Potential of hydrogen to help decarbonize the Yukon

Report prepared for the Government of Yukon Department of Energy, Mines and Resources

SUBMITTED TO

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About Us

Navius Research Inc. is an independent and non-partisan consultancy based in Vancouver. We operate proprietary energy-economy modelling software designed to quantify the impacts of climate change mitigation policy on greenhouse gas emissions and the economy. We have been active in this field since 2008 and have become one of Canada's leading experts in modelling the impacts of energy and climate policy. Our analytical framework is used by clients across the country to inform energy and greenhouse gas abatement strategy.

We are proud to have worked with:

- Most provincial and territorial governments, as well as the federal government.
- Utilities, industry associations and energy companies.
- Non-profit and research organizations with an interest in energy, climate change and economics.

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Summary

Hydrogen is an energy carrier that emits no greenhouse gas emissions when converted into useful energy, giving it the potential to help decarbonize a variety of energy end-uses across the economy. Provided that hydrogen is produced via low carbon means, it could provide an opportunity to help reduce the Yukon's emissions, especially in the context of deep reduction targets such as net zero by mid-century.

How do we simulate the potential adoption of hydrogen in the Yukon?

To examine the potential for hydrogen to decarbonize the Yukon, we employed two customized models representing the Yukon's energy-economic system.

gTech is well suited for simulating hydrogen demand because it:

1. Represents a wide range of technologies that produce and consume energy in all sectors and regions of Canada's economy.
2. Accounts for the preferences of firms and consumers when choosing which energy technologies to use, such as aversion to large up-front costs or new and unfamiliar technologies.
3. Explicitly simulates the impact of all substantive existing federal, territorial and provincial climate policies on technology choice (including how they interact).

These dynamics are critical for understanding the potential for hydrogen adoption because hydrogen technology won't be adopted in a silo. Rather, its adoption will be influenced by climate policy, its cost relative to other technologies, and firm and consumer decision making.

We also employed **IESD** to simulate electricity supply, the potential for hydrogen as seasonal storage, and production of hydrogen via electrolysis in the Yukon.

The scenarios

Three scenarios are included in this analysis:

- **Reference case**, aka *business as usual*. This scenario represents the Yukon's energy-economy in the absence of any additional climate policy.
- **Our Clean Future.** This scenario includes key policies announced in *Our Clean Future*.
- **Net zero.** This scenario assumes the Yukon meets its 2030 target of a 45% reduction in non-mining emissions below 2010, and subsequently achieves deep greenhouse gas reductions consistent with net zero by 2050.

We also conduct a sensitivity analysis to determine the impact of alternative assumptions about the availability and cost of electricity storage options in the Yukon.

Key findings

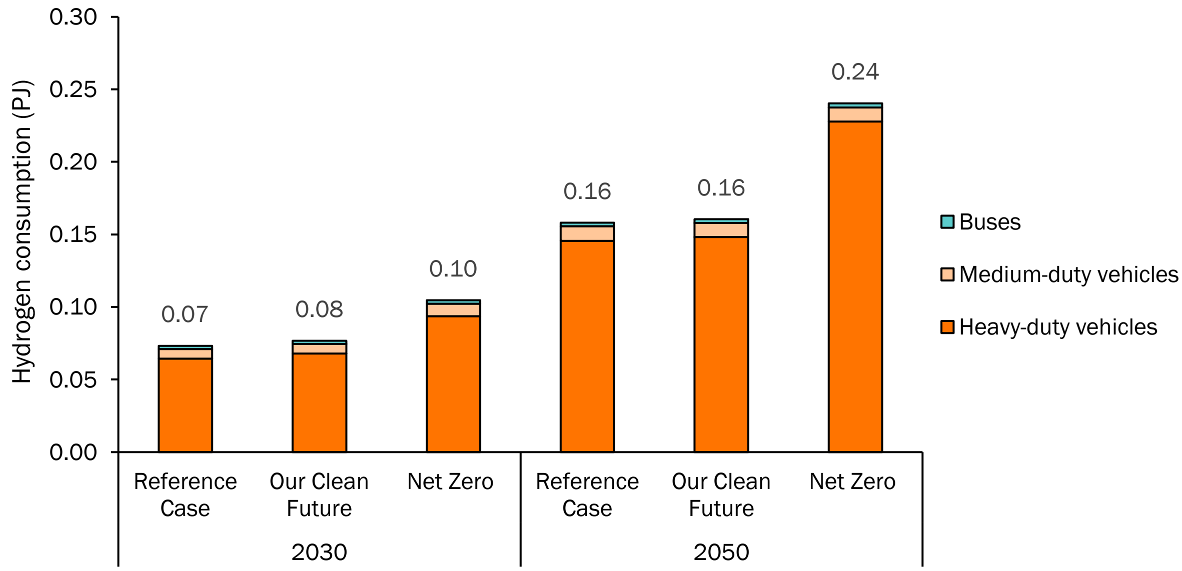
This analysis reveals four key findings, summarized below. More details about the assumptions and results are provided in the report.

1. The largest opportunity for hydrogen to reduce greenhouse gas emissions in the Yukon is in medium and heavy-duty vehicles.

Hydrogen can displace fossil fuels across a variety of end-uses. Based on plausible assumptions about technological change, the largest opportunity for hydrogen to reduce greenhouse gas emissions in the Yukon is displacing diesel consumption by medium and heavy-duty vehicles. Medium and heavy-duty vehicles frequently travel long distances, making them less conducive to electrification relative to light-duty vehicles.

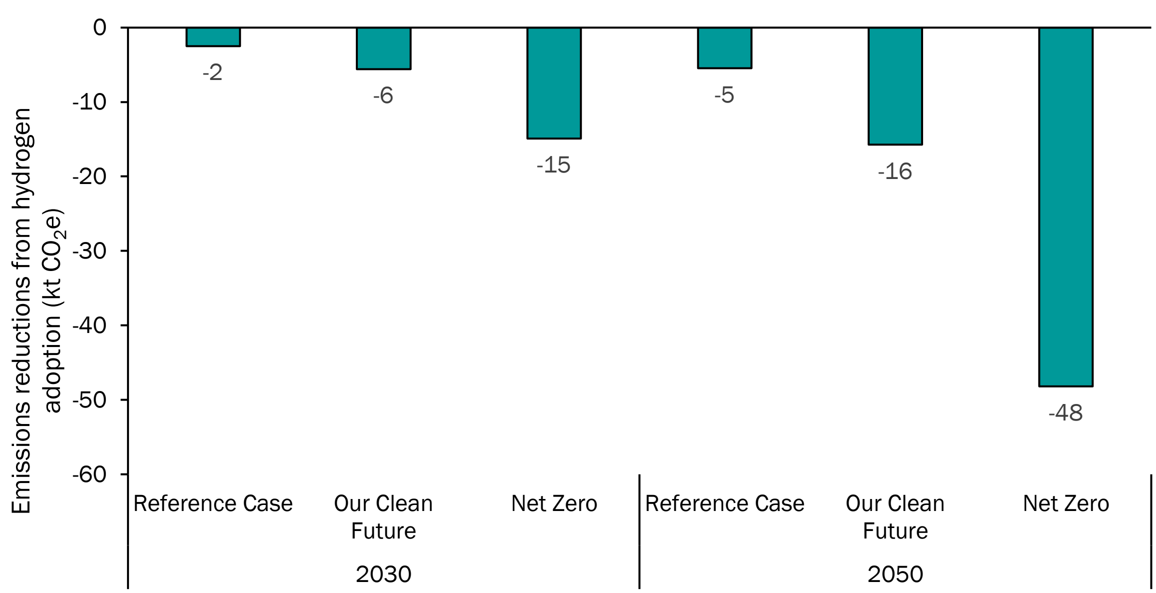
Using baseline estimates about technology costs, this analysis finds that fuel cell electric vehicles could account for over 10% of medium and heavy-duty vehicle sales by 2050. This results in up to 0.24 PJ of hydrogen consumption (Figure 1), reducing emissions by up to 48 kt CO_2e relative to 2020 levels (Figure 2). The more stringent the emission reduction efforts in the Yukon, the greater the potential adoption of fuel cell electric vehicles, and the greater the impact on emissions.

Figure 1: Hydrogen consumption in the Yukon



Source: Navius analysis using gTech-IESD.

Figure 2: Emissions reductions from hydrogen adoption relative to 2020



Source: Navius analysis using gTech-IESD.

The adoption of hydrogen fuel cell vehicles in the Yukon is uncertain, and depends on the future cost of hydrogen, hydrogen fuel cell vehicles and low carbon alternatives to hydrogen. Hydrogen fuel cell vehicle adoption could therefore be greater or lower than the estimates presented above. In particular, we note that the main low-carbon alternative to hydrogen for many of these applications is likely to be second-generation biofuels, which are chemically identical to diesel and require no vehicle engine modifications. Technology breakthroughs in either hydrogen fuel cell technology or biofuel manufacturing could lead to a situation where one option dominates.

2. Other applications for hydrogen are likely to be more limited in the Yukon.

Other opportunities for hydrogen are likely more limited from the perspective of greenhouse gas emission reductions due to (1) technical feasibility and/or (2) lack of cost competitiveness with other abatement options:

- Using hydrogen as **seasonal electricity storage**. If geology in the Yukon is conducive to underground hydrogen storage, hydrogen could be attractive for seasonal electricity storage. If such geology is not available in the Yukon, pumped storage hydro is likely to be more competitive than above ground hydrogen storage.
- Using hydrogen for stationary **equipment and electricity storage in mines**. The technology readiness for mining equipment is low, especially considering the Yukon's cold climate. Other options for achieving deep emissions reductions from mines include electrifying operations by connecting them to the grid, on-site renewables and/or the use of second-generation biofuels.
- **Decarbonizing other transportation sectors**. Marine transport may be conducive to adopting hydrogen but does not account for a significant portion of greenhouse gas emissions in the Yukon, and use of hydrogen in air transport presently requires much more technological innovation. Finally, we find limited opportunity for decarbonizing light-duty vehicles and buses using hydrogen (see Figure 1) because battery-electric technology is likely to be more competitive.
- Using hydrogen for **heating of buildings**. No pipeline infrastructure exists in the Yukon (i.e., that could potentially be employed to distribute hydrogen), and hydrogen is likely not cost-competitive with electric heating options. We note that it may be possible to develop district heating systems fueled by hydrogen.

3. The most cost-effective option for low carbon hydrogen supply in the Yukon is likely via electrolysis.

To meet any hydrogen demand in the Yukon, hydrogen must either be produced within the territory or imported from elsewhere. Imports via pipeline or truck from Alberta and British Columbia would be costly, leaving production within the Yukon – via electrolysis in particular – as the most economical option.

To investigate the potential for hydrogen production via electrolysis, we conducted a detailed analysis of the Yukon's electricity system. This analysis found that a build out of renewables, including in particular solar, could facilitate the production of low carbon hydrogen.

4. Steps to encourage hydrogen use and adoption in the Yukon

- **Ensure a growing supply of low-carbon electricity.** Achieving deep levels of greenhouse gas reduction inevitably requires greater supply of decarbonized electricity. All of the low carbon futures simulated in this analysis result in overbuilding of solar and wind capacity, with periods of curtailment when there is an excess of electricity supply. This presents an opportunity for periods of cheap electricity that can be used to generate hydrogen.
- **Explore the technical feasibility of underground storage.** Using hydrogen as seasonal electricity storage may have potential if suitable geology exists in the Yukon. Additional research would be required to review the local geology and determine whether hydrogen storage in rock caverns is feasible. Seismic activity and proximity to fault lines makes this opportunity particularly uncertain.
- **Pursue an adaptive policy approach.** The Government of Yukon's *Our Clean Future* climate change strategy includes several policies to (1) facilitate hydrogen production (by requiring that most electricity generated be from renewable sources) and (2) encourage demand for hydrogen technologies (e.g., carbon pricing and zero-emission vehicle mandates). Though these policies are largely technology-agnostic, they may encourage hydrogen adoption in the longer-term, particularly if strengthened. By monitoring the technology readiness of hydrogen (and low-carbon alternatives to hydrogen), the Government of Yukon can refine these policies and/or implement new policies as needed (e.g., if a technology breakthrough occurs with hydrogen fuel cell vehicles, the Government of Yukon could invest in hydrogen production infrastructure).

Contents

1. Introduction

In September 2020, the Government of Yukon released its *Our Clean Future* climate change strategy. This strategy will help reduce greenhouse gas emissions, though analysis suggests additional reductions will be required to achieve territorial targets in 2030[1]. The Government of Yukon Department of Energy, Mines and Resources is interested to understand the potential for hydrogen to help close this gap and to further decarbonize the territory's energy system through 2050.

Hydrogen is an energy carrier that produces no emissions when converted into useful energy. This quality makes it a good candidate to replace fossil fuels in energy systems. The 10th Clean Energy Ministerial, held in Vancouver in 2019, stimulated renewed interest in hydrogen as a global greenhouse gas reduction solution. Many governments have since announced deployment strategies, including British Columbia and the Canadian federal government.

