war in Ukraine, and the need for lower carbon alternatives. In Canada, the successful demonstration of 60% electricity production in Ontario via nuclear energy has placed the province and country in leadership positions. The technological advance vis-à-vis SMRs has stirred the interest of other provinces in Canada to unlock the potential that nuclear energy possesses, not only for electricity production but for hydrogen production as well. SMRs are promising new technologies that can provide a range of benefits in terms of economic, geopolitical, social, and environmental spheres.[59] Despite the safety concerns that arise from the waste management this can be a reliable feedstock for hydrogen production via electrolysis. The excess heat can be utilized in several ways including high-temperature steam electrolysis or thermochemical cycles.[60]

Summary of production pathways (criteria/measures framework)

This table describes that the current mode of hydrogen production from natural gas releases significant amounts of CO_2 per kilogram of hydrogen produced (~9kg CO_2e/kg). The fossil fuel pathway without CCS must be abandoned within the next few years even though it is easily scalable and hydrogen prices for this pathway are extremely competitive. Fossil fuel hydrogen production with CCS could reduce these emissions. CCS technology is still in its early development stage and has begun receiving commercial approvals. Should Canada continue using fossil fuels with CCS, this pathway could bridge the transition to clean hydrogen production. Although there are numerous advantages of using electrolysis process for hydrogen production, the practicality and scalability (ease of implementation) are fundamental challenges associated with the commercial deployment of electrolyzers. The capital costs associated with SMRs are key challenges, however, recent technological advances are moving in the right direction, and commercial use of SMRs could be realized in the medium- to long-run. The safety concerns of using nuclear are prevalent amongst Canadians according to several KIs and could be a challenge to address.

Table 2: Criteria/measures framework for different production pathways (short-term)

	Economic efficiency	**Practicality**	**Environmental sustainability**		**Safety**	**Scalability**
Feedstock and energy source	*Cost estimates*	*Current capacity*	*Climate related*	*Non-climate related*	*Safety concerns*	*Ease of implementation*
Fossil fuels w/o CCS	✓	✓	✗	○	✓	✓
Fossil fuels with CCS	✓	○	○	○	✓	○
Hydro, solar, and wind	○	✗	✓	○	✓	✗
Nuclear energy	✗	○	✓	✓	○	○

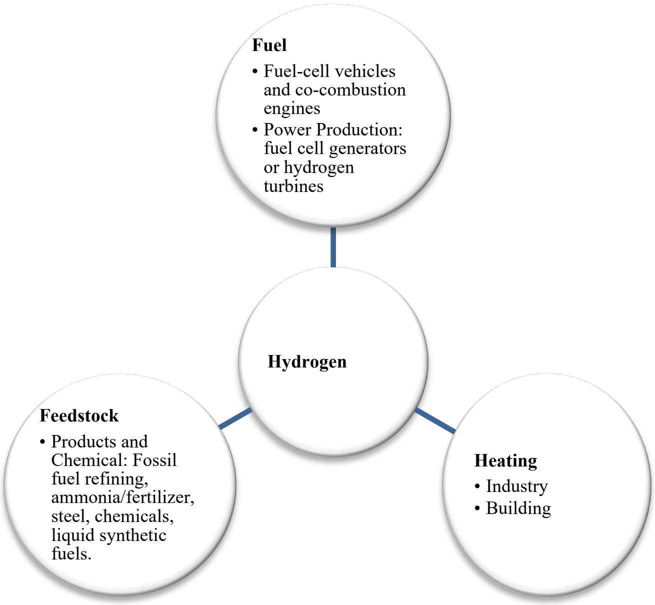
Notes: The green check marks in this table indicate that the pathway has a positive rating with regards to each metric in the short term. The orange circles indicate that the pathway has a moderate rating but is not most optimal in the short term. The red exes indicate that the pathway has a poor rating.

Source: Authors' own depiction from key informant interviews and literature review.

End-use demand for hydrogen

The high cost of hydrogen and hydrogen technologies, as well as challenges with generation, storage and transportation are hindering the smooth transition to a hydrogen-based economy. Research shows that the cost of producing low-carbon hydrogen depends on the infrastructure available in the country, the transportation network, and the end-use demand. Successful completion and connection of hydrogen production, transmission, distribution, storage, and end-use develop a new hydrogen value chain. In absence of any one of these components, the hydrogen value chain would be disrupted. Establishing strong end-use demand is also essential to provide businesses and investors the confidence they need to invest in a hydrogen-based economy. This section looks at the different potential end-uses and where government policy might play a role.

Figure 2: End-use demand for hydrogen

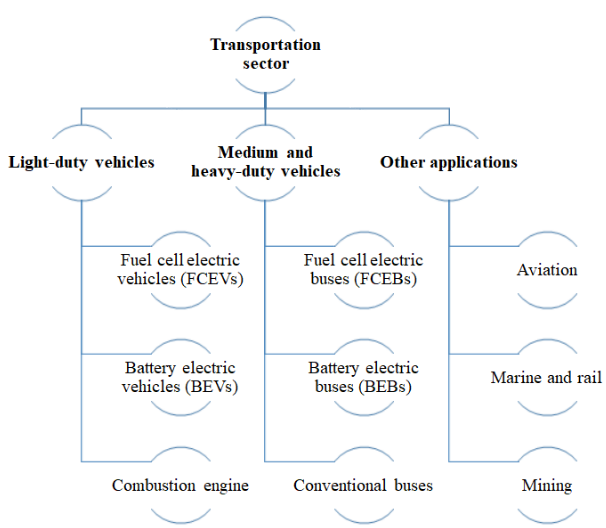


Source: Canada’s Hydrogen Strategy (NRCan)

Transportation sector

The transportation sector in Canada is the second largest contributor to carbon emissions and is responsible for 185.8 mega-tonnes of CO_2 emissions annually.[61] Hydrogen has long been considered as a potential transportation fuel, but the sector is now considering it with increasing seriousness. It is possible to convert hydrogen to hydrogen-based fuels, such as synthetic methane, methanol and ammonia, and synthetic liquid fuels so that it can be used in transportation. Moreover, hydrogen fuel cell electric vehicles (FCEVs) are considered low-carbon vehicles as they have zero tailpipe emissions.[62]

Figure 2: Summary of hydrogen use in the transportation sector



Light-duty vehicles

Light-duty FCEVs are currently available for purchase in the Canadian market; however, production and demand are not yet significant, and fueling infrastructure is lacking. Original Equipment Manufacturers (OEMs) are willing to supply their limited number of FCEVs only in regions where fueling infrastructure is available. OEMs have expressed that a region requires seven to eight fueling stations to provide coverage and redundancy to enable a larger rollout of vehicles.[63] Moreover, due to the limited supply volume of FCEVs, the price of these vehicles remains more expensive than battery electric vehicles (BEVs) which further dampens demand. British Columbia, Ontario, and Québec have already started to deploy hydrogen fueling infrastructure. As of 2022, there are only six retail fueling stations available across Canada: 4 in British Columbia, and 2 in Québec (see Appendix 2, Table 4). British Columbia is currently deploying four new stations and recently announced funding for an additional ten stations to develop a greater network.

Zero-Emission Vehicles (ZEVs) have the potential to deliver average power that is more efficient than a combustion engine. From our analysis, a combustion engine using gasoline and diesel requires 9L and 6.7L of fuel per kilometer respectively (please see Appendix 2, Table 1). Gasoline is the most carbon-intensive and has the highest annual fuel cost compared to other fuels. Although FCEVs are environmentally friendly, annual fuel cost is currently over twice as much as that of BEVs. The average fuel consumption of FCEVs is lower than gasoline and diesel which implies that FCEVs are more efficient compared to combustion engine cars, but the specific range of FCEVs depends on the size of their tanks.[64] Peak performance of FCEVs depends on the size of these cells, which can also be quite expensive. Compared to all other fuels, BEVs are environmentally friendly and most efficient in terms of fuel consumption per kilometer.

Many KIs also noted that due to the limited supply and transportation capacity of hydrogen in the short-term, it would not be economically efficient for Canada to use hydrogen in light-duty vehicles, rather, electric and hybrid vehicles make more economic sense. The markets and changing demand for hydrogen can, however, guide supply and possible government intervention. There are certain safety concerns about using hydrogen for vehicles; however, one expert diminished this concern, explaining that hydrogen tanks are intentionally built to endure high impacts, and the process of fueling hydrogen in cars would in fact be much safer than gasoline or diesel fueling.

Heavy-duty vehicles

Fuel cell technology and hydrogen have enormous potential in heavy-duty trucks, and they are expected to meet the expectations of the private sector.[65] Fuel cell electric buses (FCEBs) are gaining popularity worldwide. Many Canadian companies, for instance, Ballard Power Systems, Dana TM4, Hydrogenic, and New Flyer Industries, are leading the global FCEB value chain.[66] More than 2000 FCEBs are currently in service worldwide and nearly half of those are powered by Canadian heavy-duty fuel cell engine technology. FCEBs have more potential than battery electric buses (BEBs) since using batteries in heavy-duty vehicles decreases the vehicles' load-carrying capacity, which is not economically efficient for operators. Long charging time for BEBs is another important concern – also highlighted in the KI interviews. Many of the individuals consulted, as well as the broader literature supports the idea of using hydrogen and fuel cell technology for medium and heavy-duty vehicles. However, one caveat is that fuel cell trucks are in limited supply and there are currently not enough fueling stations to accommodate more long-range heavy-duty trucks.

FCEBs are more efficient than conventional buses while still providing equal services, therefore, transit agencies would not be required to purchase more vehicles to maintain their existing service levels. FCEBs can also be refueled at faster speeds than BEBs and have the potential to travel longer distances.[67] A significant challenge regarding the deployment of FCEBs in Canada is again the lack of fueling infrastructure. Significant capital investment for fueling infrastructure is required for the initial deployment of FCEBs.[68] Moreover, in North America the cost of FCEBs is higher than diesel buses but lower than BEBs. The price of FCEBs is almost twice the price of diesel buses.[69] According to an article in The Globe and Mail, the cost one BEB in Canada can reach $1.2 million.[70]

Diesel buses require the highest maintenance cost with high operating emissions and low engine efficiency (see appendix 2 table 2), making them an imperfect option. Capital costs for BEBs are the highest; although maintenance cost, motor efficiency, and carbon emissions are similar to FCEBs. The disadvantages of BEBs are that they require a longer charging time, the average availability of charging stations is still low, and they cannot travel long distances without requiring maintenance. Although FCEBs are expensive compared to compressed natural gas (CNG) and diesel buses, FCEBs have no operating emissions, have a high driving range and have high electric motor efficiency. The average fueling time is lower (<10 min) compared to BEBs.

Other applications for transportation

Marine: Table 6 in Appendix 2 shows that marine vehicles in Canadian waters are major contributors to Canada's carbon emissions. Marine emissions in 2019 were primarily produced by bulk carriers (25%) and container ships (16%), followed by cruise ships (11%) and chemical tankers (9%).[71] Although these vessels usually spend less than a quarter of their total operational time sailing, they were responsible for 61% of the total carbon emissions from ships in 2019. If all ships were converted to full-electric ships, carbon emissions can entirely be reduced from the marine industry. Electric ships are powered by batteries charged from the onshore electric grid while the ship is at berth. The ships require very large battery solutions, and these batteries require replacement after eight to ten years, thus causing higher lifetime capital costs than conventional diesel engines.[72] Moreover, for large ships, the energy density of batteries is not sufficient. Passenger ships are smaller and with limited power demand on fixed routes meaning that the battery's energy density could be sufficient; however, these ships emit the highest amount of CO_2 among the vessels that most of their operational time in Canadian waters. The electrification of passenger ships could therefore reduce carbon emissions.

Compared to other fuels, the volumetric energy density of hydrogen is relatively low. The cost of hydrogen is also higher than other fuel types. However, for large ships traveling routes of a few hundred to a thousand kilometers, hydrogen fuel cells are competitive to batteries.[73] Safety concerns remain regarding the storage and handling hydrogen.

Rail: Canada's railway network is responsible for emitting 3.5% of the transportation sector's GHG emissions. Rail applications are difficult to electrify because of their energy-intensive duty cycles and long ranges. Hydrogen, therefore, has substantial potential for these applications. Most of the traditional electrification options use overhead catenary wires or third rails which are very expensive and require significant infrastructure upgrades. Compared to the traditional catenary wires, hydrogen-based rail, or hydrail, provides a cost-effective way to electrify rail applications. Hydrail trains can operate using the existing unmodified tracks; thus, require no electrification infrastructure. Moreover, diesel trains cause significant greenhouse gas emissions due to the carbonaceous nature of the fuel as well as air pollution. Therefore, there is significant pressure on the rail industry to reduce GHG emissions. Hydrail trains are environmentally friendly as well as cost effective. Niederbarnimer Eisenbahn, a private railway company operating between Berlin and Brandenburg, has recently commissioned Siemens Mobility to build seven hydrail fuel cell trains. It is expected that shifting these trains from diesel energy to fuel cells will reduce annual CO_2 emissions by three million kilos.[74] This demonstrates the significant potential that exists in shifting Canadian trains from diesel-based to hydrail, when electrification proves too costly.

Mining: Canada has one of the world's largest mining industries and produces over 60 minerals and metals**.** The mining sector consumes approximately two billion liters of diesel annually.[75] The heavy dependence on diesel can be substituted by using hydrogen as a fuel for vehicles used for mining under and aboveground. Since the mining industry has a large vehicle fleet, shifting to FCEVs could significantly lower their total CO_2 emissions. FCEVs can eradicate diesel combustion exhaust emissions including carbon monoxide, nitrous oxide, and particulate matter, as well as provide operational benefits by reducing the ventilation requirements of mines which generally accounts for more than one-fourth of the total operating costs.