The purpose of this analysis is to assess the potential for hydrogen to decarbonize the Yukon's energy system and help the territory meet its greenhouse gas emissions targets.

This report is structured as follows. Section 2 introduces the approach used for this analysis, with further details provided in the appendices. Results are then presented related to both hydrogen demand and supply (Section 3), followed by a discussion of potential policy options for encouraging hydrogen adoption (Section 4).

[1] Navius Research. (2020). *Informing the development of Our Clean Future: a Yukon strategy for climate change, energy and a green economy.* https://www.naviusresearch.com/wp-content/uploads/2020/09/2020-09-05-YT-GHG-Model-Report.pdf

2. Approach

This section introduces the modelling framework of this analysis, with more details available in the appendices. It also outlines hydrogen applications and supply options considered. Finally, the scenarios modelled are presented.

2.1. Modelling framework

To examine the potential for hydrogen to decarbonize the Yukon, we employed Navius' in-house energy-economy model, **gTech**. gTech combines a realistic representation of technology and consumer preferences, exhaustive accounting of the economy at large, and detailed representation of energy supply markets across all regions in Canada and the United States. In this analysis, gTech was used to forecast electricity demand, demand for fuel cell electric vehicles and demand for hydrogen. This model is ideally suited for this task because it:

1. Represents a wide range of technologies that produce and consume energy in all sectors and regions of Canada's economy.
2. Accounts for the preferences of firms and consumers when choosing which energy technologies to use, such as aversion to large up-front costs or new and unfamiliar technologies.
3. Explicitly simulates the impact of all substantive existing federal, territorial and provincial climate policies on technology choice (including how they interact).

These dynamics are critical for understanding the potential for hydrogen adoption because hydrogen technology won't be adopted in a silo. Rather, its adoption will be influenced by climate policy, its cost relative to other technologies, and firm and consumer decision making. More details can be found in Appendix B.

We also employed Navius' in-house **Integrated Electricity Supply and Demand (IESD)** model to forecast the electricity supply, the potential for hydrogen as seasonal storage, and production of hydrogen via electrolysis in the Yukon. The model simulates capacity investment and hourly dispatch decisions in the electricity sector. The version of IESD used for this analysis covers the Yukon's integrated grid, as well as four microgrids: Beaver Creek, Destruction Bay, Watson Lake, and Old Crow. More details can be found in Appendix A.

2.2. Hydrogen applications

This section summarizes possible hydrogen demand applications considered in this analysis. It also outlines which applications were identified as most promising and hence included in the modelling. Detailed assumptions are then provided for those applications included in the modelling.

Table 1 below outlines applications considered for hydrogen demand. Based on feedback from stakeholders (see Appendix C), discussions with the Department of Energy, Mines and Resources, and Navius' research into cost and feasibility of applications, hydrogen for seasonal electricity storage and fuel cell electric vehicles were identified as the most promising applications for inclusion in the modeling. Cost assumptions for these applications are presented below.

Table 1: Potential hydrogen demand applications in the Yukon

Application	Description
Electricity storage	■ Hydrogen may be used as seasonal electricity storage. This can help integrate intermittent renewables on the electricity grid. ■ Three types of storage are theoretically feasible in the Yukon: (1) underground storage in hard rock caverns, (2) above ground liquid storage, (3) above ground gaseous storage.
Medium and heavy-duty vehicles	■ Fuel cell technology has advantages over medium and heavy-duty battery electric vehicles because (1) it does not suffer from a battery weight payload penalty and limited range and (2) it is faster to refuel hydrogen vehicles.
Buses	■ The stakeholder outreach identified potential for hydrogen fuel cell electric vehicles to decarbonize the transit sector in Whitehorse (see Appendix C). ■ Fuel cell electric buses have been adopted by several transit agencies around the world. However, battery electric technology seems to have made a larger breakthrough.
Light-duty vehicles	■ Fuel cell electric vehicles have the potential to offer a long range zero-emission alternative to internal combustion vehicles. ■ The technology is unlikely to be competitive with battery electric vehicles (especially as fast charging networks expand). Current capital costs are high relative to plug-in electric vehicles and hydrogen infrastructure will be needed for more adoption.
Marine transport and air travel	■ Hydrogen for use in airplanes require significantly more technological innovation before the technology is market ready. ■ Marine could be conductive to adopting hydrogen but does not account for a significant portion of greenhouse gas emissions in the Yukon.

Application	Description
Small off-road transportation	■ Hydrogen could be used to decarbonize small off-road transportation like ATVs or snowmobiles. ■ The stakeholder outreach outlined this as a potential application in the Yukon (see Appendix C).
Buildings	■ The stakeholder outreach (see Appendix C) identified several challenges with using hydrogen in buildings. There is no pipeline infrastructure for residential buildings, and electrification is likely to be a less costly means of decarbonization. ■ Hydrogen could be introduced in the building sector in the form of district energy fuel cell systems. These systems would heat and power dense urban areas. The stakeholder outreach found that there could be an opportunity for a district heating system for commercial buildings in Whitehorse. Application of fuel cell technology to district energy is in the very early stages and has yet to be demonstrated commercially.
Mining (equipment and electricity)[2]	■ Hydrogen used as an energy storage solution for renewable energy integration in mines could solve two problems at once. It could offer (1) a source of dispatchable electricity, and (2) a zero-emission fuel option for mining equipment currently powered by diesel or other fossil fuels. ■ All operating mines in the Yukon are connected to the grid and using hydrogen for electricity is likely a more attractive option in mines not connected to the grid. It is important to note that there are proposed off-grid mines in the Yukon, so there could be a benefit to hydrogen in mines to generate electricity in the future. ■ Our research indicates that the technology readiness for hydrogen mining equipment is low, with the cold climate in the Yukon posing an additional challenge.

Seasonal electricity storage

Three types of hydrogen storage are theoretically feasible in the Yukon to support seasonal electricity storage:

- Underground storage in hard rock caverns
- Above ground liquid storage
- Above ground gaseous storage

[2] While we do not model hydrogen as an option to decarbonize electricity generation or mining equipment in this analysis, we do model hydrogen fuel cell electric vehicles as an option to decarbonize the mining sector.

Table 2 below outlines the costs of these three storage options. Power CAPEX is defined by the cost of producing hydrogen via electrolysis[3] increased by 20% to consider regional challenges for infrastructure. For liquid hydrogen, this cost also includes that of liquefaction[4]. Storage CAPEX represents the cost of the storage infrastructure. Underground rock storage capital expenditure was estimated using a study conducted by Lord et al.[5] where various geological storage possibilities were explored. The alternative selected for cost purposes was the mined hard rock cavern as there are no known salt caverns in the Yukon and it was understood that abandoned natural gas wells in the Yukon are inaccessible at this time.

We note that there may be concerns using mined caverns due to proximity to fault lines and seismic activity[6]. Further geological research[7] would be required to determine the feasibility of mining a hard rock cavern for hydrogen storage purposes. Losses during storage were estimated to by less than 0.1% per year for underground storage[8], and the roundtrip efficiency to be 40%[9].

Capital expenditure for above ground storage of liquid hydrogen was assessed as an alternative to underground storage, should geological storage not be viable. The storage component costs were derived from a study conducted in 2015 called Technology Roadmap Hydrogen and Fuel Cells[10]. This study also provided the estimated losses during storage of liquid hydrogen which is substantially higher than the alternatives due to losses from the vaporization of the hydrogen while in storage. As mentioned for underground storage costing, the power cost is representative of electrolysis costs in addition to liquefaction costs referenced by the IEA, with a 20% assumed regional cost increase. The roundtrip efficiency was also assumed to be 40% for this technology.

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[3] IEA. (2019). The Future of Hydrogen. Accessible from: https://www.iea.org/reports/the-future-of-hydrogen

[4] IEA. (2019). The Future of Hydrogen Annex. Accessible from: https://www.iea.org/reports/the-future-of-hydrogen/data-and-assumptions

[5] Lord, A. et al. (2014). Geologic storage of hydrogen: Scaling up to meet city transportation demands

[6] Lemieux et al. (2020). Geologic feasibility of underground hydrogen storage in Canada. *International Journal of Hydrogen Energy, 45, 32243-32259.*

[7] I.e., on testing to gauge the porosity of the rock etc.

[8] Amid, A. et al. (2015). Seasonal storage of hydrogen in a depleted natural gas reservoir.

[9] Headley, A. & Schoenung, S. (2020). DOE. Hydrogen Energy Storage. Accessible from: https://www.sandia.gov/ess-ssl/wp-content/uploads/2020/12/ESHB_Ch11_Hydrogen_Headley.pdf

[10] Korner, A. (2015). Technology Roadmap Hydrogen and Fuel Cells – Technical Annex.

A study by the US Department of Energy[11] provided the basis for storage capital expenditure for gaseous hydrogen storage as well as the round-trip efficiency, a combination of production efficiency and reconversion efficiency after storage, used for all storage types. The capital cost of power for above ground gaseous hydrogen storage is equal to that of electrolysis cost used for underground storage. It is assumed that tank design for gaseous storage is such that storage losses are negligible. As with underground and liquid hydrogen storage, roundtrip efficiency was assumed to be 40%.

Table 2 below outlines the costs over time. The 2019 IEA report provided an estimated 30% cost reduction for electrolysis by 2030 and the Department of Energy report suggests an estimated 66% cost reduction by 2050. We also include a low-cost sensitivity where the power capital cost is 20% lower than under the reference cost, starting in 2030.

Table 2: Seasonal hydrogen storage costs

Storage Type	CAPEX type	2025	2030	2035	2040	2045	2050
Underground rock storage	Power CAPEX ($2021/kW)	2,444	1,711	1,491	1,271	1,051	831
Underground rock storage	Storage CAPEX ($2021/kWh)	1.4	1.4	1.4	1.4	1.4	1.4
Above ground liquid storage	Power CAPEX ($2021/kW)	2,671	1,870	1,629	1,389	1,148	908
Above ground liquid storage	Storage CAPEX ($2021/kWh)	17.3	17.3	17.3	17.3	17.3	17.3
Above ground gaseous storage	Power CAPEX ($2021/kW)	2,444	1,711	1,491	1,271	1,051	831
Above ground gaseous storage	Storage CAPEX ($2021/kWh)	57.5	57.5	57.5	57.5	57.5	57.5

[11] Headley, A. & Schoenung, S. (2020). DOE. Hydrogen Energy Storage. Accessible from: https://www.sandia.gov/ess-ssl/wp-content/uploads/2020/12/ESHB_Ch11_Hydrogen_Headley.pdf

Vehicle assumptions

We use gTech to model the demand for fuel cell electric vehicles (and hence hydrogen). The demand depends on the cost assumptions of fuel cell electric vehicles and that of the competing low carbon technologies, which are outlined below.

The cost of hydrogen fuel cell vehicles is determined endogenously in gTech (i.e., it is a modelled result based on cumulative technology adoption). Table 3 shows the fuel cell electric capital cost trajectory in the model.

Table 3: Summary of fuel cell electric vehicle capital costs (2020 CAD)

Cost	Reference
Fuel cell stack system costs decline from \$306/kW in 2015 to a minimum of \$74/kW. Fuel tanks decline from \$31/kWh in 2015 to a minimum of \$11/kWh.	SA Consultants (2016). Final report: Hydrogen storage system cost analysis. SA Consultants (2017). Mass production cost estimation of direct H2 PEM fuel cell systems for transportation applications. IEA (2020). Breakdown of cost-reduction potential for electrochemical devices by component category.

Plug-in electric vehicles and biofuels compete with fuel cell electric vehicles in the transportation sectors. Therefore, the extent of fuel cell electric vehicle adoption depends on the costs of battery electric vehicles and biofuels.

Like fuel cell electric vehicles, the cost of plug-in electric vehicles declines as a function of adoption, illustrated in Table 4 below.

Table 4: Summary of battery electric vehicle capital costs (2020 CAD)

Cost	Reference
Battery pack costs decline from \$502/kWh in 2015 to a minimum of \$84/kWh.	Bloomberg New Energy Finance (2017, 2019, 2020). Electric vehicle outlook. ICCT (2019). Update on electric vehicle costs in the United States through 2030. Nykvist, B., F. Sprei, et al. (2019). "Assessing the progress toward lower priced long range battery electric vehicles." Energy Policy 124: 144-155.

Second-generation biofuels are made from ligno-cellulosic material (i.e., woody or grassy biomass) rather than edible agricultural feedstocks. The availability of these resources is constrained by activity in the agriculture and forestry sectors. Table 5 below outlines the cost of second-generation biofuels. Note that the costs presented below may vary as a function of endogenously determined feedstock prices in the model.

Table 5: Second-generation biofuel costs (2020 CAD)

Cost	Reference
Levelized production costs of about $48/GJ.	Jones S. et al. (2013). Process design economics for the conversion of lignocellulosic hydrocarbon fuels. Swanson R. et al. (2010). Techno-economic analysis of biofuels production based on gasification. Multiple other techno-economic analyses prepared by PNNL and NREL for the USDOE BETO department[12].