Summary of end-use demand for transportation

As the previous section suggests, the use of hydrogen in different end-use applications has advantages and disadvantages. This section develops a framework that compares available low-carbon end-use applications (fuel cell and electric batteries) with traditional applications. The transportation sector has five evaluation criteria including capital cost, operational cost, efficiency, infrastructure, and CO_2 emission levels. Capital cost refers to the price of a type of transportation. Operational cost refers to mainly average fuel cost. Efficiency indicates how far it can travel with a certain amount of fuel. Infrastructure refers to the availability of refueling/charging stations. Finally, environmental sustainability indicates carbon emission levels from the use of each type of transportation.

The table shows the criteria/measures framework for end-use demand in the transportation section. Here, the green tick refers to competitive, the red cross refers to uncompetitive, and the orange circle indicates moderately competitive. N/A designates that no data is available for that category. From the table below, light-duty FCEVs are not only uncompetitive in terms of costs but also inefficient compared to their alternatives. In addition, the infrastructure for hydrogen refueling stations is insufficient. Clean hydrogen looks promising for heavy-duty vehicles. For long distance travel, BEBs are considered inefficient as they require higher charging time and are uncompetitive to FCEVs in terms of capital costs. In the marine industry, hydrogen does not have a market for small passenger ships but could become a promising marine fuel for long-distance vessels, although further research is required to show that storing hydrogen fuel on ships is safe. Local trains that travel short routes do not have a market for hydrogen. Trains traveling longer routes could us hydrogen with existing tracks. Finally, hydrogen could be a good solution for mining vehicles. In the presence of sufficient infrastructure, hydrogen can be the best solution to achieve low carbon transportation in mining.

Table 6: Criteria/measures framework for end-use demand in the transportation sector

	Light-duty vehicles	Capital cost	Operating cost	Efficiency	Infrastructure/ fuel availability	Environmental sustainability
Light-duty vehicles	Fuel cell electric vehicles (FCEVs)	✗	○	○	✗	✓
	Battery electric vehicles (BEVs)	○	✓	✓	○	✓
	Combustion engine	✓	✗	✗	✓	✗
Heavy-duty vehicles	Fuel cell electric buses (FCEBs)	○	○	✓	✗	✓
	Battery electric buses (BEBs)	✗	✓	✗	○	✓
	Conventional buses	✓	✗	○	✓	✗
Marine	Fuel cell	N/A	✗	N/A	✗	✓
	Electric	N/A	○	N/A	○	✓
	Conventional engine	N/A	✓	N/A	✓	✗
Train	Traditional electrification train	✗	N/A	N/A	✗	✓
	Hydrail train	✓	N/A	N/A	✗	✓
Mining vehicles	FCEVs in mining	✓	N/A	N/A	✗	✓
	Combustion engine vehicle in mining	✗	N/A	N/A	✓	✗

Source: Authors' depiction based on research and key informant interviews.

Building heating

Due to Canada's cold climate, 60% of energy use in homes goes towards space heating, and water heating accounts for 19%.[76] Hydrogen can be blended with the natural gas and used for heating purposes to reduce

GHG emissions, however, much of the literature and KIs were not aligned on what the recommended percentage of blending should be.[77] There are ongoing pilot projects on this subject in several jurisdictions, however, blending hydrogen can degrade pipeline materials, affect gas properties, and increase safety concerns.[78] Canada's natural gas transmission pipelines are made of high-strength steel and operate at high pressure compared to distribution networks. Therefore, under normal operation, these steels are not usually vulnerable to embrittlement effects caused by hydrogen, and the existing natural gas network can handle 5-20% of the blending.[79] However, the KIs noted that there must be more research done in this field before enacting any policy or legislation.

Although hydrogen provides a promising option for reducing CO_2 emissions from the heating sector, the cost of hydrogen production remains high. It is projected that a huge investment in this sector could reduce the cost of hydrogen by 40-50% over the next few years and by 70% in 2050.[80] Nevertheless, most of the KIs were not supportive of using hydrogen as a key source for heating in the short run, because of the high costs associated with the construction of buildings and pipelines.

Industrial applications

The top four uses of hydrogen globally include oil refining (33%), ammonia production (27%), methanol production (11%), and steel production via the direct reduction of iron ore (3%).[81] In most cases, a significant portion of this feedstock is produced through steam methane reforming of natural gas without CCS. This is common in Canada as well, where the largest use for hydrogen is currently as feedstock. Hydrogen produced from clean energy sources has potential to reduce carbon emissions from the Canadian industrial sector.

Oil refining: The oil and gas sector is a key contributor to GHG emissions and was responsible for 26% of Canada's total emissions in 2019.[82] Hydrogen is used mainly to remove impurities from crude oil and upgrade heavier crude. Low carbon intensity hydrogen can be used in both upstream extraction and downstream refining processes. Generally, hydrogen used in downstream refining processes is produced on-site from dedicated production facilities or as a by-product that only can meet the demand of small refineries running on low sulfur crude oil. According to a study, on-site by-product hydrogen has been able to meet one-third of refinery hydrogen demand.[83] Large refineries depend on merchant gas suppliers since on-site hydrogen production is unable to meet their demand. In densely industrialized areas, hydrogen can be supplied through pipelines, thus meeting refineries' hydrogen demand.

There are two main cleaner pathways for producing hydrogen for refineries, including fossil fuels with CCS and electrolysis. The current production cost of low-carbon hydrogen from renewable-based electrolysis is three times higher compared to the cost of hydrogen produced from fossil fuels with CCS.[84] According to NRCan, if hydrogen is produced at scale, then the cost of fossil fuels coupled with CCS is expected to decrease to \$1.00-2.00/kg-H_2 by 2030.[85] Moreover, the technological cost for CCS is also declining. Most existing refineries are equipped with steam methane reforming units and the incremental cost of hydrogen production with CCS facilities is limited. Therefore, fossil fuels with CCS is a more competitive route to low-carbon hydrogen than other renewable-based electrolysis in the short-term. In the long-term, however, the use of fossil fuels with CCS can be replaced with electrolysis.[86] With the falling cost of clean hydrogen produced from electrolysis, nuclear can play a significant role in providing clean hydrogen to refineries in the long-term.

Ammonia and methanol production: The global chemical industry primarily uses hydrogen as feedstock for producing ammonia (31Mt H_2/yr) and methanol (12MtH_2/yr) which generates CO_2

emission of approximately 630 MtCO_2/yr.[87] In Canada, hydrogen is already playing a critical role in ammonia and methanol production. Currently, hydrogen produced from fossil fuels is meeting the demand in the chemical industry for ammonia and methanol production. Although hydrogen produced from fossil fuels is cost-competitive with other energy sources, it produces CO_2 emissions. According to a report by the International Energy Agency (IEA), there are three cleaner pathways to producing hydrogen including fossil fuel with CCS, electrolysis, and using biomass as feedstock. This report also mentions that biomass is less competitive compared to other options; there the focus is on electrolysis and CCS facilities. Both cleaner pathways to produce hydrogen for ammonia and methanol production have higher costs compared to the commercially available pathway. When the price of electricity is low, electrolysis is considered the best option for producing low-carbon ammonia. However, with high electricity prices, fossil fuels with CCS is more competitive than electrolysis.

Iron and steel production: Hydrogen is used in a variety of sectors, the fourth largest being iron and steel production. Iron and steel production is also one of the world's largest emitters of CO_2. Currently, steel production accounts for seven to nine percent of global CO_2 emissions from the global use of fossil fuels.[88] High carbon-intensity hydrogen is used both as a feedstock and as a fuel. However, several projects have been initiated around the world to develop clean pathways to produce steel and iron.

The pathway using electrolysis is significantly more expensive than the pathway using CCS. Therefore, in the short-term, fossil fuels with CCS is more cost-competitive than the CO_2 avoidance pathway. In the long term, the CO_2 avoidance pathway could be more cost-competitive than CO_2 management if the low-carbon electricity price is decreased to around \$35/MWh (USD). With this electricity price, the cost of producing clean hydrogen would be significantly lower than current rates, which could enable the industry to use the CO_2 avoidance pathway. [89], [90]

Market barriers to scaling up the production of hydrogen

The concept of utilizing hydrogen as an alternative to high-carbon-emitting energy sources is not new. It initially emerged following the 1970s oil shocks and has since gone through cycles on the political agenda.[91] Given the renewed international commitment to address climate change at the signing of the 2015 Paris agreement, it is likely that the current spike in interest in hydrogen might be more long-term, however, this is not guaranteed thus making it difficult to justify investments in hydrogen-related projects. We find ourselves in a situation where although the benefits of hydrogen are well-understood and quite pronounced, several market barriers continue to exist, notably the high production costs, high investment risk, and lack of infrastructure. These barriers certainly overlap, suggesting that addressing them in a coordinated manner should have significant positive impacts.

High investment risk

By developing its hydrogen strategy, the Canadian federal government has signaled their interest in developing the hydrogen economy and encouraging private companies to invest in the development of hydrogen-related projects. Since hydrogen use in Canada remains limited, costs remain high as well, which serves as an impediment to further investment.

The capital costs of developing production technologies are high, and without guaranteed demand it can be difficult for companies to justify investing in these new, largely unproven and not yet commercialized technologies. There are major federal government financial supports for companies investing in net-zero projects, however, no funding is available exclusively for the emerging nuclear-to-hydrogen sector. This is a barrier to hydrogen development, as many projects require funding at all points of production (infrastructure development, operation, transportation, end-use) and applying to various funds requires an understanding of project approvals and eligibility, not to mention that these applicants will be competing against the entire net-zero sector, much of which is already achieving scale.

Once the hydrogen economy becomes more developed, producers will begin to have assurances that hydrogen produced will be matched by end-use demand, whether it be domestically or internationally through export. Without guaranteed demand, however, it is financially risky for businesses to justify investment into the hydrogen market, particularly small businesses.

The Edmonton airport recently announced a series of new initiatives that will transform the airport into a hydrogen hub. $50 million will be spent over four years, with funding coming from the Alberta Government and Alberta's Technology Innovation and Emissions Reduction fund.[92] The airport is hoping that by introducing fuel cell vehicles and hydrogen fueling stations, and by eventually creating a fleet of hydrogen aircraft, they will also increase the supply of hydrogen in the province. The size of the institution, in this case, is large, and therefor faces less risk in entering the hydrogen market, which not only eases internal concerns but also makes it easier to receive funding. Unfortunately, many companies seeking entry into the hydrogen industry will not have the advantage of being large and well-established, and without dedicated funding, they will likely face challenges entering the market.

Table 3 - Ongoing federal net-zero incentives

Title	Amount	Use	Coverage
Canada's Net-Zero Accelerator fund (part of Strategic Innovation Fund)[93]	$8 billion fund	Expediting decarbonization products, scaling up clean technology, accelerating Canada's industrial transformation	Net-zero overall
Clean Fuels Fund[94]	$1.5 billion fund over 5 years	De-risking capital investment related to clean fuel production facilities. Contribution agreements that are conditionally repayable.	Many renewable fuels, including clean H_2
Accelerated Capital Cost Allowance (tax incentive)[95]	100% project cost write-off	Cost of machinery and equipment for manufacturing, processing of goods, and production	Renewable energy
Refundable investment tax credit for Carbon Capture, Utilization, and Storage[96]	37.5-60% of project costs (depending on expense type) (budget 2022)	Costs related to purchase and installation of CCS equipment	Decarbonization

Clean Technology investment tax credit[97]	Up to 30% of project costs (budget 2022)	Details forthcoming in fall 2022 federal economic and fiscal update	Net-zero technologies, battery storage solutions, clean hydrogen
Zero Emission Vehicle Infrastructure Program[98]	$680 million fund (2022-2027)	Increasing availability of ZEV charging stations	Electric or hydrogen vehicles
Emissions Transit Fund[99]	$2.75 billion fund over 5 years	Electrification of public and school busses, purchase of ZEV busses and infrastructure	Zero emissions transportation

Source: Government of Government, NRCan, and The Canada Revenue Agency.

Beyond providing funding either directly or through tax breaks, the government can offer several additional supports in the form of continued R&D, but also, by standardizing the existing codes and regulations. Hydrogen in Canada is regulated by a variety of documents, some key ones being the Canadian Hydrogen Installation Code, the Hydrogen Technologies Code, and the 1992 Transportation of Dangerous Goods Act.[100] Hydrogen technology and clean energy preferences have developed significantly since the initial creation of these documents; therefore, many are either outdated or need to be standardized to ensure that all projects meet the same standards, notably with regard to calculating carbon intensity and safety regulations.

In Alberta, for example, the Gas Utilities Act and Gas Distribution Act do not consider hydrogen in their definition of gas, making it challenging for projects to start. Although these are already being worked on, it highlights other acts that remain outdated. In such cases, organizations hoping to pursue hydrogen projects must constantly seek exemption orders from the government, but this can impede the smooth implementation of a project. As the hydrogen economy and the related technologies continue to develop, acts, regulations, codes, and standards must also continually evolve.[101]

Infrastructure and transportation for hydrogen

Certain end-use applications require specific infrastructure transportation requirements in order to access hydrogen after it has been produced. As mentioned by a KI, most of Canada's hydrogen is produced in concentrated areas and used on site since inter-provincial, not to mention cross-country transportation infrastructure does not exist.

Hydrogen can be transported either via pipelines or trucks, and there are several projects in Canada that are piloting the introduction of hydrogen into regional natural gas pipelines. Doing so is a way of reducing the carbon footprint of natural gas consumption in a way that continues to meet local energy demands. As described by a KI, hydrogen transportation is dependent on two key features: transmission networks like pipelines, trucking, and railways, and localized distribution networks. These respective networks need not be comparable to the scale of fossil fuel transportation networks, although the existing fossil fuel infrastructure could also be used for transporting hydrogen. Investing in the infrastructure would improve its compatibility with hydrogen to ensure existing pipelines do not wear prematurely and invite safety risks.

Pilot projects related to hydrogen blending are ongoing in Markham, ON (Enbridge Gas Inc., Cummins Inc.), and Fort Saskatchewan, AB (ATCO Gas) to consider the feasibility of introducing natural gas blended with hydrogen into municipal heating systems.[102] Is remains difficult to do this on a larger scale, however, due to the lack of a sufficient infrastructure networks since the metals comprising existing natural gas pipelines cannot withstand hydrogen at a higher percentage.

Developing a pipeline system could be quite simple, as existing natural gas systems can be retrofitted in order to accommodate hydrogen. Considerations that must be factored in however, include target blend rates, the impact of hydrogen mobility on the mechanical properties of pipelines, and transport methods/end-use intentions beyond the pipeline terminus. If these conditions are unable to be met, or hydrogen demand exists in locations not accessible by pipeline, trucks can be used. In this case, hydrogen would have to be transformed into either a liquid or gas at the production facilities. This can increase domestic export potential and in-province use; however, such technologies are costly and pose a variety of safety concerns. Such capacity would have to be developed onsite at production facilities, but transforming hydrogen into a liquid is a very energy-intensive process, given that it must be cooled to -253°C.[103] Therefore, to ensure lifecycle carbon emissions remain low, it would be important that the electricity being used is clean.

Electric vehicles (EVs) have increased their sales significantly, with 136,000 being purchased as a result of the federal incentives. These vehicles, of course, are supported with adequate fueling infrastructure.[104] Hydrogen-powered, or fuel cell vehicles are being trialed in Canada and could be used to further decarbonize the high-carbon-emitting transportation sector, particularly heavy transport, however, they too will have to be supported by a network of fueling infrastructure. Whereas 7219 EV charging stations exist across 12 provinces and territories, only six fuel cell charging stations exist across two provinces.[105]

Infrastructure for storage and hydrogen hubs

Hydrogen is one of the most promising means of storing energy, however, storing it is complex and challenging because hydrogen's volumetric energy density is low. This creates problems for both bulk producers and end-use applications. The end-use need often determines the hydrogen storage method but is usually done in one of three ways: chemical carrier storage, material-based storage, and physical storage. In simple terms, hydrogen can be stored in gas or liquid form. Hydrogen used in heavy-duty vehicles and forklifts requires storage in the form of gas at a pressure of around 350 bar. Light-duty vehicles require hydrogen to be stored at higher pressure; usually, around 700 bar.[106] Since light-duty vehicle tanks are smaller than heavy-duty ones, high pressure is used to increase mileage.

Hydrogen storage in cryogenic liquid form is reasonably practical and functional for industrial applications and commercial fueling stations for light- and heavy-duty vehicles. Liquid hydrogen is much denser than a gaseous form of hydrogen, making it practical for energy storage. Liquid hydrogen is easy to transport; thus, it is much more cost-effective than the gaseous form, where higher quantities are required. Nonetheless, liquifying hydrogen is still an expensive process because hydrogen is liquified at -253°C with approximately 10kwh/kg of hydrogen, which compromises nearly 30% of the total heating value of hydrogen.[107]

Hydrogen can be stored and transported in the form of chemical carriers, like methylcyclohexane (MCH) and ammonia (NH3). Storing hydrogen in these chemical carriers makes it easy to handle and transport.

Many KIs also supported the idea of storing hydrogen in liquified or chemical carrier forms and that might reduce the long-term cost of storing.

More recent research on hydrogen shows that underground hydrogen storage in geological formations can be a cost-efficient and safe option.[108] Underground hydrogen storage can also help with reducing carbon dioxide emissions.[109] Preliminary mapping of geological feasibility for storing hydrogen shows that Canada has the potential to store hydrogen in the sedimentary basins of Atlantic Canada, Southern Ontario, and crystalline rocks in the Canadian Shield.[110]

Policy Recommendations

Hydrogen can play a key role in complementing strategies and regulations aimed at reducing greenhouse gas (GHG) emissions and moving towards net-zero. In order to reach full potential for hydrogen and given that there much new investment planned for hydrogen production in Canada, governments of all jurisdictions must devise policies and regulations to support the production and supply of hydrogen in the country.[111]

Although Canada has a comparative advantage in hydrogen production and fuel cell technology, challenges and uncertainties remain for the production, investment, and end-use demand required to achieve an economy of scale. Market uncertainty exists because the future size and scale of the clean hydrogen opportunity is uncertain. Achieving clarity in this regard will depend on seeing how hydrogen can compete with other low-carbon technology end-uses so that it might become more cost-competitive. In the short-term, however, hydrogen can be used to decarbonize hard-to-abate sectors until more targeted technologies with lower emissions are scaled. Companies and investors also face policy uncertainty with the development of the economy and need clear incentive structure and an enabling environment to justify capital investments. Moreover, the cost of end-use applications (such as FCEVs) is still high and lacks refueling infrastructure, presenting yet another barrier to its commercial use. While hydrogen can certainly reduce emissions in these sectors and help Canada reach their net-zero commitments, much of the public remains uncertain about the use of hydrogen technology, particularly when coupled with a nuclear feedstock. The removal of these various barriers will require federal support to help de-risk investments, encourage greater demand, and provide policy certainty for producers.

The purpose of these recommendations is to provide some proposed solutions and action points that the CNA, its members, and stakeholders can pursue, with regards to developing the role of nuclear energy in Canada's hydrogen economy. Recommendations are organized in four major sections focusing on the role of the CNA and governments in the short-, medium-, and long-term: 1) selecting appropriate production pathways, 2) increasing hydrogen demand certainty, 3) promoting research and development and 4) removing barriers for producers and infrastructure development.

Hydrogen will certainly play a role in Canada's net-zero future, however, the specifics of how this future will look are currently being decided. Today's policy actions will have long-lasting effects on Canadian carbon emissions, and on Canada's role as a global leader in clean energy technologies. It is important that the policy actions taken today are effective, and that they consider all parts of the hydrogen value chain. The CNA has the potential to be a player during this pivotal time in the energy transition by supporting the development of the hydrogen-based economy, thereby creating an opportunity in the long-term for increased uptake and use of nuclear technologies.

Recommendation #1: The CNA advocates for policies that support nuclear-based pathways for clean hydrogen production in the medium- to long-term, while supporting other (non-nuclear) production pathways in the short-term to help build robust hydrogen supply chains.

Table 8: Recommendation #1, sub-recommendations, and stakeholders

Recommendations	Relevant stakeholders
1a. CNA to advocate and support for the dedicated use of nuclear energy (including SMRs) for clean hydrogen production	Federal, provincial, Indigenous governments, academia, Indigenous communities, nuclear industry and financial institutions
1b. CNA to encourage the federal government to systematically phase out high carbon-emitting hydrogen production by supporting and requiring CCS to abate CO_2 emissions in the short-term as a bridge until hydrogen production using clean electricity—solar, wind, hydro, and nuclear can be fully established.	All levels of government, oil industry, e-NGOs, clean energy producers
1c. CNA should engage with governments at all levels to abandon the use of color schemes that are used for hydrogen production pathways.	All levels of government, academia, think tanks, e-NGOs, and researchers
1d. Thorough engagement and benefit sharing by CNA members with affected Indigenous communities.	All levels of governments, Indigenous communities, and private sector
1e. The CNA should engage more with the nuclear industry and federal and provincial governments to improve nuclear waste treatment technology and improve the waste minimization strategy, with a particular focus on SMR technology and the challenges around safe transportation and storage.	Nuclear industry, Nuclear Waste Management Organization, federal and provincial governments

1a: CNA to advocate and support for the dedicated use of nuclear energy (including SMRs) for clean hydrogen production

Canada is a Tier 1 nuclear country that has strategic targets associated with nuclear energy. With a skilled workforce in this sector, Canada has the leverage to become first-movers in the field. After seeing the successful operations of nuclear reactors in Ontario and New Brunswick, Canada is committed to establishing SMRs "as a source of safe, clean, affordable energy, opening opportunities for a resilient, low-carbon future and capturing benefits for Canada and Canadians."[112] This commitment to building SMRs and to producing clean electricity unlocks opportunities for hydrogen production as well, however, the scale of production needs to increase significantly. Ontario alone produces 12.6 GW of nuclear energy annually (of Canada's total annual nuclear generation of 13.5 GW). Given that this 12.6 GW only covers 59% of Ontario's energy demands, a cross-country capacity of 13.5 GW is entirely insufficient.

One of the key challenges to becoming economically competitive is establishing scale for new technologies. The current market in Canada for clean hydrogen is very small, therefore the associated technologies cannot be sold at scale. Government interventions such as policies and financing these technologies could reduce prices, drive market development, and help unlock the complete potential of producing clean hydrogen at a large scale.

There is untapped potential of using electrolyzers that can simultaneously use high-temperature heat from nuclear power plants, SMRs, geothermal, or solar thermal systems. Although the commercial deployment of SMRs is not anticipated in the short-term, there can still be a role for existing nuclear generation.

The CNA should advocate for the incenting widespread deployment of CCS for on-site hydrogen production in the oil refining sector. A number of refineries are equipped with steam methane reforming units to generate hydrogen on-site for their own needs. Imposing emission limits or using other mechanisms to incent CO_2 emissions reductions would likely encourage the uptake of CCS to abate the emissions from hydrogen production. In Canada, Shell is advancing technology to capture and store CO_2 with CCS through facilities like the Quest commercial-scale CCS facility which has captured and stored over 6 million tonnes of CO_2 to date.[113] In Germany, Shell's 200 kb/d Rhineland refinery has implemented a 10 MW electrolyzer project that supplies approximately 1 ktH_2, or 1% of the refinery's hydrogen needs.[114] Moreover, in Texas the demonstration phase of the Air Product's Port Arthur project was completed by 2017. This project supplies the stored CO_2 to upstream oil companies for enhanced oil recovery (EOR) at the West Hastings oil field. Japan and France also have similar projects that capture and sell CO_2.

Resources required: CNA should seek federal funding to deploy SMRs in Canada and build the capacity to export the technology. The SMRs roadmap is a step in the right direction, however, the efforts for implementation must be enhanced.

1b: CNA to encourage the federal government to systematically phase out high carbon-emitting hydrogen production by supporting and requiring CCS to abate CO_2 emissions in the short-term as a bridge until hydrogen production using clean electricity—solar, wind, hydro, and nuclear can be fully established.

Canada is well-positioned to safely produce, use, and export hydrogen. The transition from carbon-intense energy resources to clean hydrogen can significantly contribute to Canada's net-zero 2050 goals. To accelerate this transition a value chain needs to be established that will, in the long-run, be sustainable without ongoing and significant public investments. Alberta, particularly the Alberta Industrial Heartland region, is producing low cost but high carbon-intense hydrogen by using fossil fuels as a feedstock without applying CCS. The emissions are estimated to be about 9 kg CO_2/kg hydrogen.[115] There is an opportunity for the region to abate the CO_2 emissions by using CCS technologies. It is estimated that once the distribution plan for the new $2.6 billion funding for CCS by the federal government is developed, the effects on hydrogen costs will be like the U.S.'s 45Q tax credit.[116] This will reduce the price of employing CCS while potentially capturing up to 90% of carbon emissions. This price drop in the cost of production will make it more competitive with hydrogen produced directly from fossil fuels without management of carbon. Green electricity hydrogen production is not sufficiently mature to replace the 1.5 million cubic meters per year of hydrogen that is currently being produced in Alberta. Employing CCS for hydrogen produced from fossil fuels including methane and gasoline will require large and safe storage sites of up to

300 t CO_2/year for many years.[117] Although the Alberta government has committed to securing more storage sites, these actions must be taken sooner than later.

Since Alberta has some of the lowest prices of natural gas in world (i.e., \$1 to \$5/GJ higher heating value [hhv]), hydrogen is a suitable alternative to fossil fuels, however, at this point hydrogen produced with CCS is significantly more expensive than natural gas, with prices ranging from \$10-\$14/GJ_{hhv}.

To ease the transition to net-zero, hydrogen must be used at an increasingly larger scale. In Alberta, this is dependent on the continued use of fossil fuels in the short term. The path towards coupling fossil-fuel hydrogen production with CCS is beginning to emerge. Increasing hydrogen production will help lower its costs to make it more competitive with other fossil fuel products. ATCO Electric is currently running a pilot project to blend 5% hydrogen into Fort Saskatchewan's natural gas infrastructure. The CNA can engage with ATCO to support a subsequent pilot project that aims to increase the hydrogen blend rate from 5% to 20% in more population-dense cities, such as Edmonton or Calgary.

The CNA should play a role in advocacy campaigns regarding awareness of integration of CCS with current fossil fuel infrastructure. Coupling CCS technology with hydrogen produced from fossil fuels can help transition from high carbon-intensity hydrogen to clean hydrogen. By advocating for this, the CNA could generate increased the demand for clean hydrogen, which, in the long-term could yield benefits for the nuclear industry.

Increased clean hydrogen demand would further incentivize the production of clean electricity for hydrogen production. This can be supported by committing public funding for hydro, solar, and wind projects to the dedicated to hydrogen production. This would further establish the hydrogen market, making investments less risky and decreasing the costs of electrolyzers would further drive the hydrogen market. Nuclear energy can play a key role in the medium- to long-term, producing hydrogen without intermittence – a problem that would likely persist with wind and solar. This would present an opportunity for the CNA to introduce SMRs into the hydrogen market as a means of supplementing electrolyzer-produced hydrogen. Since this is a long-term recommendation, the costs of SMRs will have likely decreased.

Resources required: no resources are required from the CNA except for their continued advocacy (and the required funding). The federal and provincial governments should maintain their funding commitments to CCS-related projects.

1c: CNA should engage with governments at all levels to abandon the use of color schemes that are used for hydrogen production pathways.

It has been discussed above that the color-coding system for the different types of hydrogen is widely used, however, the color scheme for hydrogen production can jeopardize global acceptability. There are no clear definitions for the carbon intensity of each "color" which is simplistic, hence misleading. The critical parameter in analyzing hydrogen production and its environmental impact should instead be evidence-based lifecycle carbon intensity. Academics and scientists in the field of hydrogen production have started to advocate for intensity-based categorization. This momentum should be continued by CNA partners.

Resources required: no additional resources required.

1d: Thorough engagement and benefit sharing by CNA members with affected Indigenous communities.