2.3. Hydrogen supply options

This section summarizes possible hydrogen supply options considered for this analysis. It also outlines which applications were included in the modelling based on research into feasibility and cost, discussions with stakeholders (see Appendix C), and feedback from Government of Yukon Department of Energy, Mines and Resources.

A variety of potential production pathways exist for meeting hydrogen demand in the Yukon, as summarized in Table 6. Electrolysis is likely to be the most cost-effective pathway for production in the Yukon.

Table 6: Potential hydrogen supply options in the Yukon

Application	Description
Steam methane reforming	▪ Hydrogen produced from natural gas at temperatures of up to 950°C. Most widely used hydrogen production technology since the 1970s. ▪ It can be used both for centralized and distributed production. ▪ Likely to remain the cheapest hydrogen production technology without strong carbon constraints. ▪ Consumes 1.4 GJ of natural gas for each GJ of hydrogen, resulting in direct emissions of 68.5 kg CO_2e per GJ hydrogen. ▪ Requires access to natural gas which is not available in the Yukon.

[12] Jones, S., Meyer, P., Snowden-Swan, L., Padmaperuma, A., Tan, E., Dutta, A., Jacobson, J., Cafferty, K., 2013, Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels Fast Pyrolysis and Hydrotreating Bio-oil Pathway, National Renewable Energy Laboratory.

Application	Description
Steam methane reforming with carbon capture and storage	■ Hydrogen produced from natural gas with carbon capture and storage. Capture rates of between 60 and 90% are possible. ■ Adoption will likely be limited to centralized production plants. ■ US Department of Energy estimates levelized cost of production between $12.67 and $14.33 per GJ H_2 (in 2016 USD, 90% capture rates)[13]. ■ Same energy consumption as non-CCS. With 90% capture direct emissions are 6.85 kg CO_2e per GJ hydrogen. ■ In addition to requiring access to natural gas (which is not available in the Yukon), it also requires access to geological storage.
Polymer electrolyte membrane (PEM) electrolysis	■ Electricity is used to split hydrogen and oxygen from water at temperatures between 70 and 100°C. ■ There are a few existing plants around the world. ■ It can be used both for centralized and distributed production. ■ High levelized cost due to high capital costs and high electricity consumption. Cost assumptions summarized in Appendix A: IESD assumptions. ■ More competitive in grids with high intermittent renewable energy penetration and periods of low electricity prices.
Biomass gasification	■ Biomass gasification at 540°C produces a mix of hydrogen, methane, and carbon monoxide. ■ The hydrogen is separated with pressure swing adsorption. The process is similar to producing hydrogen from coal, which is widely used in China. ■ Centralized production technology. ■ The US Department of Energy estimates that levelized costs are likely between $14.42 and $26.67 per GJ hydrogen (in 2016 USD, variability due to plant size and feedstock price)[14]. ■ The process requires 2.2 GJ of biomass and 0.1 GJ of natural gas for every GJ of hydrogen, resulting in direct emissions of 2.6 kg CO_2e per GJ hydrogen. ■ The process is energy intensive and requires biomass feedstock which is presently limited in the Yukon. ■ While many stakeholders indicated that this has limited potential in the Yukon (see Appendix C), the Yukon may still be interested in pursuing this given the interest in building a local biomass industry.

[13] Ibid.

[14] Ibid.

Application	Description
Solid oxide electrolyser cell	■ Electricity is used to split hydrogen and oxygen at high temperatures between 500 and 850°C. Natural gas is typically used for heat. ■ Technology has yet to be commercialized but may be cheaper than PEM electrolysis. A solid oxide electrolyser cell can also produce electricity by functioning as a fuel cell. ■ The US Department of Energy estimates that levelized costs will likely be between $30.92 and $32.67 per GJ hydrogen (in 2016 USD)[15]. ■ Requires 1.1 GJ of electricity and 0.4 GJ of natural gas for every GJ of hydrogen, resulting in direct emissions of 19.9 kg CO_2e per GJ hydrogen. ■ Uncertainty with technology commercialization. Some technical challenges have yet to be addressed for full commercialization.

Hydrogen production via electrolysis

Production of hydrogen via electrolysis uses electricity to separate water molecules into hydrogen and oxygen. The carbon intensity can be close to zero if electricity from renewable energy sources is used. This is the most promising of the production pathways in the Yukon. As a result, this pathway was selected for inclusion in the modeling.

IESD, Navius' electricity model, simulates hydrogen production via electrolysis to meet demand from fuel cell electric vehicles (and potentially other end-uses), which is informed by Navius' energy-economy model, gTech. The non-energy costs of hydrogen production via electrolysis are based on the 2019 IEA Future of Hydrogen report[16]. An assumed plant life of 30 years was taken in combination with a 10% discount rate to provide an annualized cost. Electrolyser capacity was taken as 2.1 MW as the default capacity and a capacity factor of 90%. As with the hydrogen electricity storage costs, the capital cost was increased by 20% to consider regional challenges for infrastructure that are unique to the Yukon. This leads to a capital cost of $2,444/kW.

Hydrogen import analysis

An alternative to producing hydrogen in the Yukon is to import it. In particular, hydrogen could be produced via steam methane reformation (SMR) equipped with carbon capture and storage (CCS) technology in either BC or Alberta. This technology benefits from the established nature of methane reforming, and if adopted with the

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[15] National Renewable Energy Laboratory. 2019. *H2A: Hydrogen Analysis Production Case Studies*. Available from: https://www.nrel.gov/hydrogen/h2a-production-case-studies.html

[16] IEA. (2019). *The Future of Hydrogen*. Available from: https://www.iea.org/reports/the-future-of-hydrogen

Western Sedimentary Basin, may offer one of the cheapest low-carbon hydrogen production options.

Hydrogen transport over long distances is technically feasible but expensive. Because of its lightness, hydrogen must be compressed or liquefied to be transported economically. When the cost of importing hydrogen (outlined below) is added to the cost of producing hydrogen in the first place, these transport costs are likely to render imported hydrogen uneconomic relative to domestic production via electrolysis.

Table 7 below outlines the cost breakdown assumed for transportation of hydrogen to the Yukon via truck. Four alternatives were considered[17]:

1. Liquified hydrogen from Edmonton, Alberta
2. Liquified hydrogen transport from the Montney Region in British Columbia
3. Gaseous hydrogen from Alberta
4. Gaseous hydrogen from British Columbia

These locations were selected for sourcing as they are natural gas processing hubs, making them ideal for grey hydrogen production. Using Google Maps, a distance of 1990 kilometers was assumed from Edmonton to Whitehorse, and a distance of 1320 kilometers was assumed from the Montney Region to Whitehorse.

Variable operating costs (VOPEX) include hourly driver labor cost of $28.69 (2019 CAD), driving constraints of a maximum driving time of 13 hours and an off-duty requirement of 10 hours[18] and the IEA assumed average driving speed of 50 km/hour.[19] The IEA 2019 report titled The Future of Hydrogen provided the preponderance of the remaining transportation costing assumptions used. The figures in Table 1 are a summation of trailer and truck costs from the IEA annex. The capital costs (CAPEX) influenced the assumed fixed operating costs (FOPEX) for transport. Annual truck FOPEX was representative of 12% of the total CAPEX, where annual trailer FOPEX was only 2% of total CAPEX. Table 7 costs are representative of full tanker loads of hydrogen. That is, 670 kg of gaseous hydrogen and 4300 kg of liquid hydrogen. Off-loading times of an hour and a half for gaseous hydrogen and three hours for liquid hydrogen were assumed.

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[17] The use of ammonia as a hydrogen carrier fluid was not fully considered. During scoping research, the multi conversion process appeared to reduce this alternative's cost competitiveness.

[18] Ministry of Transportation and Infrastructure. Hours-Of-Service-Rules. Accessible from: https://cvse.ca/national_safety_code/pdf/HOS_Service_Rules.pdf

[19] IEA. (2019). The Future of Hydrogen Annex. Accessible from: https://www.iea.org/reports/the-future-of-hydrogen/data-and-assumptions

An assumed discount rate of 8% and anticipated truck life of 12 years were adapted from the IEA report annex. Calculating an associated capital recovery factor allowed for an annualization for the CAPEX, FOPEX, and VOPEX. These figures were then spread over the energy capacity of the tanker of hydrogen. Kilograms of hydrogen were converted to gigajoules of transported capacity using the higher heating value of hydrogen, 0.1417 GJ/ kg H_2. Fuel costs for a single trip to and from the Yukon were used, based on diesel prices of $25.64/ GJ (2015 CAD) from Alberta and $29.53/ GJ (2015 CAD) from British Columbia.

Table 7: Transportation Costs for Liquid and Gaseous Hydrogen

Transport Cost from AB		Transport Cost from BC	
Liquified Hydrogen via truck		**Liquified Hydrogen via truck**	
life (years)	12	life (years)	12
capex (2015 CAD/GJ)	$18.23	capex (2015 CAD/GJ)	$18.23
fopex (2015 CAD/GJ)	$2.42	fopex (2015 CAD/GJ)	$2.42
vopex (2015 CAD/GJ)	$0.10	vopex (2015 CAD/GJ)	$0.05
Fuel (2015 CAD/GJ)	$31.64	Fuel (2015 CAD/GJ)	$20.99
capacity (GJ)	609.31	capacity (GJ)	609.31
Total (2015 CAD/GJ)	$52.39	Total (2015 CAD/GJ)	$41.69
Gaseous Hydrogen via truck		**Gaseous Hydrogen via truck**	
life (years)	12	life (years)	12
capex (2015 CAD/GJ)	$81.43	capex (2015 CAD/GJ)	$81.43
fopex (2015 CAD/GJ)	$12.79	fopex (2015 CAD/GJ)	$12.79
vopex (2015 CAD/GJ)	$0.62	vopex (2015 CAD/GJ)	$0.32
Fuel (2015 CAD/GJ)	$200.61	Fuel (2015 CAD/GJ)	$133.07
capacity (GJ)	94.939	capacity (GJ)	94.939
Total (2015 CAD/GJ)	$295.44	Total (2015 CAD/GJ)	$227.60

As outlined in Table 7 above, importing liquified hydrogen into the Yukon is likely to be more economic than gaseous hydrogen as the price for liquified hydrogen transport ranges from $42-52/GJ ($12-14/MWh), while the price for gaseous hydrogen transport ranges from $228-295/GJ ($63-82/MWh). These costs are likely on the low side as there are additional considerations with the technical feasibility of maintaining the compression needed to transport over such vast distances. When the cost of producing hydrogen in the first place is added the cost of transportation described in the table above, it is likely to render imported hydrogen uneconomic relative to domestic production via electrolysis.

2.4. Scenarios

This analysis considers three scenarios:

- **Reference case**, aka *business as usual*. This scenario represents the Yukon's energy-economy in the absence of any additional climate policy. The carbon price rises to \$50/tCO_2e by 2022 and stays constant thereafter. As per the federal Fuel Charge Regulations, the electricity sector is not covered by carbon pricing. The Yukon Energy Corporation's 10-year Renewable Electricity Plan[20] is incorporated in all policies modelled.

- **Our Clean Future.** This scenario includes key policies announced in *Our Clean Future*[21], such as the renewable portfolio standard on the integrated grid reaching 93% by 2025 and 97% by 2030. It also includes a zero-emissions vehicle mandate, building envelope efficiency improvements, and financial supports for low-carbon heating systems, which affect electricity demand. It excludes any policies directly impacting electricity supply in remote communities.

- **Net zero.** This scenario assumes the Government of Yukon implements *Our Clean Future* and meets its 45% reduction in non-mining emissions below 2010 levels target. Emissions subsequently decline to net zero in 2050 (i.e., representing decarbonization of most energy-related emissions).

In addition, we model nine sensitivities on electricity storage. They account for alternative assumptions about the availability and cost of electricity storage options in the Yukon.

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[20] Yukon Energy Corporation. (2020). *10-year Renewable Electricity Plan Technical Report.* Available from: https://yukonenergy.ca/media/site_documents/YEN20093rpt_Technical_web2_compressed.pdf

[21] Government of Yukon. (2020). *Our Clean Future: A Yukon strategy for climate change, energy and green economy.* Available from: https://yukon.ca/sites/yukon.ca/files/env/env-our-clean-future.pdf

3. Results

This section presents our findings from this analysis. Section 3.1 outlines potential demand for hydrogen in the Yukon, covering potential applications and the extent to which they can help decarbonize the Yukon. Section 3.2 outlines hydrogen supply options in the territory.

3.1. Hydrogen applications

As discussed in Section 2.2, a number of potential applications for hydrogen exist in the Yukon. The analysis below presents the adoption of the most promising options, including seasonal electricity storage and fuel cell electric vehicles.