During the implementation of any new hydrogen projects, thorough, early and effective engagement with the appropriate Indigenous communities should be carried out. During new investment in hydrogen infrastructure build-out, there must be an opportunity for Indigenous peoples to contribute as well as seek ownership of projects. It is anticipated that hydrogen distribution corridors will likely pass-through Indigenous lands. It must be made sure that all the environmental assessment protocols should be satisfied, and that fulsome Indigenous engagement is conducted.

Resources required: No additional resources required for this recommendation

1e. The CNA should engage more with the nuclear industry and federal and provincial governments to improve nuclear waste treatment technology and improve the waste minimization strategy, with a particular focus on SMR technology and the challenges around safe transportation and storage.

In Canada, waste management is based on the 'polluter pays' principle according to which waste owners are responsible for managing their waste in a secure and safe manner. Canadian Nuclear Safety Commission (CNSC) has developed a Regulatory Document REGDOC-2.11 that explains that waste owners should minimize the radioactive waste they produce to the greatest extent practicable. Canada also has adopted an international waste management approach called the 'waste hierarchy' which states that prevention, reduction (minimization), re-using, and re-cycling should be prioritized before waste disposal.

Resources required: No additional resources required

Recommendation #2: The CNA should advocate for policies that increase end-use demand for clean hydrogen, mitigate investment risks and address market barriers

Table 9: Recommendation #2, sub-recommendations, and stakeholders

Recommendations	Relevant Stakeholders
Heavy Industrial Sector 2a. CNA to encourage and lobby with the government to allow tax credits for companies using electrolysis to produce hydrogen 2b. CNA to engage with all tiers of government to explore opportunities for developing SMRs near industrial complexes	Oil industry, federal and provincial governments, chemical industry
Transportation Sector 2c. CNA to engage with members and other stakeholders for ensuring market certainty for fuel cell electric vehicles by supporting private sector for building hydrogen refueling infrastructure 2d. CNA to advocate for clear municipal policies to expand fuel cell electric buses as means of public transportation 2e. The CNA should influence the federal and provincial governments to develop a roadmap for expanding fuel cells for long-distance ships and to implement pilot projects to help develop safety protocols.	Private sector, construction industry, all levels of government, financial institutions, manufacturers of fuel-cell technologies,

2f. CNA to lobby for increasing demand-side hydrogen investments/projects/policies to complement the existing supply side investments	All levels of the governments, private sector

Heavy Industrial Sector

2a: CNA to encourage and lobby the government to allow tax credits for companies using electrolysis to produce hydrogen

Increased tax incentives, funding opportunities, and infrastructure projects will of course have to be financed with public spending, however, this is limited. In 2020 it was estimated that $4.8 billion was paid in fossil fuel subsidies (at the federal and provincial levels).[118] This has the effect of removing funding from net-zero opportunities and countering the emissions-reductions work being done by other low-carbon industries by effectively contributing to the already low operating prices enjoyed by the fossil fuels industry. The hydrogen economy on the other hand, is struggling to emerge in part due to the high costs of their end-use product, and increased government subsidies could help bring this cost down. According to one study, it is estimated that Canada's carbon tax will yield $66 billion in gross revenue by 2030, with a significant portion being returned to households. [119] This money could be well spent in funding low-carbon hydrogen development projects. A feasibility study should be pursued to determine the net benefits of such a funding pathway.

Resources required: No additional resources are required.

2b: CNA to engage with all tiers of government to explore opportunities for developing SMRs near industrial complexes

Currently, hydrogen used in chemical production is mainly produced from fossil fuel without CCS. Research studies show that electrolysis becomes the best option for low-carbon ammonia and methanol production when electricity prices are low compared to that of natural gas. Policy measures can increase the demand for low-carbon hydrogen in the chemical sector. The government can provide tax credits to industrial companies using electrolysis or fossil fuel with CCS to produce low carbon hydrogen for ammonia and methanol production.

Resources required: No additional resources are required.

Transportation Sector

2c. CNA to engage with members and other stakeholders for ensuring market certainty for fuel cell electric vehicles by supporting private sector for building hydrogen refueling infrastructure

To achieve net-zero in the transportation sector, the roll-out of hydrogen infrastructure is essential for FCEVs. According to the OEMs, a region requires seven to eight refueling stations in order to provide coverage and enable a larger rollout of vehicles. Throughout Canada there are only six hydrogen fueling stations to date including four in BC, and two in Québec (see appendix 2). In 2015 the Canadian government allocated $76 million for the "Green Infrastructure – Electric Vehicle Infrastructure Demonstration Program (EVID)" to address the challenges to the deployment, operation, and management of charging and refueling technologies. However, most of the program achievements are related to the deployment of charging infrastructure for BEVs rather than for fuel cell vehicles.[120] Considering the potential use of hydrogen as transportation fuel, the government needs to focus on building more hydrogen refueling stations.

Tensions exist between the cost of hydrogen, the cost of building a hydrogen fueling station, the size of hydrogen refueling stations, and hydrogen demand, which is slowing down the growth of hydrogen uptake for transportation. The costs associated with building a hydrogen fueling station vary by country and region. According to the IEA, the investment cost for hydrogen fueling stations varies between $0.6-2 million (USD) for hydrogen at a pressure of 700 bar.[121] Tanks for hydrogen storage require different pressure levels and investment costs increase with more pressure. For instance, compared to the previous figures, when pressure is only 350 bar, costs are between $0.15–1.6 million (USD). Furthermore, the lower ratio of FCEVs to fueling stations signals weak coordination between FCEVs and infrastructure deployment which leads to higher hydrogen prices. Since the demand for hydrogen is insufficient in the initial deployment phase, small stations are considered more economically viable as they are more likely to achieve higher capacity utilization rates. The time it takes to build a fueling station is also an important consideration. Although hydrogen fueling stations can be built at the same time as building conventional fueling stations, supplying hydrogen to the fueling station may take longer than conventional transport fuel.

The federal government must play a supportive role in the initial stage by supporting companies to build infrastructure of hydrogen fueling stations throughout Canada. At the initial phase, the government can consider deploying small stations which are more economically justifiable. If each region requires seven stations to provide full-coverage and the capital costs for building each station with 700 bars is $0.6-2 million (USD), then the government would require $4.2-14 million (USD) for each region. This is just one-fifth of the EVID program fund.

Resources required: The CNA should engage with related stakeholders (urban planners, transportation authorities, municipalities, and hydrogen producers) to identify the number and location of hydrogen fueling stations that need to be deployed in each province. Then, they can advocate for the government to support those needs. No additional resources are required of the CNA.

2d. CNA to advocate for clear municipal policies to expand fuel cell electric buses as means of public transportation

The Canadian government should provide more funding to municipalities to purchase more FCEBs and implement policies to influence municipalities so that they introduce FCEBs as means of public transportation. FCEBs could be more advantageous for the Canadian economy than BEBs as they can be developed in Canada and not imported. Fuel cell technology was first commercialized by Ballard and other manufacturers in Canada and a key manufacturer of FCEBs is New Flyer, based in Manitoba.[122] By contrast, lithium cells used in BEBs are imported from Asia. Moreover, FCEBs are more cost-competitive, and the overall performance of FCEBs is superior to BEBs, especially in cold weather.[123]

The Alberta provincial government, Ballard Power Systems, and Dana Inc. have collaborated to initiate the Alberta Zero Emissions Truck Electrification Collaboration (AZETEC) project. The project is piloting the transport of two freightliner class heavy-duty battery-electric vehicles on the Queen Elizabeth II Highway between Edmonton and Calgary. The project aims to learn about and develop the use of fuel cells in heavy-duty trucking.

Resources required: No resources required.

2e. The CNA should influence the federal and provincial governments to develop a roadmap for expanding fuel cells for long-distance ships and to implement pilot projects to help develop safety protocols.

Large, long-distance ships have a very promising market for hydrogen as batteries cannot meet the fuel demand for travel long routes. The International Maritime Organization (IMO) mentions that hydrogen and ammonia (when produced from renewable hydrogen) can be used directly in shipping to help decarbonize the industry. NRCan has identified hydrogen as a potential marine fuel but has not yet provided a path for how Canada can establish a market for hydrogen in the shipping industry. Currently, Canada does not have any marine hydrogen deployments.[124] Therefore, any efforts to implement pilot projects for the marine industry or to develop associated safety protocols should be supported by the CNA.

Low-carbon marine fuels are costly when compared to oil and LNG, and the fuel consumption per kilometer is high for ships. This makes low carbon fuels less cost-competitive than oil and LNG. According to the IEA, the high cost of liquefying hydrogen and high storage costs for long-distance traveling ships make hydrogen more expensive than other low-carbon marine fuels.[125] Given this, the federal government must increase the carbon price high enough so that switching to low carbon fuels becomes cost competitive as well as introduce clean fuel standard. Moreover, the decision of fuel switching also depends on the available infrastructure deployment which is not under the control of ship owners. Building sufficient infrastructure could be another policy measure to address the challenge of reducing carbon emissions.

Sweden and Norway have set targets for low-carbon alternatives in the domestic shipping industry. The European Commission's strategy is to reduce CO_2 emissions by actively monitoring and reporting the CO_2 emissions of large ships.[126]

Resources required: CNA and members should engage with research organizations to investigate the prospects for using hydrogen fuel in ships. CNA will require resources for this task, however, due to a lack of information, this report is unable to determine the required resources.

2f. CNA to lobby for increasing demand-side hydrogen investments/projects/policies to complement the existing supply-side investments

Many of the ongoing financial subsidies are targeting the supply and production side of the emerging economy, whereas the demand side experiences less consistency. Projects to increase demand, such as the EV vehicle targets, or even the AMTA and ATCO pilot projects are done in a sporadic way, without any guarantee of ongoing or consistent hydrogen demand. During the lifecycle of the project, the producers and distributors are being engaged, but they are unable to enjoy this consistently, since the projects often have fixed terms. As such, hydrogen demand must continue increasing in a manner that is reliable, predictable, and consistent.

The ATCO blending project has the goal of gradually increasing hydrogen blending into natural gas from the current 5% to 20%. Beyond the current project, however, they hope to introduce hydrogen into many other pre-existing pipelines beyond just Strathcona County. The scope of this project would make it difficult to accomplish through only self-advocacy, as navigating hydrogen supply challenges, public acceptance, end-use demand infrastructure, and all associated costs would be a laborious process. If, however, the federal government were to implement a mandate requiring gas utilities to reduce their carbon emissions by a certain point, many of these challenges would be alleviated. Such a mandate would signal to suppliers that the demand for hydrogen will be permanent, at least in the utilities sector, enabling them to produce more infrastructure, which will produce more hydrogen and will eventually decrease costs.

Other such projects that make hydrogen demand more consistent should be explored further and supported adequately, not just in Alberta but across Canada.

Resources required: The CNA to conduct a desk review to analyze the misalignment between supply ambitions and demand-side investments/capacity more closely.

Recommendation #3 *Promote research and development, and evidence-based policy advocacy*

Table 10: Recommendation #3, sub-recommendations, and stakeholders

Recommendations	Relevant stakeholders
3a. In collaboration with the nuclear industry, the CNA should design a government relations campaign to urge the government for more R&D expenditures for clean, nuclear-based hydrogen production and for the timely allocation of current resources allocated in the 2022 federal budget	Nuclear industry, think tanks, academia, all levels of government
3b. CNA should collaborate with the Canadian Hydrogen and Fuel Cell Association for advocacy and communication campaigns to promote sustained support for R&D for innovative technologies, subsidies and cost reduction of fuel cell technologies to support the sector.	CHFCA, fuel-cell producers, federal and provincial governments
3c. CNA to collaborate with think tanks, academia, and other research institutions to conduct research to better understand public and industrial perception, knowledge, and willingness about moving towards a hydrogen-based economy, particularly one that emphasizes nuclear-based production	Nuclear industry, think tank, academia, research institutions.
3d. CNA to develop a communications plan for the financial sector that focuses on the financial needs of nuclear hydrogen producers	Financial institutions

3a. In collaboration with the nuclear industry, the CNA should design a government relations campaign to urge the government for more R&D expenditures for clean, nuclear-based hydrogen production and for the timely allocation of current resources allocated in the 2022 federal budget

The 2022 federal budget, allocated funds for nuclear energy and SMRs for the first time; these allocations are for clean energy production, safety provisions, and reducing waste from nuclear reactors.[127] Countries around the world have been increasingly investing in hydrogen RD&D for many years now, whereas the Canadian federal government had reduced its investment prior to the 2022 budget.[128] The data from NRCan also shows that Canada has fewer hydrogen pilot projects than other developed countries. Many OECD countries implementing robust GHG reduction policies have clean hydrogen production projects. As mentioned above, Canada's federal, provincial/territorial governments have adopted strategies for hydrogen production, storage, and transportation; however, there are very limited budgetary allocations for the start-ups and nuclear sector to produce, transport, store and use hydrogen.

Nuclear energy can be key to producing clean hydrogen, however, continued R&D is required for SMRs and their role in the hydrogen economy. With rich uranium reserves as Canada's third-largest primary energy production source, the government of Canada could utilize available uranium resources to produce clean hydrogen.

Resources required: This is a short-term recommendation, and no additional resources are required, understanding that advocacy and communication fall within the mandate and objectives of the CNA.

3b. CNA should collaborate with the Canadian Hydrogen and Fuel Cell Association for advocacy and communication campaigns to promote sustained support for R&D for innovative technologies, subsidies, and cost reduction of fuel cell technologies to support the sector.

Canadian firms are well-positioned and have a comparative advantage in supplying fuel cell vehicles (buses, heavy-duty vehicles, railways, forklifts) and other hydrogen production, transportation, and storage technologies.[129] Canadian firms also have expertise in building components and equipment for fuel cell technology.

Resources required: This is a short-term recommendation, and no additional resources are required.