Hydrogen as electricity storage

Three types of hydrogen storage options are theoretically possible:

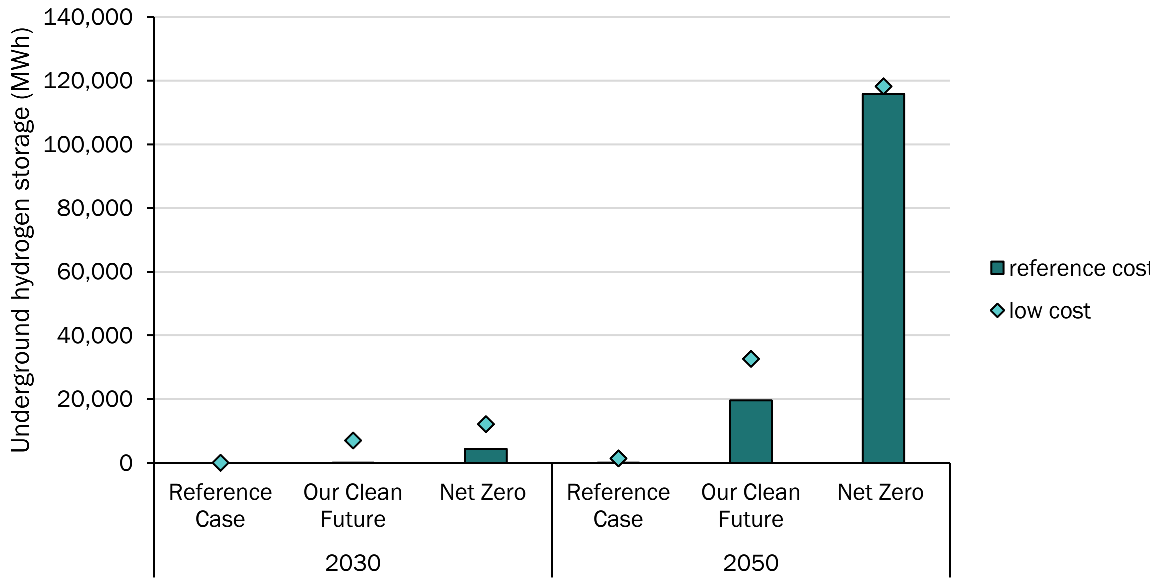
- Underground storage in hard rock caverns
- Above ground liquid storage
- Above ground gaseous storage

All three options were explored using IESD, Navius' electricity model, to determine their potential on the Yukon's integrated grid. Further details about how these technologies were parameterized can be found in Appendix A.

The analysis suggests that above ground liquid and gaseous storage of hydrogen is not cost-competitive with the other storage options in the Yukon, namely pumped storage hydro and batteries. However, if technically feasible, underground hydrogen storage in hard rock caverns could be competitive with pumped storage hydro (which would occur on the Yukon's integrated grid, but not in remote communities).

Figure 3 below shows the potential extent of underground storage of hydrogen in hard rock caverns adopted in 2030 and 2050 on the Yukon's integrated grid. The more stringent the climate policy, the greater the adoption of hydrogen as seasonal electricity storage. In 2050, 19.5 MWh is adopted in the reference case, 19,558 MWh under our clean future, and 115,835 MWh under a net zero scenario with reference cost assumptions.

Figure 3: Seasonal electricity storage using underground hydrogen storage



Source: Navius analysis using gTech-IESD.

It is however important to note that further geological research would be required to determine the feasibility of mining a hard rock cavern for hydrogen storage purposes in the Yukon which is beyond the scope of this analysis. Proximity to fault lines and seismic activity makes it particularly uncertain[22].

Role of hydrogen in decarbonizing transportation

Hydrogen offers the potential to decarbonize transport modes, such as long-haul trucking, marine and air. Medium and heavy-duty vehicles frequently travel long distances, making them less conducive to electrification relative to light-duty vehicles. Figure 4 quantifies the potential adoption of hydrogen fuel cell vehicles across medium and heavy-duty applications through 2050.

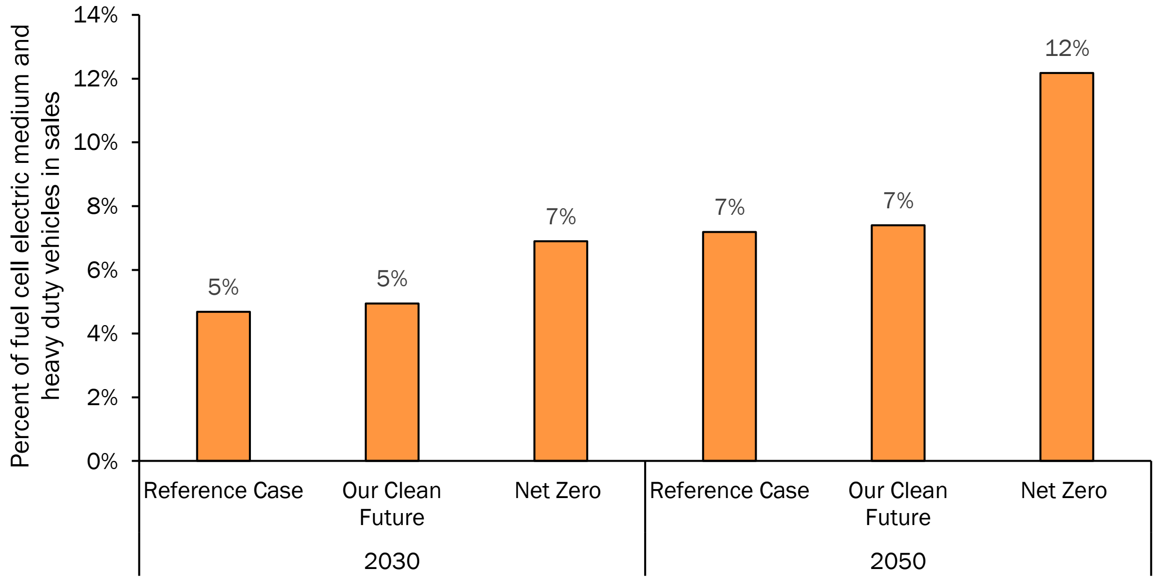
In 2030, 5% of the Yukon's medium and heavy-duty vehicle sales are fuel cell electric in the reference case and Our Clean Future scenarios (using baseline assumptions about the cost of hydrogen fuel cells). This increases to 7% of sales in both scenarios by 2050. Under a net zero scenario, 7% of the Yukon's medium and heavy-duty vehicle sales are fuel cell electric by 2030, increasing to 12% of sales by 2050. The sales of battery electric vehicles are comparable to fuel cell electric vehicles across all

[22] Lemieux et al. (2020). Geologic feasibility of underground hydrogen storage in Canada. *International Journal of Hydrogen Energy, 45, 32243-32259.*

scenarios in 2030 but exceed those of fuel cell electric vehicles by around 1.5 times in 2050.

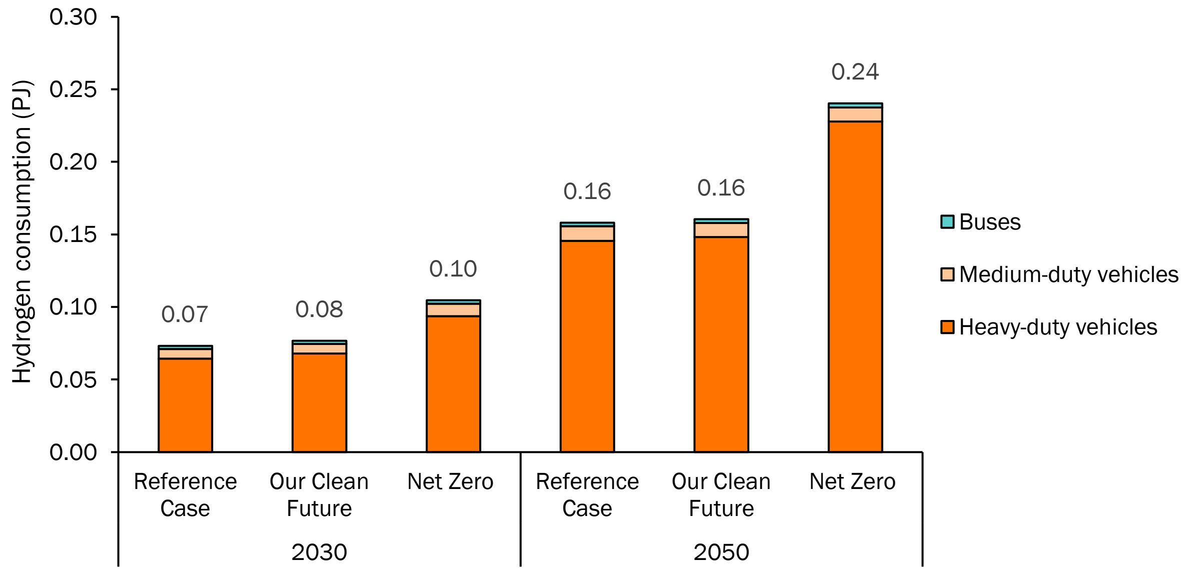
The adoption of hydrogen fuel cell vehicles translates to a consumption of 0.16 PJ hydrogen in the reference case and Our Clean Future scenarios, and 0.24 PJ under net zero in 2050 (see Figure 5 below). This analysis shows that by 2050, hydrogen adoption in medium and heavy-duty vehicles in the Yukon could reduce emissions by 6-48 kt CO2e relative to 2020 levels depending on the stringency of the climate policy (see Figure 6).

Figure 4: Medium and heavy-duty fuel cell electric vehicles in sales



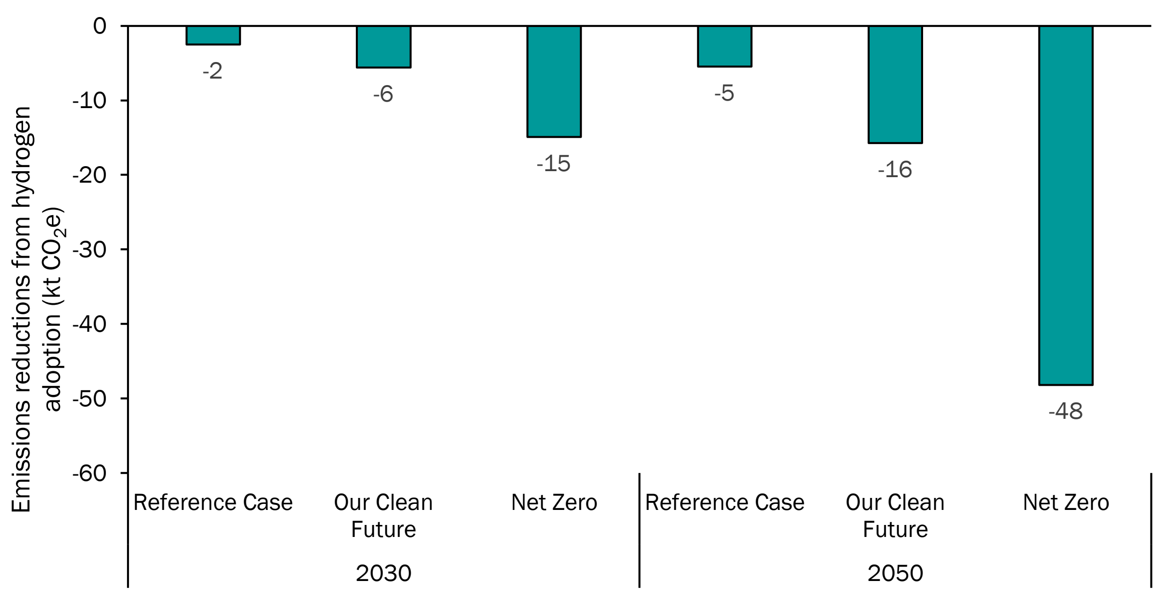
Source: Navius analysis using gTech-IESD.

Figure 5: Hydrogen consumption in the Yukon



Source: Navius analysis using gTech-IESD.

Figure 6: Emissions reductions from hydrogen adoption relative to 2020



Source: Navius analysis using gTech-IESD.

The adoption of hydrogen fuel cell electric vehicles in the Yukon is uncertain, and depends on the future cost of hydrogen, hydrogen fuel cell vehicles and low carbon alternatives to hydrogen, such as biofuels and plug-in electric vehicles. Hydrogen fuel cell electric vehicle adoption could therefore be greater or lower than the estimates presented above.

In particular, we note that the main low-carbon alternative to hydrogen for many hard to electrify applications is likely to be second-generation biofuels, which are chemically identical to diesel and require no vehicle engine modifications. Technology breakthroughs in either hydrogen fuel cell technology or biofuel manufacturing could lead to a situation where one or the other option dominates.

The stakeholder outreach identified that there might also be potential for hydrogen to decarbonize transit in Whitehorse (see appendix C). However, battery-electric buses are likely to be more cost competitive, accounting for 50% of bus sales from 2030 onwards under all scenarios (please see Figure 5 above).