3c. CNA to collaborate with think tanks, academia, and other research institutions to conduct research to better understand public and industrial perception, knowledge, and willingness about moving towards a hydrogen-based economy, particularly one that emphasizes nuclear-based production

Two types of surveys are required, one with the industries subject to high carbon taxes who could benefit from clean hydrogen production, and the second a nationally representative survey of the general population.

The first survey could aim to understand industrial organizations' readiness, perception, and attitude towards using clean hydrogen and the role of nuclear energy. This survey would help the CNA build its evidence-based policy advocacy component. This survey can be conducted in either collaboration with Statistics Canada or could incorporate questions into the Annual Survey of Manufacturers. The second survey would help understand the knowledge, attitudes, and perception (KAP), and safety concerns of households and consumers in embracing hydrogen energy produced through nuclear energy for daily usage, for example, in transportation and building heating.

There is still limited understanding of the safety and use of hydrogen in different sectors of the economy especially using nuclear energy as feedstock. As highlighted by multiple KIs, safety concerns by the general population about using hydrogen vis-à-vis safety concerns associated with using nuclear as a feedstock for hydrogen remains a major challenge.

Many KIs were of the view that public perception is not easy to change; it needs significant effort from the Government of Canada and the CNA to build confidence and address the issues. There is also international research that discusses public willingness to use hydrogen. For example, Dumbrell et al. (2022) in Australia highlighted that safety concerns by the general population remain a high priority compared to climate change mitigation strategies. There is a need for similar research in Canada to understand the dynamics of production and hydrogen use; this would help inform policy and investment decisions in the short and medium terms. Both the qualitative data and secondary research shows that the governments in Canada need to focus on the behavioral and adaptability aspects of using hydrogen and nuclear energy as a source for clean hydrogen production.

Resources required: These survey and analysis can be conducted within one to two years (short-term). The costs for these surveys would depend on the sample size and geographical coverage. At this stage, it won't be possible to calculate the costs.

Both the qualitative and secondary research shows that the governments in Canada must focus on the behavioral and adaptability aspects of using hydrogen and nuclear energy as a source for clean hydrogen production. Consumers can also benefit from information on the reduced cost of using hydrogen in modern-day technologies and its effectiveness in tackling GHG emissions.

3d. CNA to develop a communications plan for the financial sector that focuses on the financial needs of nuclear hydrogen producers

The federal government has mandated Canada Infrastructure Bank (CIB) to provide $10 billion over the next three years for developing SMRs, and other clean fuel technologies.[130] The financial sector can play a significant role in providing long-term loans to the nuclear industry for setting up SMRs for hydrogen production. For this communications plan to work, the CNA will have to provide evidence of using nuclear as a potential feedstock for hydrogen production in the country.

Resources Required: This is a short-term recommendation, and no additional resources are to be allocated.

Recommendation #4: Advocating for removing market barriers for hydrogen producers through infrastructure development

Table 11: Recommendation #4, sub-recommendations, and stakeholders

Recommendation	Relevant stakeholders
4a. CNA to engage with players in all parts of the value chain to gather an understanding of key legislative and regulatory gaps so that they can be addressed appropriately	Federal and provincial governments, nuclear industry, other hydrogen producers
4b. CNA to assist with and learn from the ongoing technical assessment that evaluates hydrogen export from Canada	Think tanks and academia

4c. CNA and members to work with other stakeholder to provide technical expertise to improve the storage and transportation component of hydrogen and conduct mapping of regions where hydrogen can be stored underground	Think tanks, academia, federal, and provincial governments, nuclear industry, NRCan
4d. CNA to conduct mapping of existing and potential infrastructure for hydrogen hubs and work with the nuclear industry to establish SMRs in regions where hydrogen deployment hubs are feasible	Nuclear industry, Indigenous populations, other residents, academia, and think tanks

4a. CNA to engage with players in all parts of the value chain to gather an understanding of key legislative and regulatory gaps so that they can be addressed appropriately

Most of the core pieces of legislation that are to be identified as not considering hydrogen are likely overarching codes and standards. Updating these will guide the development of hydrogen production, however, without addressing smaller-scale provincial or municipal regulations as well, the industry could continue to face challenges. Additional work in this regard should be done at the municipal level to ensure that emergency response services have established protocol for dealing with hydrogen emergencies. By engaging with players at all parts of the hydrogen value chain, key legislative gaps that might be overlooked at the federal level can be brought to light.

Strategies are not regulations. Implementing a hydrogen production project can be difficult because of the lack of standards, codes, and regulations, and their consideration of hydrogen. Since hydrogen production is still in its early stages and uptake of hydrogen has only happened in a few provinces, there are gaps in existing federal codes and standards. The Hydrogen Strategy for Canada refers to harmonized codes and standards across all the jurisdictions to explore export markets, safety, and standardization of hydrogen production, supply, and transportation, but the federal or provincial strategies provide a roadmap for the implementation of laws and regulations. By conducting a formal review of the regulatory framework, the CNA can identify and convey not only legislative gaps, but their impact on the emerging industry. They can then tailor their advocacy plan accordingly

Resources required: This is a short-term recommendation, and no additional resources are required.

4b. CNA to assist with and learn from the ongoing technical assessment that evaluates hydrogen export from Canada

While realizing the potential for hydrogen exports, the federal government has issued a tender to access the export potential for hydrogen.[131] The CNA must present a case on behalf of the nuclear industry and provide their inputs to build a case for using nuclear energy as a feedstock for exporting clean hydrogen.

The literature and qualitative data depict that Canada has a comparative advantage in the short-term for producing and exporting hydrogen; however, this depends on competition from the rest of the world. Hydrogen strategies from Alberta, British Columbia, and Québec discuss the export potential for hydrogen. Given the potential of Ontario's nuclear industry, we suggest that hydrogen can be exported to the U.S., European and African countries.

Canada is selling oil and natural gas at discounted rates to the U.S., so it would make sense for the country to produce and export hydrogen instead and charge higher prices to the U.S. and in the international market alike.[132] The hydrogen price in the world market and in the U.S. is already very high, for example, the retail price in California for fuel cell-grade hydrogen is $13-17 (USD) per kg of hydrogen, while the cost of producing hydrogen in Alberta right now is $3-4 (USD).[133]

A Transition Accelerator report provides estimates for the hydrogen export market and how much of that market can be captured by the Canadian hydrogen production. One estimate shows that if Canada could capture half of the potential hydrogen market in South Korea, Japan, and Germany, and the price for selling hydrogen was $3.5 (USD) per kg, it would contribute $14.2 billion to the Canadian economy.[134] If this was coupled with the rest of the American markets, the potential for hydrogen exports could reach $100 billion. If the Canadian nuclear industry could capture just one-third of this market by 2030, its revenues could increase by y $33.33 billion.

As mentioned by many KIs, Canada is an export-driven market, and global demand for fossil fuels is expected to decline over the next several decades. As such, it is important for Canada to explore markets for hydrogen and support policies encouraging export. Hydrogen exports now largely depend on the number of emissions produced in its production, because countries are generally favouring cleaner energy. In the medium-term, hydrogen production from renewables will increase significantly, and many countries already have a comparative advantage in solar energy to produce hydrogen, so if Canada focuses on clean hydrogen with renewable energy sources and nuclear energy it would help the country to meet the domestic and international demand. On the question of whether hydrogen exports would be able to offset some of the possible declines in fossil fuel exports, the experts are cautious about drawing any conclusions at this time.

Resources required: This is a short-term recommendation, and no additional resources are required.

4c. CNA and members to work with other stakeholder to provide technical expertise to improve the storage and transportation component of hydrogen and conduct mapping of regions where hydrogen can be stored underground

Storage and transportation of hydrogen remain a major problem, as discussed in the analysis. The gaseous form of hydrogen is not useful, and it would only be sustainable to produce gaseous form until the utilization is in hydrogen hubs, if at all. However, the liquified form of hydrogen is easy to transport and store.

In Europe, the U.K., and the U.S., gaseous hydrogen is stored in underground salt caverns. Canada also has many regions where underground hydrogen storage can happen, so any excess hydrogen produced by the nuclear industry could utilize these formations.[135] Dried and compressed hydrogen can be infused in boreholes and stored there indefinitely. Depleted gas wells can also be used for storing hydrogen in parts of Alberta, Saskatchewan, and Newfoundland and Labrador. However, this would require significant lobbying with the provincial and territorial governments.

Resources required: CNA to lobby for additional funding from the federal government, but mapping and other research would be expensive.

4d. CNA to conduct mapping of existing and potential infrastructure for hydrogen hubs and work with the nuclear industry to establish SMRs in regions where hydrogen deployment hubs are feasible

Transportation and storage have been a major technical challenge for the hydrogen supply and demand. Creating hydrogen hubs would drive demand for hydrogen and deal with other issues by co-locating demand and production of hydrogen.[136]

Countries are building hydrogen hubs based on their comparative advantage and the needs of the industry. Countries in the European Union are way ahead of developing hydrogen hubs; for example, Hamburg and other northern German states have collaborated to develop hydrogen hubs to supply hydrogen to nine key industries in the region. Nearly $9 billion (euros) were allocated to these hubs.[137] France has also selected 11 companies to form an alliance to develop a hydrogen hub for airports and provide fuel for Airbus's initiative to introduce hydrogen-powered aircraft in 2035.[138]

Current potential regions for hydrogen hubs where nuclear energy can cater to the needs of the industries using or the potential to use hydrogen[139]:

1) The Alberta Industrial Heartland. [140]
2) Coastal ports in British Columbia, Ontario, Québec, and the Atlantic region.
3) The transportation corridor between Montréal and Detroit.
4) Near chemical industries in Greater Toronto Area (Oshawa) and Southern Ontario
5) Varennes, Québec.

Cost and Benefits: Germany's northern states and the U.S. have each spent around $9 billion (USD) to develop hydrogen hubs.[141] We can estimate a similar cost for a large-scale hydrogen hub in Canada, which would be impossible without government support. However, multiple nuclear industries in one region can create a smaller hub with an estimated cost of $1.3 billion (this would be similar to Air Products Ltd.'s investment).

Resources required: Mapping by a professional firm can cost between $200,000 -300,000.

Table 12: Action plan for recommendations

	Recommendation	Activity				Timeline for the activities		
		Fund	Advocacy	Engagemen	Research	Short term	Medium term	Long term
Production	Dedicated use of nuclear energy (SMRs) for hydrogen production	✓	✓			✓	✓	
	Investment in CCS and clean electricity		✓			✓	✓	
	Abandon the use of the color scheme			✓		✓		
	Thorough engagement and benefit sharing with Indigenous communities			✓		✓	✓	✓
	Improve nuclear waste treatment technology and improve the waste minimization strategy with a particular focus on SMR			✓	✓	✓	✓	✓
Demand	Tax credits for companies using electrolysis		✓			✓	✓	
	Developing small modular reactors near industrial complexes			✓		✓	✓	
	Ensuring market certainty for fuel cell electric vehicles			✓		✓	✓	
	Expand fuel cell electric buses as means of public transportation		✓			✓	✓	
	Roadmap for expanding fuel cell for long distance ships	✓		✓		✓	✓	
	Increase demand-side hydrogen investments/projects/policies		✓	✓		✓	✓	
Research and	Increase R&D expenditures for clean nuclear based hydrogen production	✓	✓	✓	✓	✓	✓	✓
	Collaboration with CHFCA for sustained support for fuel cell technologies		✓	✓	✓	✓	✓	✓
	Conduct research on public and industrial perception, knowledge, and willingness	✓			✓	✓	✓	
	Develop a communications plan for the financial sector	✓	✓	✓	✓	✓	✓	
Market barriers	Understand key legislative and regulatory gaps	✓	✓	✓		✓		
	Learn from the ongoing technical assessment for hydrogen exports	✓	✓	✓	✓	✓		
	Provide technical expertise to improve the storage and transportation and conduct mapping for underground storage		✓	✓	✓	✓	✓	
	Conduct mapping of existing and potential infrastructure for hydrogen hubs and deployment of SMRs	✓			✓	✓	✓	

Bibliography

Air Products. "Air Products Announces Multi-Billion Dollar Net-Zero Hydrogen Energy Complex in Edmonton, Alberta, Canada," 2021, 1–9. https://www.airproducts.com/news-center/2021/06/0609-air-products-net-zero-hydrogen-energy-complex-in-edmonton-alberta-canada.

Aitken, Jonathan M., Sandor M. Veres, Affan Shaukat, Yang Gao, Elisa Cucco, Louise A. Dennis, Michael Fisher, Jeffrey A. Kuo, Thomas Robinson, and Paul E. Mort. "Autonomous Nuclear Waste Management." *IEEE Intelligent Systems* 33, no. 6 (2018): 47–55. https://doi.org/10.1109/MIS.2018.111144814.

Aydin, Muhammed Iberia, Ibrahim Dincer, and Harry Ha. "Development of Oshawa Hydrogen Hub in Canada: A Case Study." *International Journal of Hydrogen Energy* 46, no. 47 (2021): 23997–10. https://doi.org/10.1016/j.ijhydene.2021.05.011.

Ballard. "Fuel Cell Electric Buses: The Proven Solution for Canada's Climate and Economy," no. 38 (n.d.): 1–14. https://blog.ballard.com/zero-emission-buses-canada.

Bataille, Chris, Jordan Neff, and Blake Shaffer. "The Role of Hydrogen in Canada's Transition to Net-Zero Emissions" 14, no. November (2021).

Billimoria, Sherri, Leia Guccione, Mike Henchen, and Leah Louis-Prescott. "The Economics of Electrifying Buildings." *Rocky Mountain Institute*, 2018, 1–9. https://rmi.org/wp-content/uploads/2018/06/RMI_Economics_of_Electrifying_Buildings_2018.pdf.

Canada. Economic Development. "A Simpler , More Flexible Tool to Grow Canada ' s Economy," n.d., 1–11.

Canadian Small Modular Reactor Roadmap Steering Committee. "A Call to Action: A Canadian Roadmap for Small Modular Reactors." *Natural Resources Canada* 28, no. 1 (2018): 1–2.

CER. "Provincial and Territorial Energy Profiles – Ontario." *Canada Energy Regulator*, 2022, 1–15. https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-ontario.html.

Christopher, Bystrom. "Promoting Hydrogen in Canada: Cross-Country Check-Up," 2022.

CNA. "Government Indicates Clear Support for the Role of Nuclear in Canada ' s Clean Energy Transition in Federal Budget 2022," 2022, 4–7.

David Suzuki Foundation. "Shifting Power: Zero-Emissions Electricity Across Canada by 2035." *Economist*. Vol. 366, 2022. https://doi.org/10.1017/s1742058x18000206.

Dodds, Paul E., Iain Staffell, Adam D. Hawkes, Francis Li, Philipp Grünewald, Will McDowall, and Paul Ekins. "Hydrogen and Fuel Cell Technologies for Heating: A Review." *International Journal of Hydrogen Energy* 40, no. 5 (2015): 2065–83. https://doi.org/10.1016/j.ijhydene.2014.11.059.

Edmonton Journal. "Edmonton International Airport to Become Hydrogen Hub for Piloting New Technology," 2022.

El-Emam, R. S., and I. Khamis. "International Collaboration in the IAEA Nuclear Hydrogen Production Program for Benchmarking of HEEP." *International Journal of Hydrogen Energy* 42, no. 6 (2017): 3566–71. https://doi.org/10.1016/j.ijhydene.2016.07.256.

Enbridge. "Clean Hydrogen Enters the Markham Energy Mix Hydrogen Blending Project Now Operational , Reducing Carbon Footprint of Natural Gas Delivered by Enbridge Gas," 2022.

"Energie NB Power - Nuclear," n.d. https://www.nbpower.com/en/about-us/divisions/nuclear.

"Energie NB Power - Our Energy," n.d. https://www.nbpower.com/en/about-us/our-energy.

Energy, Compendium of Hydrogen. "Hydrogen Underground Storage," 2016.

Finan, Ashley. "Nuclear Technology & Canadian Oil Sands: Integration of Nuclear Power with In-Situ Oil Extraction," 2019, 1–7.

FutureFlight. "11 PARTNERS SELECTED TO SUPPORT FRANCE'S HYDROGEN HUB INITIATIVE," 2021.

Government of Canada. "2030 Emission Reduction Plan: Canada's Next Steps for Clean Air and a Strong Economy," n.d. https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/erp/Canada-2030-Emissions-Reduction-Plan-eng.pdf.

Government of Canada. "B.C. Hydrogen Strategy," n.d.

Government of Canada. "Canada's Leadership Advantage: Hydrogen and Fuel Cells," 2019. http://www.chfca.ca/wp-content/uploads/2019/09/GOC-CDA-Leadership-HFC_en_4pager_WEB1.pdf.

Government of Canada. "Canada Strengthens Energy Partnership with Germany," n.d. https://www.canada.ca/en/natural-resources-canada/news/2021/03/canada-strengthens-energy-partnership-with-germany.html.

Government of Canada. "Clean Fuels Fund - Building New Domestic Production Capacity." *Nrcan.Gc.Ca*, 2021, 4–7. https://www.nrcan.gc.ca/clean-fuels-fund-building-new-domestic-production-capacity/23726.

Government of Canada. "Electric Vehicle Infrastructure Demonstration (EVID) Program Program Background," 2017, 4–7.

Government of Canada. "Government of Canada Advances Supports for Zero Emission Bus Transportation," 2022, 3–7.

Government of Canada. "Hydrogen Scaling up: A Sustainable Pathway for the Global Energy Transition." *Hydrogen Scaling up: A Sustainable Pathway for the Global Energy Transition*, no. November (2017): 80.

Government of Canada. "Investment Tax Credit for Carbon Capture, Utilization, and Storage." *European University Institute*, no. 2 (2012): 2–5. https://eur-lex.europa.eu/legal-content/PT/TXT/PDF/?uri=CELEX:32016R0679&from=PT%0Ahttp://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52012PC0011:pt:NOT.

Government of Canada. “New EV Chargers Coming to British Columbia,” 2022.

Government of Canada. “Overview of Hydro-Québec’s Energy Resources: Setting New Sights with Our Clean Energy,” 2019.

Government of Canada. “Provincial and Territorial Energy Profiles – Ontario,” 2017. https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-ontario.html#:~:text=In 2018%2C about 96%25 of,natural gas%2C with some biomass.

Government of Canada. “Technical Assessment of the Potential for Hydrogen Export (NRCan 5000063696) Tender Notice - Request for Proposal (RFP) Businesses,” no. NRCan 5000063696 (2022): 21–23.

Government of Canada. “Zero Emission Vehicle Infrastructure Program.” *Government of Canada*, 2020, 1–7. https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/zero-emission-vehicle-infrastructure-program/21876.

Government of Canada. “The Future of Hydrogen: Seizing Today’s Opportunities.” *IEA Publications*, no. June (2019): 203.

Hydrogen, Clean, Manufacturing Programs, and Transportation Sectors. “DOE Establishes Bipartisan Infrastructure Law’s $ 9.5 Billion Clean Hydrogen Initiatives,” 2022, 4–7.

Hydrogen Council. “Hydrogen Insights,” no. February (2021): 58. https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf.

Hydro-Québec. “Comparison of Electricity Prices in Major North American Cities 2021.” *Hydro-Québec*, 2021, 80. http://www.hydroquebec.com/publications/en/comparison_prices/index.html%5Cnhttp://www.hydroquebec.com/publications/en/corporate-documents/comparaison-electricity-prices.html.

International Energy Agency. “Global Hydrogen Review 2021.” *Global Hydrogen Review 2021*, 2021. https://doi.org/10.1787/39351842-en.

Jeong, Byongug, Hayoung Jang, Wookjae Lee, Chybyung Park, Seungman Ha, Do Kyun Kim, and Nak Kyun Cho. “Is Electric Battery Propulsion for Ships Truly the Lifecycle Energy Solution for Marine Environmental Protection as a Whole?” *Journal of Cleaner Production* 355, no. June 2021 (2022): 131756. https://doi.org/10.1016/j.jclepro.2022.131756.

Karaca, Ali Erdogan, and Ibrahim Dincer. “An Updated Overview of Canada’s Hydrogen Related Research and Development Activities.” *International Journal of Hydrogen Energy* 46, no. 69 (2021): 34515–25. https://doi.org/10.1016/j.ijhydene.2021.07.235.

Laan, Tara, and Vanessa Corkal. “International Best Practices : Estimating Tax Subsidies for Fossil Fuels in Canada,” no. December (2020): 30. https://www.iisd.org/system/files/2020-12/tax-subsidies-fossil-fuels-canada.pdf.

Lapides, Michael, Insoo Kim, David Fishman, and Chao Ji. “Green Hydrogen. The next Transformational Driver of the Utilities Industry.” *Goldman Sachs Global Investment Research, European Commission*, 2020. https://www.goldmansachs.com/insights/pages/gs-research/green-hydrogen/report.pdf.

Layzell, DB, J Lof, C Young, and J Leary. "Buidling A Transition Pathway To A Vibrant Hydrogen Economy In The Alberta Industrial Hertland" 2, no. 5 (2020): 1–59. https://transitionaccelerator.ca/building-a-transition-pathway-to-a-vibrant-hydrogen-economy/.

Lemieux, Alexander, Alexi Shkarupin, and Karen Sharp. "Geologic Feasibility of Underground Hydrogen Storage in Canada." *International Journal of Hydrogen Energy* 45, no. 56 (2020): 32243–59. https://doi.org/10.1016/j.ijhydene.2020.08.244.

Natural Resources Canada. "Carbon Capture, Utilization, and Storage 'Funding CCUS Technology,'" n.d., 1–3. https://www.nrcan.gc.ca/our-natural-resources/energy-sources-distribution/carbon-capture-utilization-and-storage/4275.

Natural Resources Canada. "EnerGuide Label for Battery-Electric Vehicles," n.d., 17–18. https://www.nrcan.gc.ca/energy/efficiency/energy-efficiency-transportation-and-alternative-fuels/choosing-right-vehicle/tips-buying-fuel-efficient-vehicle/energuide-vehicles/energuide-label-battery-electric-vehicles/21379.

Natural Resources Canada. "Energy Fact Book 2021-2022," 2021, 1–144. https://www.nrcan.gc.ca/sites/nrcan/files/energy/energy_fact/2021-2022/PDF/2021_Energy-factbook_december23_EN_accessible.pdf.

Natural Resources Canada. "Energy Innovation Program - Carbon Capture, Utilization and Storage Stream," n.d. https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/funding-grants-incentives/energy-innovation-program/energy-innovation-program-carbon-capture-utilization-and-storage-stream/23815.

Natural Resources Canada. "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen," 2020. https://www.nrcan.gc.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf.

Nicoletti, Giovanni, Natale Arcuri, Gerardo Nicoletti, and Roberto Bruno. "A Technical and Environmental Comparison between Hydrogen and Some Fossil Fuels." *Energy Conversion and Management* 89 (2015): 205–13. https://doi.org/10.1016/j.enconman.2014.09.057.

Offer, G. J., D. Howey, M. Contestabile, R. Clague, and N. P. Brandon. "Comparative Analysis of Battery Electric, Hydrogen Fuel Cell and Hybrid Vehicles in a Future Sustainable Road Transport System." *Energy Policy* 38, no. 1 (2010): 24–29. https://doi.org/10.1016/j.enpol.2009.08.040.

Ohaeri, Enyinnaya, Ubong Eduok, and Jerzy Szpunar. "Hydrogen Related Degradation in Pipeline Steel: A Review." *International Journal of Hydrogen Energy* 43, no. 31 (2018): 14584–617. https://doi.org/10.1016/j.ijhydene.2018.06.064.

Ontario Government. Green Energy and Green Economy Act, 2009. (n.d.).

Peakman, Aiden, and Robert Gregg. "The Fuel Cycle Implications of Nuclear Process Heat." *Energies* 13, no. 22 (2020): 1–19. https://doi.org/10.3390/en13226073.

Petrunic, Josipa, Elnaz Abotalebi, and Abhishek Raj. "Best Practices and Key Considerations for Transit Electrification and Charging Infrastructure Deployment to Deliver Predictable, Reliable, And Cost-

Effective Fleet Systems. ," no. June (2020).

Quest, The. "The Quest Carbon Capture and Storage," 2022.

Rödl, Anne, Christina Wulf, and Martin Kaltschmitt. "Assessment of Selected Hydrogen Supply Chains-Factors Determining the Overall GHG Emissions." *Hydrogen Supply Chain: Design, Deployment and Operation*, 2018, 81–109. https://doi.org/10.1016/B978-0-12-811197-0.00003-8.

Şahin, Sümer, and Hacı Mehmet Şahin. "Generation-IV Reactors and Nuclear Hydrogen Production." *International Journal of Hydrogen Energy* 46, no. 57 (2021): 28936–48. https://doi.org/10.1016/j.ijhydene.2020.12.182.

Samson, Rachel, Jonathan Arnold, Weseem Ahmed, and Dale Beugin. "Sink or Swim: Transforming Canada's Economy for a Global Low-Carbon Future," no. October (2021). https://climatechoices.ca/wp-content/uploads/2021/10/CICC-Sink-or-Swim-English-Final-High-Res.pdf.

Scita, Rossana, Pier Paolo Raimondi, Michel Noussan, Michel Noussan, Fondazione Eni, and Enrico Mattei. "The Future Hydrogen Economy," n.d.

Siemens Mobility GmbH, "First hydrogen-powered trains for the Berlin-Brandenburg metropolitan region," 27 June 2020, https://press.siemens.com/global/en/pressrelease/first-hydrogen-powered-trains-berlin-brandenburg-metropolitan-region.

Silva Veras, Tatiane da, Thiago Simonato Mozer, Danielle da Costa Rubim Messeder dos Santos, and Aldara da Silva César. "Hydrogen: Trends, Production and Characterization of the Main Process Worldwide." *International Journal of Hydrogen Energy* 42, no. 4 (2017): 2018–33. https://doi.org/10.1016/j.ijhydene.2016.08.219.

Smith, K. A. "Greenhouse Gas Emissions." *Encyclopedia of Soils in the Environment* 4 (2004): 145–53. https://doi.org/10.1016/B0-12-348530-4/00094-1.

Statistics Canada. "New Motor Vehicle Registrations: Quarterly Data Visualization Tool." *Queen's Printer for Ontario*, 2021, 1–3. https://www150.statcan.gc.ca/n1/pub/71-607-x/71-607-x2021019-eng.htm.

Stefanelli, Robert D., Chad Walker, Derek Kornelsen, Diana Lewis, Debbie H. Martin, Jeff Masuda, Chantelle A.M. Richmond, Emily Root, Hannah Tait Neufeld, and Heather Castleden. "Renewable Energy and Energy Autonomy: How Indigenous Peoples in Canada Are Shaping an Energy Future." *Environmental Reviews* 27, no. 1 (2019): 95–105. https://doi.org/10.1139/er-2018-0024.

The Globe and Mail. "Canada's Carbon Pricing: How Much Is It and How Does It Work? What You Need to Know." *The Globe and Mail*, 2021, 1–2. https://www.theglobeandmail.com/canada/article-canada-carbon-tax-explained/.

Government of Canada. "Most Canadians Are in Favour of Electric Buses . What ' s Standing in the Way ?," 2020.

Toronto Star. "City Buses Could Help Kick-Start Canada ' s Domestic Hydrogen Industry," 2021.

Transition Accelarator. "Transitioning to Low- or Zero-Emissions Hydrogen Fuel.," n.d., 1–8.

United Nations, "United Nations Declaration on the Rights of Indigenous Peoples." 2007. https://www.un.org/development/desa/indigenouspeoples/.

Way, Rupert, Penny Mealy, J. Doyne Farmer, and Matthew Ives. "Empirically Grounded Technology Forecasts and The…." *INET Oxford Working Paper No. 2021-01*, 2021. https://www.inet.ox.ac.uk/publications/no-2021-01-empirically-grounded-technology-forecasts-and-the-energy-transition/.