We also examined the potential for hydrogen fuel cell electric light-duty vehicles. However, like with buses, battery electric vehicles are more competitive. Our projections result in no light-duty fuel cell electric vehicles in any scenario.

3.2. Hydrogen supply

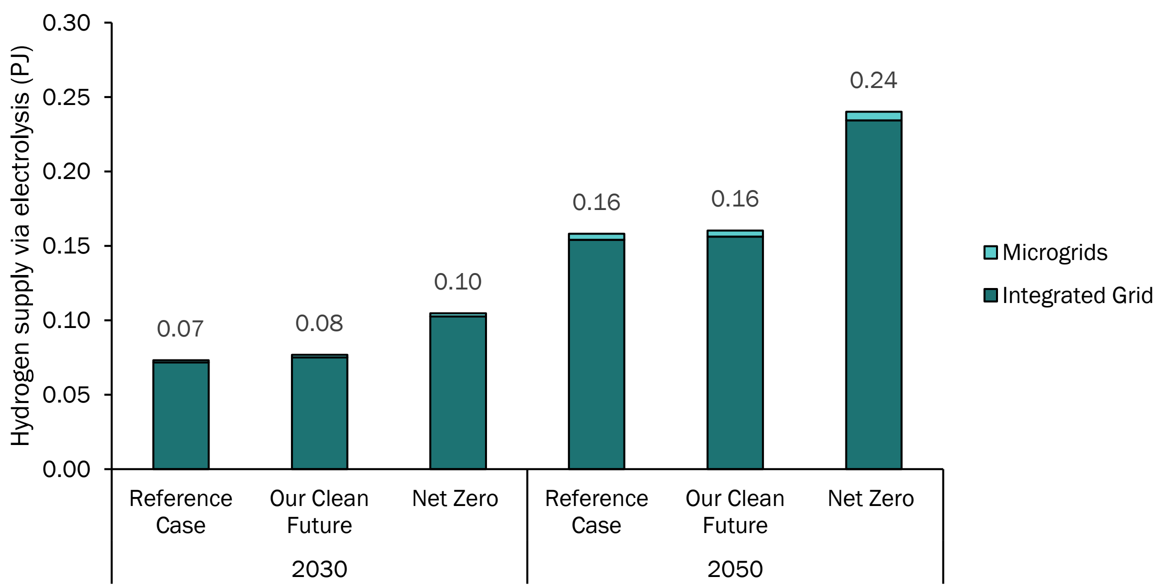
To meet demand for hydrogen from the transportation sector, the Yukon must either import or produce hydrogen. As outlined in section 2.3, domestic hydrogen production via electrolysis is likely the most viable supply option in the Yukon.

Production of hydrogen via electrolysis uses electricity to separate water molecules into hydrogen and oxygen. The carbon intensity can be close to zero if electricity from renewable energy sources is used.

This analysis finds that hydrogen demand in the Yukon can be met via electrolysis under all scenarios examined. The more stringent the policy, the greater the demand and supply of hydrogen. Hydrogen production via electrolysis relies on building new renewable capacity. Having renewables available to ensure that the hydrogen is produced using clean electricity is crucial to ensure low emissions intensity of production. Additionally, a high penetration of intermittent renewables results in times when there is surplus electricity available at very low costs. Using this electricity reduces the energy cost of hydrogen produced via electrolysis.

Figure 7 shows hydrogen produced via electrolysis under the three policy scenarios with batteries and pumped storage hydro available as storage options (consistent with the Yukon Energy Corporation's 10-year Renewable Electricity Plan[23]). Hydrogen production increases over time in all scenarios modelled. By 2050, 0.15 PJ of hydrogen is produced via electrolysis on the integrated grid, and 0.004 PJ is produced on the microgrids in the reference case and under Our Clean Future. Under net zero, 0.23 PJ is produced on the integrated grid and 0.006 PJ on the microgrids in 2050. This supports about 100-200 medium and heavy-duty fuel cell electric vehicles (depending on policy scenario) and around four fuel cell electric buses in 2050.

Figure 7: Hydrogen produced via electrolysis in the Yukon



Source: Navius analysis using gTech-IESD.

Figure 8 below shows the cost of hydrogen produced via electrolysis[24]. On the integrated grid, costs are $69/GJ in the reference case, $77/GJ under Our Clean Future, and $82/GJ under net zero in 2030. In 2050 the cost increases in all scenarios, to $73/GJ for the reference case, $78/GJ, and $93/GJ under net zero.

Costs are higher in all scenarios on the microgrids. In 2030, costs are $86/GJ in the reference case and under Our Clean Future, and $101/GJ under net zero. By 2050, costs decrease in all scenarios in the microgrids. In the reference case and under *Our Clean Future* costs are $82/GJ, and under net zero they are $97/GJ.

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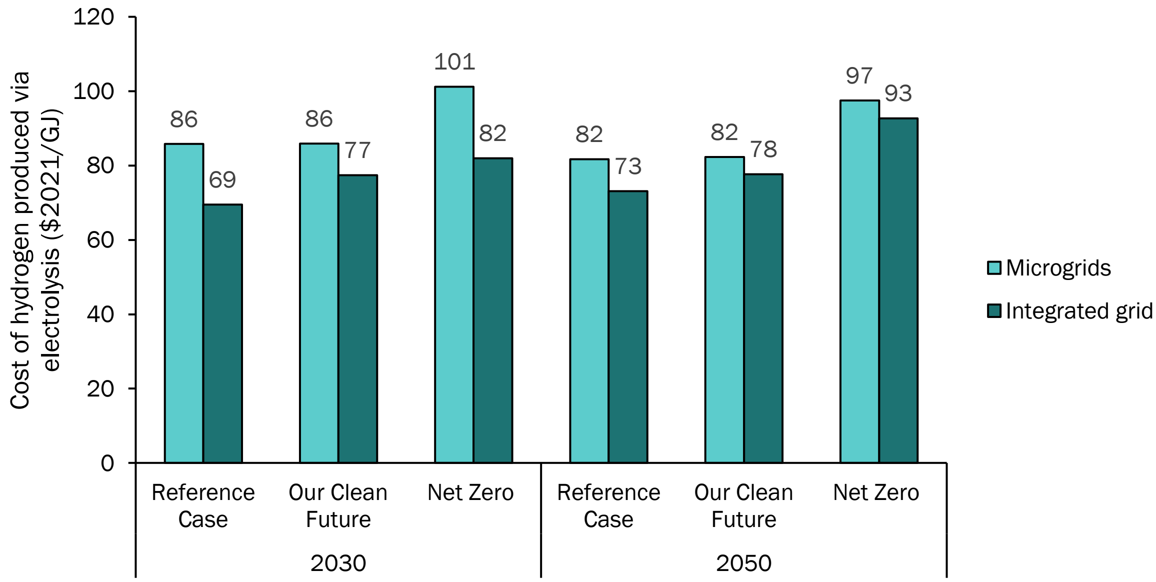
[23] Yukon Energy Corporation. (2020). *10-year Renewable Electricity Plan Technical Report.* Available from: https://yukonenergy.ca/media/site_documents/YEN20093rpt_Technical_web2_compressed.pdf

[24] With pumped hydro (on the integrated grid) and lithium-ion batteries available as storage options.

Table 8 reports the cost of hydrogen production via electrolysis in $2021/kWh.

Figure 8: Cost of hydrogen produced via electrolysis ($2021/GJ)



Source: Navius analysis using gTech-IESD.

Table 8: Cost of hydrogen produced via electrolysis ($2021/kWh)

Region	2030			2050		
	Reference Case	Our Clean Future	Net Zero	Reference Case	Our Clean Future	Net Zero
Integrated Grid	0.25	0.28	0.30	0.26	0.28	0.33
Microgrids	0.31	0.31	0.36	0.29	0.30	0.35

Source: Navius analysis using gTech-IESD.

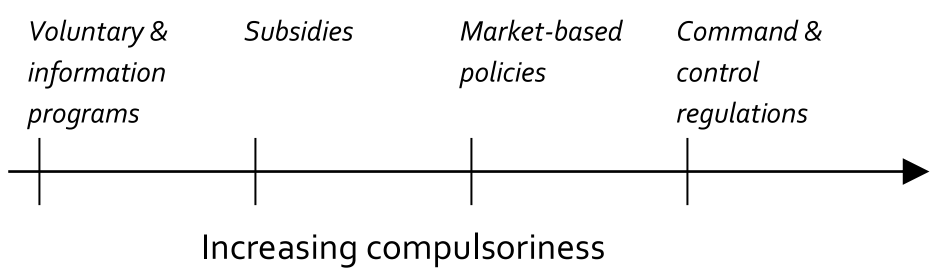
4. Policy options to support hydrogen adoption

This section outlines potential policy options to support hydrogen adoption in the Yukon. We begin by introducing a policy taxonomy and then provide examples of hydrogen-supportive policies in Canada.

4.1. Policy taxonomy

Policies can be categorized based on their compulsoriness, or the degree to which certain technologies or practices are required by government. As shown in Figure 9 below, the left end of the spectrum depicts policies that are completely non-compulsory in which governments simply encourage voluntary behaviour by consumers and businesses. The right end of the spectrum depicts policies that require a specific action.

Figure 9: Spectrum of policy compulsoriness[25]



Based on this taxonomy, the following types of policies could potentially be used to support hydrogen adoption:

- **Voluntary and information programs** encourage consumers and businesses to undertake an action. The government functions as an information provider, facilitator, or role model. For example, the government might provide information about the benefits of hydrogen fuel cell vehicles by operating public trials and

[25] Adapted from: Rivers & Jaccard. 2005. Canada's efforts towards greenhouse gas emission reduction: a case study on the limits of voluntary action and subsidies. Int. J. Global Energy Issues, 23(4): 307-323.

demonstration programs. Please note that this approach isn't expected to have a substantive impact on hydrogen adoption.

- **Subsidies or financial incentives** offer financial returns to those who take specified actions to reduce emissions. The financial returns could be in the form of grants, low-interest loans and tax credits. For example, the government could subsidize the purchase of hydrogen fuel cell vehicles or invest in hydrogen supply infrastructure.

- **Market-based policies** include carbon pricing and flexible regulations:

  - **Carbon pricing** imposes a cost on greenhouse gas emissions, providing a financial disincentive for consumers and businesses to use fossil fuels. This policy can be implemented via a carbon tax, cap-and-trade, or tradable performance standard. These policies don't specify a particular action (i.e., individuals may choose between taking no action to reduce emissions and paying taxes, or reducing emissions in order to pay less tax). In addition, individuals may choose to undertake any action to reduce emissions. For example: purchase a smaller vehicle, buy a plug-in electric vehicle or a hydrogen fuel-cell vehicle.

  - **Flexible regulations** adopt the market-oriented approach of carbon pricing but apply it to specific sectors. In practice, this policy can look like a tradable performance standard that sets a target (e.g., greenhouse gas emissions intensity) while providing firms and consumers the flexibility to minimize compliance costs. Examples of flexible regulations include vehicle emission standards and low-carbon fuel standards. Neither of these policies require the adoption of hydrogen technology specifically but allow for hydrogen as one among many compliance options.

- **Command and control regulations** require specific actions be taken, with noncompliance incurring stringent financial or legal penalties. For example, the government could require that new mines purchase hydrogen fuel cell equipment.

4.2. Hydrogen-supportive policies in Canada

Various levels of government in Canada have implemented a range of hydrogen-supportive policies. Key policies include:

- Federal and provincial incentives for the purchase of hydrogen vehicles and the installation of hydrogen fueling infrastructure.

- Carbon pricing, which provides an incentive to switch away from fossil fuels towards low carbon alternatives such as hydrogen.

- A range of flexible regulations that allow for hydrogen technology as a compliance option, including federal vehicle emission standards, Québec, and BC's zero emission vehicle standards and the federal clean fuel standard.
- As of yet, no command and control regulations have been implemented that require the adoption of hydrogen technology.

Below, we summarize examples of hydrogen-supportive policies that have been implemented in Canada.

Subsidies and financial incentives

- **Investment in hydrogen fueling infrastructure.** Through the Electric Vehicle and Alternative Fuel Infrastructure Deployment Initiative, the federal government is investing $96 million to support electric charging stations, natural gas stations and hydrogen fueling stations[26].
- **Zero emission vehicle purchase incentives.** The Yukon[27], British Columbia[28], Québec[29] and the federal government[30] currently offer incentives for the purchase of light-duty zero-emission vehicles. Eligible vehicles include hydrogen fuel cell vehicles as well as battery-electric and plug-in hybrid electric vehicles. The amount of the incentives is typically in the range of $5,000 per hydrogen vehicle.
- **Tax write-offs.** The federal government offers a tax write-off for zero-emission vehicles to support business adoption[31]. Eligible vehicles include hydrogen light-, medium- and heavy-duty vehicles purchased by a business.