Westhagemann, Michael. "Hydrogen : Hamburg Is Setting the Pace for Europe," n.d., 2–4.

Yu, Minli, Ke Wang, and Harrie Vredenburg. "Insights into Low-Carbon Hydrogen Production Methods: Green, Blue and Aqua Hydrogen." *International Journal of Hydrogen Energy* 46, no. 41 (2021): 21261–73. https://doi.org/10.1016/j.ijhydene.2021.04.016.

Yue, Meiling, Hugo Lambert, Elodie Pahon, Robin Roche, Samir Jemei, and Daniel Hissel. "Hydrogen Energy Systems: A Critical Review of Technologies, Applications, Trends and Challenges." *Renewable and Sustainable Energy Reviews* 146, no. April (2021): 111180. https://doi.org/10.1016/j.rser.2021.111180.

Annexure

Annex 1: Methodology

Search Restrictions

We followed the same approach for all the databases, where publications were only selected if they were ten years old. We used this criterion because we wanted to support our analysis and qualitative data and recommend CNA based on the most recent available literature in the field of hydrogen. As far as possible, we tried to narrow down our research by reviewing peer-reviewed articles; however, we realized that a lot of gray literature, organizational reports, news articles also have the most recent data and information, so we have included these reports and findings after careful consideration.

Criteria-measures analysis

The team agreed on certain selection criteria to narrow down our research to include relevant literature in the report. The papers and reports selected for our analysis and recommendations were carefully selected, where we looked at the credibility of journals, databases, and conflict of interest by the authors. Articles that were purely focused on the scientific data and chemistry of hydrogen were excluded because of the non-scientific nature of the report.

Annex 2: Demand-side hydrogen application

Table 1: Comparison between light-duty vehicles that use different energy sources

Fuel type	Average fuel consumption	Annual fuel cost (CAD)	Average fuel price (CAD)	Carbon emissions	Carbon rating
	L/100 Km	For annual distance of 20,000km	Fuel price per liter or per KWh	g CO_2 /Km	
Gasoline	9	1962	1.09	207	6
Diesel	6.7	1501	1.12	181	7
Hydrogen fuel cell	4.2	1221	5.55	0	10
Electric battery	2.4	506	0.12	0	10

Source:NRCan (2018)[142]

Table 2: Comparison between heavy-duty vehicles that use different energy sources

	FCEBs	BEBs	CNG	Diesel buses
Capital costs (USD)	800,000–2,400,000	1,180,000–1,300,000	550,000–575,000	350,000-380,000
Average maintenance costs ($/km)	0.37	0.37	0.31	0.44
Average fuel economy (KWh/km)	3.347	1.285	2.415	-
Distance between road calls (km)	14,049	6234	23,237	27,000
Electric motor efficiency	High	High	Low	Low
Operating emission	Low	Low	High	High

Source: Aydin et al. (2021)[143]

Table 3: BEB sales across Canadian provinces

Region	Battery Electric Vehicles (BEVs)	All Vehicles	BEVs as % of Total Sales
Canada	12,693	375,826	3.34%
British Columbia	4,826	50,973	9.48%
Québec	4,708	85,486	5.51%
Ontario	2,568	141,788	1.81%
Prince Edward Island	12	1,759	0.68%

Saskatchewan	70	11,506	0.61%
New Brunswick	37	8,105	0.45%
Manitoba	53	11,697	0.45%

Source: StatsCan data from Q1 2021[144]

Table 4: Number of fueling/charging stations across Canada, 2022

Province	Fuel type	
	Hydrogen (Fueling station)	Electric (Charging station)
Alberta	0	292
British Columbia	4	1269
Manitoba	0	67
New Brunswick	0	127
Newfoundland and Labrador	0	42
Northwest Territories	0	1
Nova Scotia	0	124
Nunavut	0	0
Ontario	0	1945

Prince Edward Island	0	52
Québec	2	3216
Saskatchewan	0	71
Yukon	0	13

Source: NRCan [145]

Table 5: Percentage of total sales of vehicles using different fuels over time

Fuel type	Percentage of total sales				
	2017	2018	2019	2020	2021
Gasoline	94.6	92.9	92	89.6	86
Diesel	3.2	3.6	3.1	4.2	4
BEV	0.4	1.1	1.8	2.5	3.6
HEV	1.2	1.3	2	2.7	4.8
PHEV	0.5	1.1	1.1	1	1.7

Source: Statistics Canada[1]

Table 6: Ship emissions in Canadian waters, 2019

[1] Statistics Canada, "New Motor Vehicle Registrations: Quarterly Data Visualization Tool," *Queen's Printer for Ontario*, 2021, 1–3, https://www150.statcan.gc.ca/n1/pub/71-607-x/71-607-x2021019-eng.htm.

Type of vessel	Carbon emissions (tonnes)	Percentage of total emissions
Chemical tankers	730	9%
Gas tankers	34	0%
Bulk carriers	2025	25%
General cargo ships	369	5%
Container ships	1302	16%
Ro-Ro cargo ships	384	5%
Refrigerated cargo ships	5	0%
Offshore supply ships	248	3%
Other service offshore vessels	42	1%
Other activities	494	6%
Fishing vessels	150	2%
Crude oil tankers	433	5%
Oil product tankers	132	2%
Passenger ships	725	9%
Cruise ships	900	11%

Source: Statistics Canada

Annex 3: List of Acronyms

AMTA: Alberta Motor Transport Association

AZETEC: Alberta Zero Emissions Truck Electrification Collaboration

BEV: Battery electric vehicle

BEB: Battery electric bus

CAD: Canadian dollar

CCS: Carbon capture, utilization, and storage

CIB: Canada Infrastructure Bank

CHFCA: Canadian Hydrogen and Fuel Cell Association

CNA: Canadian Nuclear Association

CO_2: Carbon dioxide

EOR: Enhanced oil recovery

EV: Electric vehicle

FCEB: Fuel cell electric bus

GHG: Greenhouse gas(ses)

GW: Gigawatt

H_2: Hydrogen

IAEA: International Atomic Energy Agency

IEA: International Energy Agency

IMO: International Maritime Organization

KAP: Knowledge, attitude, and perception

Kg: Kilogram

KI: Key informant

NOx: Nitrous oxide

NRCan: Natural Resources Canada

Mt: Megaton

MW: Megawatt

OEM: Original equipment manufacturer

RD&D: Research design and development

SMRs: SMRs

USD: US dollar

ZEV: Zero emissions vehicle

Annex 4: Organizations consulted

The Transition Accelerator

IDDRI, Paris

The University of Alberta

The Canadian Hydrogen and Fuel Cell Association

Carleton University

Smart Prosperity Institute

David Suzuki Foundation

Di Zanno and Associates Inc.

Natural Resources Canada, Student Energy

Alberta Motor Transport Association

Ontario Power Generation

ATCO

End Notes

---

[1] Government of Canada, "2030 Emission Reduction Plan: Canada's Next Steps for Clean Air and a Strong Economy," n.d., https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/erp/Canada-2030-Emissions-Reduction-Plan-eng.pdf.

[2] Government of Canada, "Net-zero Emissions by 2050." https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html

[3] Natural Resources Canada, "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen."

[4] Natural Resources Canada, "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen," 2020, https://www.nrcan.gc.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf.

[5] DB Layzell et al., "Buidling A Transition Pathway To A Vibrant Hydrogen Economy In The Alberta Industrial Hertland" 2, no. 5 (2020): 1–59, https://transitionaccelerator.ca/building-a-transition-pathway-to-a-vibrant-hydrogen-economy/.

[6] Natural Resources Canada, "Energy Innovation Program - Carbon Capture, Utilization and Storage Stream," n.d., https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/funding-grants-incentives/energy-innovation-program/energy-innovation-program-carbon-capture-utilization-and-storage-stream/23815.

[7] Michael Lapides et al., "Green Hydrogen. The next Transformational Driver of the Utilities Industry," *Goldman Sachs Global Investment Research, European Commission*, 2020, https://www.goldmansachs.com/insights/pages/gs-research/green-hydrogen/report.pdf.

[8] Hydrogen Council, "Hydrogen Scaling up: A Sustainable Pathway for the Global Energy Transition," *Hydrogen Scaling up: A Sustainable Pathway for the Global Energy Transition*, no. November (2017): 80, www.hydrogencouncil.com.%0Awww.hydrogencouncil.com.

[9] Costs are assumed to be CAD, unless specified otherwise

[10] Natural Resources Canada, "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen."

[11] Total dollar value is $168 billion CAD

[12] Natural Resources Canada, "Energy Fact Book 2021-2022," 2021, 1–144, https://www.nrcan.gc.ca/sites/nrcan/files/energy/energy_fact/2021-2022/PDF/2021_Energy-factbook_december23_EN_accessible.pdf.

[13]Natural Resources Canada. Energy Fact Book 2020-21

[14] Natural Resources Canada. Energy Fact Book 2020-21

[15] Tatiane da Silva Veras et al., "Hydrogen: Trends, Production and Characterization of the Main Process Worldwide," *International Journal of Hydrogen Energy* 42, no. 4 (2017): 2018–33, https://doi.org/10.1016/j.ijhydene.2016.08.219.

[16] Carbon Capture, Utilization, and Storage (CCS) is a technology that can capture and make effective use of the high concentrations of CO_2 emitted by industrial activities.

[17] https://transitionaccelerator.ca/wp-content/uploads/2020/11/Building-a-Transition-Pathway-to-a-Vibrant-Hydrogen-Economy-in-the-Alberta-Industrial-Heartland-November-2020-4.pdf

[18] Key informant interview

[19] Hydro-Québec, "Comparison of Electricity Prices in Major North American Cities 2021," *Hydro-Québec*, 2021, 80, http://www.hydroquebec.com/publications/en/comparison_prices/index.html%5Cnhttp://www.hydroquebec.com/publications/en/corporate-documents/comparaison-electricity-prices.html.

[20] Key informant interview

[21] Rupert Way et al., "Empirically Grounded Technology Forecasts and The…," *INET Oxford Working Paper No. 2021-01*, 2021, https://www.inet.ox.ac.uk/publications/no-2021-01-empirically-grounded-technology-forecasts-and-the-energy-transition/.

[22] David Suzuki Foundation, "Shifting Power: Zero-Emissions Electricity Across Canada by 2035," *Economist*, vol. 366, 2022, https://doi.org/10.1017/s1742058x18000206.

[23] https://world-nuclear.org/information-library/country-profiles/countries-a-f/canada-nuclear-power.aspx#:~:text=The%20government%20established%20Atomic%20Energy,at%20Chalk%20River%20in%201957.

[24] Government of Canada, "Provincial and Territorial Energy Profiles – Ontario," 2017, https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-ontario.html#:~:text=In 2018%2C about 96%25 of,natural gas%2C with some biomass.

[25] "Energie NB Power - Nuclear," n.d., https://www.nbpower.com/en/about-us/divisions/nuclear.

[26] "Energie NB Power - Our Energy," n.d., https://www.nbpower.com/en/about-us/our-energy.

[27] Canadian Small Modular Reactor Roadmap Steering Committee, "A Call to Action: A Canadian Roadmap for Small Modular Reactors," *Natural Resources Canada* 28, no. 1 (2018): 1–2.

[28] Canadian Small Modular Reactor Roadmap Steering Committee.

[29] Meiling Yue et al., "Hydrogen Energy Systems: A Critical Review of Technologies, Applications, Trends and Challenges," *Renewable and Sustainable Energy Reviews* 146, no. April (2021): 111180, https://doi.org/10.1016/j.rser.2021.111180.

[30] Giovanni Nicoletti et al., "A Technical and Environmental Comparison between Hydrogen and Some Fossil Fuels," *Energy Conversion and Management* 89 (2015): 205–13, https://doi.org/10.1016/j.enconman.2014.09.057.

[31] Steam–methane reforming is the benchmark process that has been employed over a period of several decades for hydrogen production. The process involves reforming natural gas in a continuous catalytic process in which the major reaction is the formation of carbon monoxide and hydrogen from methane and steam.

[32] Natural Resources Canada, "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen."

[33] Minli Yu, Ke Wang, and Harrie Vredenburg, "Insights into Low-Carbon Hydrogen Production Methods: Green, Blue and Aqua Hydrogen," *International Journal of Hydrogen Energy* 46, no. 41 (2021): 21261–73, https://doi.org/10.1016/j.ijhydene.2021.04.016.

[34] Ali Erdogan Karaca and Ibrahim Dincer, "An Updated Overview of Canada's Hydrogen Related Research and Development Activities," *International Journal of Hydrogen Energy* 46, no. 69 (2021): 34515–25, https://doi.org/10.1016/j.ijhydene.2021.07.235.

[35] Natural Resources Canada, "Energy Fact Book 2021-2022."

[36] Karaca and Dincer, "An Updated Overview of Canada's Hydrogen Related Research and Development Activities."

[37] Rachel Samson et al., "Sink or Swim: Transforming Canada's Economy for a Global Low-Carbon Future," no. October (2021), https://climatechoices.ca/wp-content/uploads/2021/10/CICC-Sink-or-Swim-English-Final-High-Res.pdf.

[38] Samson et al.

[39] Samson et al.

[40] Natural Resources Canada.

[41] United Nations, "United Nations Declaration on the Rights of Indigenous Peoples." 2007. https://www.un.org/development/desa/indigenouspeoples/

[42] Robert D. Stefanelli et al., "Renewable Energy and Energy Autonomy: How Indigenous Peoples in Canada Are Shaping an Energy Future," *Environmental Reviews* 27, no. 1 (2019): 95–105, https://doi.org/10.1139/er-2018-0024.

[43] Government of Canada, "Canada Strengthens Energy Partnership with Germany," n.d., https://www.canada.ca/en/natural-resources-canada/news/2021/03/canada-strengthens-energy-partnership-with-germany.html.

[44] Bystrom Christopher, "Promoting Hydrogen in Canada: Cross-Country Check-Up," 2022.