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[26] Natural Resources Canada. 2019. Electric Vehicle and Alternative Fuel Infrastructure Deployment Initiative. www.nrcan.gc.ca/energy-efficiency/energy-efficiency-transportation/electric-vehicle-alternative-fuels-infrastructure-deployment-initiative/18352

[27] Government of Yukon. n.d. *Apply for a rebate for a new zero-emission vehicle*. Available from: https://yukon.ca/en/driving-and-transportation/apply-rebate-new-zero-emission-vehicle

[28] Government of British Columbia. 2019. *CEVforBC™ Vehicle Incentive Program*. Available from: https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/clean-transportation-policies-programs/clean-energy-vehicle-program/cev-for-bc

[29]Gouvernement du Québec. 2019. *Discover Electric Vehicles*. Available from: https://vehiculeselectriques.gouv.qc.ca/english/

[30] Transport Canada. 2019. *Zero-emission vehicles*. Available from: www.tc.gc.ca/en/services/road/innovative-technologies/zero-emission-vehicles.html

[31] Ibid.

- **Venture capital support.** The federal government allocated a portion of the $450 million from its Venture Capital Catalyst Initiative to support venture capital fund managers that invest in clean technologies[32].

Carbon pricing

- **Carbon pricing** has been implemented in various forms across Canada, including carbon tax (e.g., British Columbia), cap-and-trade (e.g., Québec), tradable performance standard (e.g., Alberta) and hybrid combinations (e.g., the federal carbon levy and output-based pricing system) [33]. While these approaches all differ, they share the objective of increasing the price of carbon emissions and thus encouraging firms and consumers to switch to lower carbon fuels and processes. The federal backstop is intended to ensure that all jurisdictions have a minimum carbon price of $50/t CO_2e by 2022, thus guaranteeing that all emission abatement actions costing up to this amount would be undertaken. Additionally, the federal government has announced an increase in the carbon price to $170/t CO_2e by 2030[34].

Flexible regulations

- **Regulations Amending the Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations.** New passenger vehicles and light-commercial vehicles/light trucks sold in Canada must meet fleet-wide greenhouse gas emission standards[35]. The combined requirement for cars and light trucks in 2025 is 119 g CO_2/km, about 30% below the current required fleet average. Although this policy doesn't directly require the deployment of zero emission vehicles, selling them helps manufacturers comply with the policy through the generation of special credits.

- **Zero emission vehicle standards.** This policy requires that zero emission vehicles account for a growing share of sales over time. Compliance with this policy could be achieved through plug-in electric and/or hydrogen fuel cell vehicles:

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[32] Government of Canada. 2019. *Venture Capital Catalyst Initiative*. Available from: https://www.ic.gc.ca/eic/site/061.nsf/eng/h_03052.html

[33] Government of Canada. (2019). Pricing pollution: how it will work. www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work.html

[34] Environment and Climate Change Canada. (2020). *A Healthy Environment and A Healthy Economy.* https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climate-plan/healthy_environment_healthy_economy_plan.pdf

[35] Government of Canada. 2018. *Regulations Amending the Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations*. Available from: www.gazette.gc.ca/rp-pr/p2/2014/2014-10-08/html/sor-dors207-eng.html

- ➢ The federal government will require 20% of light-duty vehicles sold to be zero emission by 2026, 60% by 2030, and 100% by 2035[36]. They also aim to have 35% of all medium and heavy-duty vehicles sold be zero emission by 2030, and 100% by 2040 for certain subgroups.

- ➢ Québec's credit requirement increases from 3.5% in 2018 to 22% by 2025[37]. The government estimates that the policy will result in zero-emission vehicles accounting for 9.9% of new sales in 2025.

- ➢ British Columbia requires a minimum share of light-duty vehicles sold in BC to be zero-emission. This mandate achieves 10% zero emission vehicle sales by 2025, 30% by 2030, and 100% by 2040.

- **Clean Fuel Regulation (CFR)[38,39].** The federal government is developing a performance-based fuel supply standard requiring liquid fuel suppliers to reduce the lifecycle greenhouse gas intensity of their fuels. The standards for the liquid stream require a carbon intensity reduction of 2.4 g/MJ in 2022, increasing to 12 g/MJ in 2030. This requirement translates into a 13% reduction in carbon intensity by 2030, measured relative to a liquid fuel stream average carbon intensity of 94.2 g/MJ in 2016. Numerous compliance options exist, including fuel switching to hydrogen.

- **Low Carbon Fuel Requirement**[40]. British Columbia introduced this policy in 2008 as part of the Low Carbon Fuel Standard. This regulation requires a decrease in average carbon intensity of transportation fuels by 10% by 2020 and by 20% by 2030 relative to 2010. Hydrogen can be used as a compliance option.

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[36] Government of Canada. (2022). *2030 Emission Reduction Plan – Canada's Next Steps for Clean Air and a Strong Economy.* Available from: https://www.canada.ca/en/environment-climate-change/news/2022/03/2030-emissions-reduction-plan--canadas-next-steps-for-clean-air-and-a-strong-economy.html

[37] Gouvernement du Québec. 2017. *Analyse d'impact réglementaire du règlement d'application de la Loi visant l'augmentation du nombre de véhicules automobiles zéro émission au Québec afin de réduire les émissions de gaz à effet de serre et autres polluants*. Available from: http://www.environnement.gouv.qc.ca/changementsclimatiques/vze/AIR-reglement201712.pdf

[38] Government of Canada. (2020). *Canada Gazette, Part I, Volume 154, Number 51: Clean Fuel Regulations.* Available from: https://gazette.gc.ca/rp-pr/p1/2020/2020-12-19/html/reg2-eng.html

[39] Government of Canada. (2021). *Canada's Climate Actions for a Healthy Environment and a Healthy Economy*. Available from: https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/actions-healthy-environment-economy.html

[40] Government of British Columbia. (2020). *Greenhouse Gas Reduction (Renewable and Low Carbon Fuel Requirements) Act¸SBC 2008, c.16.* Available from: https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/08016_01

- **Renewable Natural Gas Regulations**[41,42]**.** British Columbia requires that 15% of natural gas consumption be provided by renewable sources by 2030. In Québec, a minimum renewable fuel content of 1% in distributed natural gas is required as of 2020, rising to 2% in 2023, and 5% in 2025. Hydrogen qualifies for compliance under these policies.

Command and control regulations

As of yet, no command and control regulations have been implemented that require the adoption of hydrogen technology in Canada.

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41 Government of British Columbia. (2019). *CleanBC*. Available from: https://cleanbc.gov.bc.ca/

42 Gouvernement du Québec. (n.d.). *Renewable natural gas*. Available from: https://www.quebec.ca/en/agriculture-environment-and-natural-resources/energy/energy-production-supply-distribution/bioenergy/renewable-natural-gas

Appendix A: IESD assumptions

IESD estimates the impact of government policies and economic conditions on electricity demand, supply, and prices by simulating how utilities meet electric load by adding new capacity and by dispatching new and existing units on an hourly basis, including electricity storage.

IESD's electricity supply module includes a detailed representation of the different units available to generate or store electricity in each region, including their unique costs and generation constraints. The electricity supply simulation determines new generation and storage capacity additions, hourly dispatch of each unit to meet electric load over the course of the year, GHG emissions from the electricity sector and the wholesale price for electricity.

The version of IESD used for this analysis covers the Yukon's integrated grid, as well as four remote regions: Beaver Creek, Destruction Bay, Watson Lake, and Old Crow.

Electricity supply options

To meet the electricity demand (from Navius' gTech model), IESD may choose to generate via a range of technologies, depending on their costs. In the Yukon these include diesel, liquified natural gas (LNG), hydro, solar, and wind.

Capacity factors for solar are based on weather data from Environment and Climate Change Canada[43]. Capacity factors for wind are based on scaled surface windspeeds from the The Modern-Era Retrospective Analysis for Research and Applications, version 2 data (MERRA2).

Cost of generation technologies

Table 9 shows the assumed costs of generation resources. These costs are based on YEC's 10-year Renewable Electricity Plan[44], with two exceptions. First, LNG capital costs are based on Navius' internal technology database, while LNG fixed operating

[43] Government of Canada. n.d. *Historical Data.* https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

[44] Yukon Energy Corporation. (2020). *10-year Renewable Electricity Plan Technical Report.* https://yukonenergy.ca/media/site_documents/YEN20093rpt_Technical_web2_compressed.pdf

costs are based on YEC's 2021 General Rate Application[45]. Second, costs for solar and wind are projected to decrease over time as illustrated in Table 10.

Table 9: Cost of generation technologies

Generation type	CAPEX ($2021/kW)	FOPEX ($2021/kW)	VOPEX($2021/MWh)
Solar	1,775	34	
Wind	4,688	9	
Hydro	7,587	327	
Run-of-river	1,562	47	
Diesel	2,220	78	19
LNG	1,168	59	19

Diesel and LNG facilities are assumed to have thermal efficiencies of 37.5%. The heat rate for thermal facilities was calculated using historical emissions data, fuel consumption and reported generation.

The costs of solar and wind have decreased historically and are expected to continue decreasing due to technological improvements and learning (see Table 10). The rate of decline is based on National Renewable Energy Laboratory's Annual Technology Baseline, using a CAD-USD exchange rate of 1.3.

Table 10: Capital cost of solar and wind ($2021/kW)

Generation Type	2020	2030	2050
Solar	1,775	932	666
Wind	4,688	3,869	3,604

Hydrological supply module

The Yukon Water Board and YEC publish hydrological data for each of YEC's three major dams (Whitehorse, Aishihik, and Mayo). We've used this data to create a hydrological model within IESD.

The model includes the following constraints:

45 Yukon Energy Corporation. (2020). *Yukon Energy Corporation 2021 General Rate Application.* https://yukonenergy.ca/media/site_documents/2021_General_Rate_Application_-_WEB_READY.pdf

(1) **Turbine capacity**: at Whitehorse, Aishihik, and Mayo, generation must be less than 40 MW, 37 MW, and 15 respectively

(2) **Generation is proportional to turbine discharge**: electrical output is equal to:

$$Output(MW)\ \alpha\ Discharge\left(\frac{m^3}{s}\right) * Hydraulic\ Head\ (m)^{46} * \ Gravitational\ Constant\ \left(\frac{MJ}{m^4}\right)$$

(3) **Conservation of water**: the change in hourly reservoir level is inflows minus outflows, divided by reservoir surface area[47]

(4) **Allowable lake levels**: YEC's water licenses specify minimum and maximum levels for Marsh, Aishihik, and Mayo Lake

(5) **Minimum outflows**: turbine discharge plus spillage must be greater than regulated minimum flows in every hour

(6) **Maximum outflows**: outflows from the Whitehorse dam are restricted to about 170 cubic meters/second in winter to prevent flooding

(7) **Minimum spillage**: the Aishihik dam water license specifies that some water must be spilled over a waterfall and not used for generation.

(8) **Ramping constraints**: simplified hourly ramping constraints for the dams were added to reflect the fact that YEC's facilities have daily limitation on how much they can change their output.

Together, these constraints result in a reasonable depiction of how YEC uses its assets. We note a couple of simplifications related to ramping constraints and the exclusion of operational costs associated with opening/closing a spillway.

For the Atlin Dam, expected to come online in the model year 2025, detailed data from historical facility operation is not available. Inputs for head, reservoir area, inflows, and minimum flows were created to align with the expectation that Atlin will have a capacity of 8.5 MW and annual generation of 40-50 GWh.

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[46] We were able to use public sources for the height of the three dams, which don't account for hydraulic and generator losses. We adjusted these numbers slightly downwards to calibrate generation using historical lake levels.

[47] Surface areas were measured in Google Maps. The linkage between Marsh and Tagish lakes was not considered, resulting in a more conservative estimate of available storage at the Whitehorse Dam.

Electricity storage options

In addition to seasonal storage using hydrogen as described in section 2.2, IESD also has lithium-ion batteries and pumped storage hydro as electricity storage options in the Yukon.

Table 11 presents costs for lithium-ion batteries and pumped hydro. Costs for pumped hydro are based on Moon Lake from YEC's 10-year Renewable Electricity Plan[48]. Costs for batteries are based on the National Renewable Energy Laboratory[49] (low cost scenario, to provide a bookend relative to a scenario with no storage) and increased by 20% to consider regional challenges for infrastructure that are unique to the Yukon. Table 12 outlines how the cost of lithium-ion batteries declines over time.

Table 11: Cost of storage technologies

Storage Type	Power CAPEX ($2021/kW)	Storage CAPEX ($2021/kWh)
Lithium-ion battery	529.7	221.6
Pumped hydro	10135.8	1.1

Table 12: Cost of lithium-ion batteries over time

CAPEX type	2030	2050
Storage CAPEX ($2021/kW)	101.6	48.0
Power CAPEX ($2021/kWh)	242.7	114.7

Roundtrip efficiency is assumed to be 85% for lithium-ion batteries and 70% for pumped storage hydro.

Commodity prices

This section outlines electricity and fuel price assumptions in the Yukon IESD model.

[48] Yukon Energy Corporation. (2020). *10-year Renewable Electricity Plan Technical Report.* https://yukonenergy.ca/media/site_documents/YEN20093rpt_Technical_web2_compressed.pdf

[49] National Renewable Energy Laboratory. 2020. *Cost Projections for Utility-Scale Battery Storage: 2020 Update.* https://www.nrel.gov/docs/fy20osti/75385.pdf

Electricity prices

Electricity prices are input as an assumption in 2015, the model's base year. Table 13 below shows the prices in 2015. The industrial electricity price is based on the Canada Energy Regulator's 2020 version of Canada's Energy Future[50], while the residential and commercial sectors are based on electrical rates from the Yukon Energy Corporation (YEC). Electricity prices in the years after 2015 is determined endogenously in the model based on changes in the cost of electricity generation.

Table 13: 2015 IESD electricity prices ($2021/GJ)

Region	Residential	Commercial	Industrial
Integrated Grid	53.2	42.4	29.5
Watson Lake	53.2	42.4	
Beaver Creek	49.4	42.4	
Destruction Bay	53.2	42.4	
Old Crow	49.4	42.4	

Fuel prices

Fuel prices are determined exogenously in the model in all years (though carbon pricing could increase these prices). Table 14 shows prices for diesel and LNG in the regions modelled in the Yukon. Historical prices are based on data from ATCO and YEC, and prices are extrapolated to future years based on Canada's Energy Future 2020.

Table 14: Fuel prices ($2021/GJ)

Region	Fuel	2020	2025	2030	2035	2040	2045	2050
Integrated Grid	LNG	15.9	16.5	17.0	17.6	18.1	18.7	19.4
Integrated Grid	Diesel	20.5	20.7	21.0	21.2	21.5	21.7	22.0
Watson Lake	Diesel	22.4	22.6	22.9	23.2	23.5	23.7	24.0
Beaver Creek	Diesel	27.0	27.3	27.7	28.0	28.3	28.7	29.0
Destruction Bay	Diesel	26.8	27.1	27.4	27.8	28.1	28.4	28.8
Old Crow	Diesel	58.0	58.7	59.4	60.1	60.8	61.6	62.3

[50] Canada Energy Regulator. (2020). *Canada's Energy Future 2020.* https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2020/covid/index.html

Appendix B: gTech assumptions

gTech is well positioned to forecast low carbon technology and fuel adoption because it accounts for:

- **The competitiveness of electric and low carbon technologies relative to conventional alternatives.** This competitiveness depends not only on the attributes of end-use technologies themselves (such as their capital cost and operating performance), but also on the availability and price of electricity, fuels, and other energy carriers (like hydrogen). The competitiveness will change based on the amount of electrification, the unique energy resources in each province and energy trade among regions).
- **Firm and consumer preferences.** Electric or hydrogen technologies may be perceived as an imperfect substitute for existing technologies. For example, a given household may prefer a conventional vehicle over a battery or fuel cell electric vehicle because of its lower upfront cost and greater model variety. In addition, some preferences may change as a technology gains market share. For example, if electric vehicles become widespread and fast charging stations are broadly deployed, concerns about running out of a battery charge would decline.
- **The impact of existing federal and territorial climate policies on technology choice (including how they interact).** Accounting for existing policies is important because electrification (or adoption of hydrogen) is highly affected by their interactive and duplicative effects. For example, battery and fuel cell electric vehicle adoption is influenced by zero-emission vehicle (ZEV) mandates, financial incentives, clean/low carbon fuel standards, fuel economy regulations and carbon pricing.

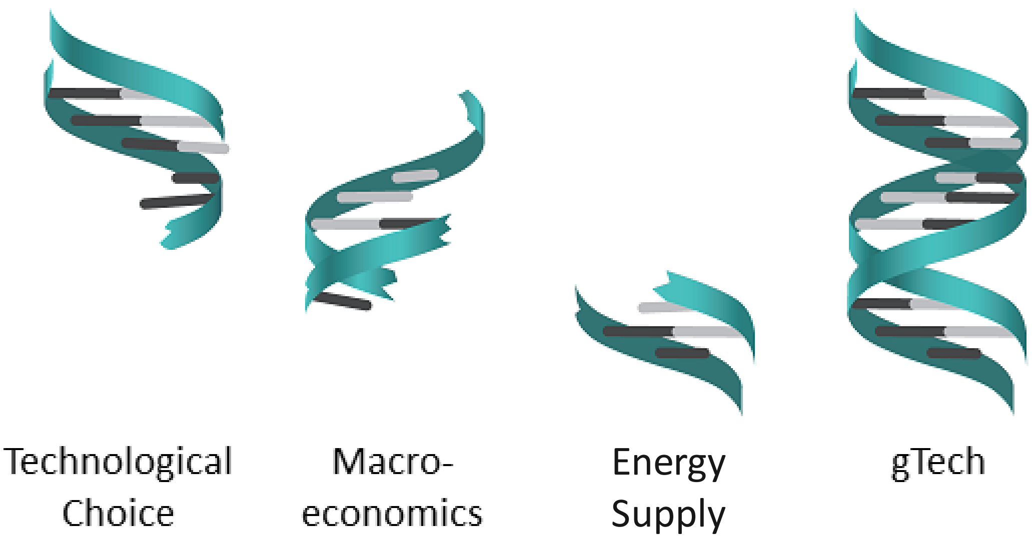
These various features mean that gTech can provide insight into future load in response to any combination of (1) existing and/or new policies that directly or indirectly affect electricity or hydrogen supply and demand and (2) the cost of electrification or hydrogen technologies relative to alternative options.

Introduction to gTech

gTech provides a comprehensive representation of all economic activity, energy consumption and greenhouse gas emissions in Canada. gTech is unique among energy-economy models because it combines features that are typically only found in separate models:

- A realistic representation of how households and firms select technologies and processes that affect their energy consumption and greenhouse gas emissions;
- An exhaustive accounting of the economy at large, including how provinces and territories interact with each other and the rest of the world; and
- A detailed representation of energy supply, including liquid fuel (crude oil and biofuel), gaseous fuel (natural gas and renewable natural gas), hydrogen and electricity.

Figure 4: The gTech model



gTech builds on three of Navius' previous models (CIMS, GEEM and OILTRANS/IESD), combining their best elements into a comprehensive integrated framework.

Simulating technological choice

Technological choice is one of the most critical decisions that influence greenhouse gas emissions in Canada. For example, if a household chooses to purchase an electric vehicle over a gasoline car, that decision will reduce their emissions. Similarly, if a mining facility chooses to electrify its operations, that decision reduces its emissions.

gTech provides a detailed accounting of the types of energy-related technologies available to households and businesses. In total, gTech includes 200 technologies across more than 50 end-uses (e.g., light-duty vehicle travel, residential space heating, industrial process heat, management of agricultural manure).

Naturally, technological choice is influenced by many factors. Table 8 summarizes key factors that influence technological choice and the extent to which these factors are included in gTech.

Table 8: Technological choice dynamics captured by gTech

Criteria	Description
Purchasing (capital) costs	Purchasing costs are simply the upfront cost of purchasing a technology. Every technology in gTech has a unique capital cost that is based on research conducted by Navius. Everything else being equal (which is rarely the case), households and firms prefer technologies with a lower purchasing cost.
Energy costs	Energy costs are a function of two factors: (1) the price for energy (e.g., cents per litre of gasoline) and (2) the energy requirements of an individual technology (e.g., a vehicle's fuel economy, measured in litres per 100 km). In gTech, the energy requirements for a given technology are fixed, but the price for energy is determined by the model. The method of "solving" for energy prices is discussed in more detail below.
Time preference of capital	Most technologies have both a purchasing cost as well as an energy cost. Households and businesses must generally incur a technology's purchasing cost before they incur the energy costs. In other words, a household will buy a vehicle before it needs to be fueled. As such, there is a tradeoff between near-term capital costs and long-term energy costs. gTech represents this tradeoff using a "discount rate". Discount rates are analogous to the interest rate used for a loan. The question then becomes: is a household willing to incur greater upfront costs to enable energy or emissions savings in the future? Many energy modelers use a "financial" discount rate (commonly between 5% and 10%). However, given the objective of forecasting how households and firms are likely to respond to climate policy, gTech employs behaviourally realistic discount rates of between 8% and 25% to simulate technological choice. Research consistently shows that households and firms do not make decisions using a financial discount rate, but rather use significantly higher rates[51]. The implication is that using a financial discount rate would overvalue future savings relative to revealed behaviour and provide a poor forecast of household and firm decisions.

[51] For example, see: Rivers, N., & Jaccard, M. (2006). Useful models for simulating policies to induce technological change. *Energy policy*, *34*(15), 2038-2047; Axsen, J., Mountain, D.C., Jaccard, M., 2009. Combining stated and revealed choice research to simulate the neighbor effect: The case of hybrid-electric vehicles. Resource and Energy Economics 31, 221-238.

Criteria	Description
Technology specific preferences	In addition to preferences around near-term and long-term costs, households (and even firms) exhibit "preferences" towards certain types of technologies. These preferences are often so strong that they can overwhelm most other factors (including financial ones). For example, buyers of passenger vehicles can be concerned about the driving range and available charging infrastructure of vehicles, some may worry about the risk of buying new technology, and some may see the vehicle as a "status symbol" that they value[52]. gTech quantifies these technology-specific preferences as "non-financial" costs, which are added to the technology choice algorithm.
The diverse nature of Canadians	Canadians are not a homogenous group. Individuals are unique and will weigh factors differently when choosing what type of technology to purchase. For example, one household may purchase a Toyota Prius while their neighbour purchases an SUV and another takes transit. gTech uses a "market share" equation in which technologies with the lowest net costs (including all the cost dynamics described above) achieve the greatest market share, but technologies with higher net costs may still capture some market share[53]. As a technology becomes increasingly costly relative to its alternatives, that technology earns less market share.
Changing costs over time	Costs for technologies are not fixed over time. For example, the cost of electric vehicles has come down significantly over the past few years, and costs are expected to continue declining in the future[54]. Similarly, costs for many other energy efficient devices and emissions-reducing technologies have declined and are expected to continue declining. gTech accounts for whether and how costs for technologies are projected to decline over time and/or in response to cumulative production of that technology.
Policy	One of the most important drivers of technological choice is government policy. Current federal, provincial and territorial initiatives in Canada are already altering the technological choices households and firms make through various policies: (1) incentive programs, which pay for a portion of the purchasing cost of a given technology; (2) regulations, which either require a group of technologies to be purchased or prevent another group of technologies from being purchased; (3) carbon pricing, which increases fuel costs in proportion to their carbon content; (4) variations in other tax policy (e.g., whether or not to charge GST on a given technology); and (5) flexible regulations, like the federal clean fuel standard which will create a market for compliance credits. gTech simulates the combined effects of all these policies implemented together.

[52] Kormos, C., Axsen, J., Long, Z., Goldberg, S., 2019. Latent demand for zero-emissions vehicles in Canada (Part 2): Insights from a stated choice experiment. Transportation Research Part D: Transport and Environment 67, 685-702.
[53] Rivers, N., & Jaccard, M. (2006). Useful models for simulating policies to induce technological change. *Energy policy*, *34*(15), 2038-2047.
[54] Nykvist, B., Sprei, F., & Nilsson, M. (2019). Assessing the progress toward lower priced long range battery electric vehicles. *Energy Policy*, 124, 144-155.

Understanding the macroeconomic impacts of policy

As a full macroeconomic model (specifically, a "general equilibrium model"), gTech provides insight about how policies affect the economy at large. The key macroeconomic dynamics captured by gTech are summarised in Table 9.

Table 9: Macroeconomic dynamics captured by gTech

Dynamic	Description
Comprehensive coverage of economic activity	gTech accounts for all economic activity in Canada as measured by Statistics Canada national accounts[55]. Specifically, it captures all sector activity, all gross domestic product, all trade of goods and services and the transactions that occur between households, firms and government. As such, the model provides a forecast of how government policy affects many different economic indicators, including gross domestic product, investment, household income and jobs.
Full equilibrium dynamics	gTech ensures that all markets in the model return to equilibrium (i.e., that the supply for a good or service is equal to its demand). This means that a decision made in one sector is likely to have ripple effects throughout the entire economy. For example, greater demand for electricity requires greater electricity production. In turn, greater production necessitates greater investment and demand for goods and services from the electricity sector, increasing demand for labor in construction services and ultimately leading to higher wages. The model also accounts for price effects. For example, the electricity sector can pass policy compliance costs on to households, who may alter their demand for electricity and other goods and services (e.g., by switching to technologies that consume other fuels and/or reducing consumption of other goods and services).
Sector detail	gTech provides a detailed accounting of sectors in Canada. In total, gTech simulates how policies affect over 80 sectors of the economy. Each of these sectors produces a unique good or service (e.g., the mining sector produces ore, while the trucking sector produces transport services) and requires specific inputs into production.
Labor and capital markets	Labor and capital markets must also achieve equilibrium in the model. The availability of labor can change with the "real" wage rate (i.e., the wage rate relative to the consumption level). If the real wage increases, the availability of labor increases. The model also accounts for "equilibrium unemployment".
Interactions between regions	Economic activity in Canada is highly influenced by interactions among provinces/territories, with the United States and with countries outside of North America. Each province and territory in the model interact with other regions via (1) the trade of goods and services, (2) capital movements, (3) government taxation and (4) various types of "transfers" between regions (e.g., the federal government provides transfers to provincial and territorial governments). The version of gTech used for this project accounts for the 10 Canadian provinces, the 3 territories and the United States. The model simulates each of the interactions described above, and how interactions may change in response to policy.

[55] Statistics Canada. Supply and Use Tables. Available from: www150.statcan.gc.ca/n1/en/catalogue/15-602-X

Dynamic	Description
Households	On one hand, households earn income from the economy at large. On the other, households use this income to consume different goods and services. gTech accounts for each of these dynamics, and how either change with policy.

Understanding energy supply markets

gTech accounts for all major energy supply markets, such as electricity, refined petroleum products and natural gas. Each market is characterized by resource availability and production costs by province, as well as costs and constraints (e.g., pipeline capacity) of transporting energy between regions.

Low carbon energy sources can be introduced within each fuel stream in response to policy, including renewable electricity, bioenergy and hydrogen. The model accounts for the availability and cost of bioenergy feedstocks, allowing it to provide insight about the economic effects of emission reduction policy, biofuels policy and the approval of pipelines.

gTech: The benefits of merging macroeconomics with technological detail

By merging the three features described above (technological detail, macroeconomic dynamics, and energy supply dynamics), gTech can provide extensive insight into the effects of climate and energy policy.

First, gTech can provide insights related to technological change by answering questions such as:

- How do policies affect technological adoption (e.g., how many electric vehicles are likely to be on the road in 2030)?
- How does technological adoption affect greenhouse gas emissions and energy consumption?

Second, gTech can provide insights related to macroeconomics by answering questions such as:

- How do policies affect national and provincial gross domestic product?
- How do policies affect individual sectors of the economy?
- Are households affected by the policy?

- Does the policy affect energy prices or any other price in the model (e.g., food prices)?

Third, gTech answers questions related to its energy supply modules:

- Will a policy generate more supply of renewable fuels?
- Does policy affect the cost of transporting refined petroleum products, and therefore the price of gasoline in Canada?

Finally, gTech expands our insights into areas where there is overlap between its various features:

- What is the effect of investing carbon revenue into low- and zero-carbon technologies? This question can only be answered with a model like gTech.
- What are the macroeconomic impacts of technology-focused policies (e.g., how might a zero-emissions vehicle standard impact GDP)?
- Do biofuels-focused policies affect (1) technological choice and (2) the macroeconomy?

Limits to forecasting

Despite using the best available forecasting methods and assumptions, the evolution of our energy economy is uncertain. In particular, forecasting greenhouse gas emissions is subject to two main types of uncertainty.

First, all models are simplified representations of reality. Navius' gTech model is, effectively, a series of mathematical equations that are intended to forecast the future. This raises key questions: "are the equations selected a good representation of reality?" and "do the equations selected overlook important factors that may influence the future?"

The use of computable general equilibrium models (gTech) is well founded in the academic literature. In addition, Navius undertakes significant efforts to calibrate and back-cast the model to ensure that it captures key dynamics in the energy-economic system.

However, Navius' tools do not account for every dynamic that will influence technological change. For example, household and firm decisions are influenced by many factors, which cannot be fully captured by even the most sophisticated model.

The inherent limitation of energy-economy forecasting is that virtually all projections of the future will differ, to some extent, from what ultimately transpires.

Second, the assumptions used to parameterize the models are subject to uncertainty. These assumptions include, but are not limited to, oil prices, improvements in labour productivity and a stable climate. If any of the assumptions used prove incorrect, the resulting forecast could be affected.

In sum, gTech is the most comprehensive model available for forecasting the techno-economic impacts of climate policy in Canada. Its representation of technological change, macroeconomic dynamics and fuels markets (as described above) mean that it is ideally positioned to forecast electricity and hydrogen demand in the Yukon.

Economic growth

Economic growth assumptions influence electricity demand used to inform the IESD model. Economic activity in gTech was calibrated to the Conference Board of Canada's GDP forecast for the Yukon, relying on this forecast for growth in the mining sector and other industrial sectors[56]. Simulated GDP by income from gTech is presented in Table 15, below.

Table 15: GDP by income (million 2015 CAD)

	2015	2030	2040	2050
Transportation	231	396	361	416
Manufacturing	10	11	15	16
Resources	245	918	744	871
Utilities	48	45	57	48
Construction	189	421	216	364
Services	1,837	2,506	2,958	3,180
Total	2,560	4,297	4,351	4,896

The electricity and emissions intensity of the mining sector was adjusted from its baseline 2015 values to match YEC's forecast of industrial electricity consumption for the 2020-2025 period.

[56] Conference Board of Canada, April 2021, *New Projects, Bright Prospects: Yukon's 20-year Output,* data tables (provided by Yukon Climate Action Secretariat)

Appendix C: Stakeholder outreach

Navius conducted a stakeholder outreach with local stakeholders and hydrogen experts with the following key objectives:

- Ensure the analysis takes into consideration all available data and resources, as well as questions, concerns and areas of interest specific to hydrogen uptake in the Yukon.
- Engage local stakeholders in the analysis and its results, and what the results mean for them as a participant in the decarbonization of the Yukon's economy.

These conversations aided Navius in understanding the level of knowledge about hydrogen in these groups and in understanding locally specific concerns and considerations. This appendix summarizes the results of the stakeholder outreach.

Information was gathered from over 20 stakeholders during individual video calls (20-45 minutes in length), listed in the table below:

Table 16: List of stakeholders

Name	Company/organization/department
Local government	
Ryan Hennessey	Highways and Public Works
Maurice Colpron	Geological Survey
Lauren Haney	Mineral Resources
Dustin Biero	Mineral Resources
Lisa Walker	Forestry
Gavin Dykshoom	Forestry
Local utility	
Victoria Zeppa	Yukon Development Corp
Norm Curzon	ATCO

John Williams	ATCO
Duncan McInnis	ATCO
Mila Milojevic	Yukon Energy Corp
Local business	
Blaine Mason	Whitehorse Toyota
Hector Campbell	Yukon Chamber of Commerce
Christian Roldan	Coffee Mine, Newmont
Local municipality	
Cody Reaume	City of Whitehorse
Local research organization	
Scott Pressnail	Yukon Conservation Society
Michael Ross	Yukon Research Centre
National hydrogen or remote community energy expert	
Dylan Hereema	Ecotrust Canada
Guy Gensey	BC Ministry of Energy, Mines and Low Carbon Innovation
Marvin Quitoras	Pembina Institute
David Layzell	CESAR and Transition Accelerator
Mark Kirby	CHFCA

Key opportunities

The most widely identified opportunities in the stakeholder outreach for hydrogen in the Yukon are provided in the table below.

Table 17: Key opportunities identified in the stakeholder outreach

Opportunity	Description
1. Seasonal electricity storage	The Yukon cannot currently meet peak electricity demand during the winter without the use of a backup diesel generator. Electricity demand is also expected to increase (by 40%) over the next 10 years, exacerbating this peak demand issue. Intermittent renewables like wind and solar don't help with this problem, as peak demand occurs in the winter months when renewable generation is low. A key opportunity for hydrogen is its use as a dispatchable energy source that can address the seasonal imbalance and support the addition of intermittent renewables to the Yukon's electricity system.
2. Electrolysis-derived hydrogen	Hydrogen produced via electrolysis was identified most often as an opportunity for the Yukon, compared to other hydrogen production options. Some stakeholders mentioned the opportunity to transport blue hydrogen by truck from BC or Alberta but noted that hydrogen is usually more economic when produced on site.
3. Heavy-duty transport	A significant portion of the Yukon's emissions come from the transport sector and many stakeholders identified this as a key opportunity for hydrogen to reduce emissions. Stakeholders indicated that passenger vehicles are more likely to be electric, although noting that hydrogen vehicles may be better adapted to the cold climate given the need for long range (batteries can lose charge in cold weather) and the need for heating. Commonly indicated reasons for the opportunity in HDVs include: • Rebates for electric and plug-in electric vehicles were recently put in place and could incentivize hydrogen vehicles as well. There is also a government initiative to decarbonize the Alaska highway, which hydrogen could help achieve. • Electric vehicles would increase the demand on the electricity system, which already struggles to meet peak demand. Hydrogen could help avoid this problem by using electricity during off-peak hours. • Transport is highest in the summer when renewables are at their best and excess generation can be used to produce hydrogen. This is opposite to the electricity system, as demand for hydrogen fuel for transport would be highest when renewable generation is also highest. Hydrogen becomes an almost free transportation fuel if it uses off-peak electricity to be produced. • Transit vehicles and other vehicle fleets were mentioned specifically by many stakeholders, see section 4.
4. Culture and political pressure	Many stakeholders noted an environmentally progressive culture in the Yukon, particularly in remote communities, and a desire to decarbonize, move away from diesel, and be a leader in clean energy innovation. There is currently a wait list for plug-in hybrid vehicles at Whitehorse Toyota, suggesting a market for clean energy technologies.
5. Dual fuel engines	Given the many challenges associated with the Yukon being an early adopter of hydrogen technologies (see section 3), especially in the short-term (2030), many stakeholders identified hydrogen blending into dual fuel engines as an opportunity.

	This technology is readily available for vehicle engines as well as back-up generators and doesn't require full turnover of technology.

Additional opportunities identified for hydrogen in the Yukon are provided in the table below.

Table 18: Additional opportunities for hydrogen identified in the stakeholder outreach

Opportunity	Description
Remote communities	Many stakeholders noted the potential for hydrogen to offset diesel consumption in remote communities and to capitalize on curtailment of electricity from renewable projects in these communities. Battery storage allows for increased penetration of renewables but doesn't replace reliance on diesel in the winter months. If hydrogen could be stored for use in the winter, it could help to reduce reliance on diesel. Hydrogen could also provide an economic opportunity in some communities, as some renewable projects being developed are large, and instead of curtailment, energy that the IPP can't sell into the system could be used to make hydrogen and sold back to the grid.
High energy costs	The Yukon is unique in that energy costs are high. Hydrogen will therefore not be competing with cheap natural gas or diesel as it does in other parts of Canada. This may present an opportunity for hydrogen as a more expensive fuel to compete economically with other energy alternatives.
Diversification of energy portfolio	Energy resilience and security are important values in the Yukon. Diversification of the energy portfolio is an important way to reduce the risk of running out of energy. Access to an additional energy source like hydrogen could help diversify the energy system and increase resilience.
Ammonia	One stakeholder mentioned the opportunity of using ammonia as fuel, which is less expensive to transport by truck than hydrogen, and could be brought to the Yukon from BC or Alberta with economics comparable to diesel.
Long term	Many stakeholders acknowledged that the hydrogen opportunity in the Yukon is in the longer term (2050) rather than the shorter term (2030). The use of dual fuel engines were mentioned as a shorter term solution before a potentially more significant transition to hydrogen technology and infrastructure in the long term.

Key challenges

The most widely identified challenges for hydrogen in the Yukon identified during the stakeholder outreach are provided in the table below.

Table 19: Key challenges identified during the stakeholder outreach

Challenge	Description
1. Regulatory challenges	Since the primary objective of the utility is to provide a reliable and safe supply of electricity while protecting the rate payer, there is no regulatory incentive to decarbonize or to invest in low carbon technologies like hydrogen. The regulated utility is exempt from carbon taxes on fuel consumption to avoid increases in energy costs and the regulatory environment is focused on keeping rate payer costs down, not on reducing emissions. There is a need for adherence to environmental performance as a regulated requirement for utilities in order to provide the incentive for them to invest in clean energy sources such as hydrogen. Many stakeholders mentioned the complicated relationship between utilities, IPPs and remote communities. ATCO is the sole purchaser of energy from these communities and pays a given rate to the IPP, which is tied to the diesel price and may not reflect the true price of energy in the community. Therefore, if the utility invests in a technology like an electrolyser, it will be paying the cost of diesel anyway under the current system, so it's not an economic investment. Also, the utility can't operate a battery if they own diesel, because they must protect the rate payer (note that some communities are overcoming this challenge by purchasing the battery and then giving it to the utility under an agreement to maximize renewable generation). The IPPs therefore need to be the ones to invest in new technologies like hydrogen. In this regulatory environment, renewable projects with IPPs can't function without subsidies. Grant funding is currently available from Government of Yukon and the federal government to help mitigate this challenge. Other regulatory challenges that were mentioned include: • Alignment and communication between different levels of government. For example, one stakeholder mentioned that the federal goal to reduce reliance on diesel in remote communities was rolled out without an understanding of the regulatory environment in these communities or the IPPs that are currently in place. Another stakeholder mentioned that the goals set out the Government of Yukon's "Our