[45] We also reviewed reports from Transition Accelerator.

[46] International Energy Agency, "Global Hydrogen Review 2021," *Global Hydrogen Review 2021*, 2021, https://doi.org/10.1787/39351842-en.

[47] Layzell et al., "Buidling A Transition Pathway To A Vibrant Hydrogen Economy In The Alberta Industrial Hertland."

[48] Layzell et al.

[49] Key informant interview

[50] Key informant interview

[51] Hydro-Québec, "Overview of Hydro-Québec's Energy Resources: Setting New Sights with Our Clean Energy," 2019.

[52] Layzell et al., "Buidling A Transition Pathway To A Vibrant Hydrogen Economy In The Alberta Industrial Hertland."

[53] CER, "Provincial and Territorial Energy Profiles – Ontario," *Canada Energy Regulator*, 2022, 1–15, https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-ontario.html.

[54] Canadian Small Modular Reactor Roadmap Steering Committee, "A Call to Action: A Canadian Roadmap for SMRs," *Natural Resources Canada* 28, no. 1 (2018): 1–2.

[55] Sümer Şahin and Hacı Mehmet Şahin, "Generation-IV Reactors and Nuclear Hydrogen Production," *International Journal of Hydrogen Energy* 46, no. 57 (2021): 28936–48, https://doi.org/10.1016/j.ijhydene.2020.12.182.

[56] Jonathan M. Aitken et al., "Autonomous Nuclear Waste Management," *IEEE Intelligent Systems* 33, no. 6 (2018): 47–55, https://doi.org/10.1109/MIS.2018.111144814.

[57] Nuclear Waste Management Organization. "SMRs: Managing Used Fuel", (2018) https://www.nwmo.ca/~/media/Site/Files/PDFs/2018/03/28/09/24/EN_Backgrounder_SMRs2018_Feb28.ashx?la=en

[58] International Atomic Energy Agency. "COSTING METHODS AND FUNDING SCHEMES FOR RADIOACTIVE WASTE DISPOSAL PROGRAMMES", n.d https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1900_Web.pdf

[59] Canadian Small Modular Reactor Roadmap Steering Committee, "A Call to Action: A Canadian Roadmap for Small Modular Reactors."

[60] R. S. El-Emam and I. Khamis, "International Collaboration in the IAEA Nuclear Hydrogen Production Program for Benchmarking of HEEP," *International Journal of Hydrogen Energy* 42, no. 6 (2017): 3566–71, https://doi.org/10.1016/j.ijhydene.2016.07.256.

[61] K. A. Smith, "Greenhouse Gas Emissions," *Encyclopedia of Soils in the Environment* 4 (2004): 145–53, https://doi.org/10.1016/B0-12-348530-4/00094-1.

[62] Fuel cell electric vehicles (FCEVs) are powered by pure hydrogen gas stored in a tank on the vehicle and only emit water vapor and warm air.

[63] Natural Resources Canada, "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen."

[64] G. J. Offer et al., "Comparative Analysis of Battery Electric, Hydrogen Fuel Cell and Hybrid Vehicles in a Future Sustainable Road Transport System," *Energy Policy* 38, no. 1 (2010): 24–29, https://doi.org/10.1016/j.enpol.2009.08.040.

[65] Hydrogen Council, "Hydrogen Insights," no. February (2021): 58, https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf.

[66] Hydrogen Council.

[67] Josipa Petrunic, Elnaz Abotalebi, and Abhishek Raj, "Best Practices and Key Considerations for Transit Electrification and Charging Infrastructure Deployment to Deliver Predictable, Reliable, And Cost-Effective Fleet Systems. ," no. June (2020).

[68] Natural Resources Canada, "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen."

[69] Toronto Star, "City Buses Could Help Kick-Start Canada ' s Domestic Hydrogen Industry," 2021.

[70] The Globe and Mail, "Most Canadians Are in Favour of Electric Buses . What ' s Standing in the Way ?," 2020.

[71] Table 6, appendix 2

[72] Table 6, appendix 2

[73] Byongug Jeong et al., "Is Electric Battery Propulsion for Ships Truly the Lifecycle Energy Solution for Marine Environmental Protection as a Whole?," *Journal of Cleaner Production* 355, no. June 2021 (2022): 131756, https://doi.org/10.1016/j.jclepro.2022.131756.

[74] "First hydrogen-powered trains for the Berlin-Brandenburg metropolitan region," Siemens Mobility GmbH, 27 June 2020, https://press.siemens.com/global/en/pressrelease/first-hydrogen-powered-trains-berlin-brandenburg-metropolitan-region.

[75] Jeong et al.

[76]https://www.nrcan.gc.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf

[77] Paul E. Dodds et al., "Hydrogen and Fuel Cell Technologies for Heating: A Review," *International Journal of Hydrogen Energy* 40, no. 5 (2015): 2065–83, https://doi.org/10.1016/j.ijhydene.2014.11.059.

[78] Enyinnaya Ohaeri, Ubong Eduok, and Jerzy Szpunar, "Hydrogen Related Degradation in Pipeline Steel: A Review," *International Journal of Hydrogen Energy* 43, no. 31 (2018): 14584–617, https://doi.org/10.1016/j.ijhydene.2018.06.064.

[79] Ohaeri, Eduok, and Szpunar.

[80] Sherri Billimoria et al., "The Economics of Electrifying Buildings," *Rocky Mountain Institute*, 2018, 1–9, https://rmi.org/wp-content/uploads/2018/06/RMI_Economics_of_Electrifying_Buildings_2018.pdf.

[81] Natural Resources Canada.

[82] Natural Resources Canada.

[83] International Energy Agency, "The Future of Hydrogen: Seizing Today's Opportunities," *IEA Publications*, no. June (2019): 203.

[84] Aiden Peakman and Robert Gregg, "The Fuel Cycle Implications of Nuclear Process Heat," *Energies* 13, no. 22 (2020): 1–19, https://doi.org/10.3390/en13226073.

[85] Natural Resources Canada, "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen."

[86] Ashley Finan, "Nuclear Technology & Canadian Oil Sands: Integration of Nuclear Power with In-Situ Oil Extraction," 2019, 1–7.

[87] International Energy Agency, "The Future of Hydrogen: Seizing Today's Opportunities."

[88] Natural Resources Canada, "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen."

[89] International Energy Agency, "The Future of Hydrogen: Seizing Today's Opportunities."

[90] Natural Resources Canada, "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen."

[91] Rossana Scita et al., "The Future Hydrogen Economy," n.d.

[92] Edmonton Journal, "Edmonton International Airport to Become Hydrogen Hub for Piloting New Technology," 2022.

[93] Economic Development Canada, "A Simpler , More Flexible Tool to Grow Canada ' s Economy," n.d., 1–11.

[94] Government of Canada, "Clean Fuels Fund - Building New Domestic Production Capacity," *Nrcan.Gc.Ca*, 2021, 4–7, https://www.nrcan.gc.ca/clean-fuels-fund-building-new-domestic-production-capacity/23726.

[95] P M Accelerated and Investment Incentive, "Accelerated Investment Incentive On This Page," n.d., 1–20.

[96] Government of Canada, "Investment Tax Credit for Carbon Capture, Utilization, and Storage," *European University Institute*, no. 2 (2012): 2–5, https://eur-lex.europa.eu/legal-content/PT/TXT/PDF/?uri=CELEX:32016R0679&from=PT%0Ahttp://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52012PC0011:pt:NOT.

[97] Government of Canada.

[98] Government of Canada, "Zero Emission Vehicle Infrastructure Program," *Government of Canada*, 2020, 1–7, https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/zero-emission-vehicle-infrastructure-program/21876.

[99] Government of Canada, "Government of Canada Advances Supports for Zero Emission Bus Transportation," 2022, 3–7.

[100] Canadian Nuclear Laboratories, Feb 2022 (Not published yet, but in our shared literature doc)

[101] Aaron Hoskin Interview, 13 June 2022

[102] Enbridge, "Clean Hydrogen Enters the Markham Energy Mix Hydrogen Blending Project Now Operational , Reducing Carbon Footprint of Natural Gas Delivered by Enbridge Gas," 2022.

---

[103] Anne Rödl, Christina Wulf, and Martin Kaltschmitt, "Assessment of Selected Hydrogen Supply Chains-Factors Determining the Overall GHG Emissions," *Hydrogen Supply Chain: Design, Deployment and Operation*, 2018, 81–109, https://doi.org/10.1016/B978-0-12-811197-0.00003-8.

[104] Government of Canada, "New EV Chargers Coming to British Columbia," 2022.

[105] See table in appendix 2 (EV and hydrogen fuelling stations by province)

[106] See table in appendix 2

[107] Natural Resources Canada.

[108] Alexander Lemieux, Alexi Shkarupin, and Karen Sharp, "Geologic Feasibility of Underground Hydrogen Storage in Canada," *International Journal of Hydrogen Energy* 45, no. 56 (2020): 32243–59, https://doi.org/10.1016/j.ijhydene.2020.08.244.

[109] Yu, Wang, and Vredenburg, "Insights into Low-Carbon Hydrogen Production Methods: Green, Blue and Aqua Hydrogen."

[110] Yu, Wang, and Vredenburg.

[111] Chris Bataille, Jordan Neff, and Blake Shaffer, "The Role of Hydrogen in Canada'sTransition to Net-Zero Emissions" 14, no. November (2021).

[112] Canadian Small Modular Reactor Roadmap Steering Committee, "A Call to Action: A Canadian Roadmap for Small Modular Reactors."

[113] The Quest, "The Quest Carbon Capture and Storage," 2022.

[114] International Energy Agency, "The Future of Hydrogen: Seizing Today's Opportunities."

[115] Layzell et al., "Buidling A Transition Pathway To A Vibrant Hydrogen Economy In The Alberta Industrial Hertland."

[116] Natural Resources Canada, "Carbon Capture, Utilization, and Storage 'Funding CCUS Technology,'" n.d., 1–3, https://www.nrcan.gc.ca/our-natural-resources/energy-sources-distribution/carbon-capture-utilization-and-storage/4275.

[117] Natural Resources Canada.

[118] Tara Laan and Vanessa Corkal, "International Best Practices : Estimating Tax Subsidies for Fossil Fuels in Canada," no. December (2020): 30, https://www.iisd.org/system/files/2020-12/tax-subsidies-fossil-fuels-canada.pdf.

[119] Laan and Corkal.

[120] Government of Canada, "Electric Vehicle Infrastructure Demonstration (EVID) Program Program Background," 2017, 4–7.

[121] International Energy Agency, "The Future of Hydrogen: Seizing Today's Opportunities."

[122] Ballard, "Fuel Cell Electric Buses: The Proven Solution for Canada's Climate and Economy," no. 38 (n.d.): 1–14, https://blog.ballard.com/zero-emission-buses-canada.

[123] Ballard.

[124] Natural Resources Canada, “Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen.”

[125] International Energy Agency, “The Future of Hydrogen: Seizing Today’s Opportunities.”

[126] International Energy Agency.

[127] CNA, “Government Indicates Clear Support for the Role of Nuclear in Canada ’ s Clean Energy Transition in Federal Budget 2022,” 2022, 4–7.

[128] Natural Resources Canada, “Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen.”

[129] Government of Canada, “Canada’S Leadership Advantage: Hydrogen and Fuel Cells,” 2019, http://www.chfca.ca/wp-content/uploads/2019/09/GOC-CDA-Leadership-HFC_en_4pager_WEB1.pdf.

[130] CNA, “Government Indicates Clear Support for the Role of Nuclear in Canada ’ s Clean Energy Transition in Federal Budget 2022.”

[131] Government of Canada, “Technical Assessment of the Potential for Hydrogen Export (NRCan 5000063696) Tender Notice - Request for Proposal (RFP) Businesses,” no. NRCan 5000063696 (2022): 21–23.

[132] Transition Accelarator, “Transitioning to Low- or Zero-Emissions Hydrogen Fuel.,” n.d., 1–8.

[133] Transition Accelarator

[134] Transition Accelarator

[135] Compendium of Hydrogen Energy, “Hydrogen Underground Storage,” 2016.

[136] Government of Canada, “B.C. Hydrogen Strategy,” n.d.

[137] Michael Westhagemann, “Hydrogen : Hamburg Is Setting the Pace for Europe,” n.d., 2–4.

[138] FutureFlight, “11 PARTNERS SELECTED TO SUPPORT FRANCE ’ S HYDROGEN HUB INITIATIVE,” 2021.

[139] Natural Resources Canada, “Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen.”

[140] Air Products, “Air Products Announces Multi-Billion Dollar Net-Zero Hydrogen Energy Complex in Edmonton, Alberta, Canada,” 2021, 1–9, https://www.airproducts.com/news-center/2021/06/0609-air-products-net-zero-hydrogen-energy-complex-in-edmonton-alberta-canada.

Learning from Air Products Ltd. Hydrogen hub strategy in Alberta.

[141] Clean Hydrogen, Manufacturing Programs, and Transportation Sectors, “DOE Establishes Bipartisan Infrastructure Law’s $ 9 . 5 Billion Clean Hydrogen Initiatives,” 2022, 4–7.

[142] Natural Resources Canada, “EnerGuide Label for Battery-Electric Vehicles,” n.d., 17–18, https://www.nrcan.gc.ca/energy/efficiency/energy-efficiency-transportation-and-alternative-fuels/choosing-right-vehicle/tips-buying-fuel-efficient-vehicle/energuide-vehicles/energuide-label-battery-electric-vehicles/21379.

[143] Muhammed Iberia Aydin, Ibrahim Dincer, and Harry Ha, "Development of Oshawa Hydrogen Hub in Canada: A Case Study," *International Journal of Hydrogen Energy* 46, no. 47 (2021): 23997–10, https://doi.org/10.1016/j.ijhydene.2021.05.011.

[144] Statistics Canada, "Wholesale Sales for Motor Vehicle and Parts Merchant," 2022, 2–3.

[145] Natural Resources Canada, "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen."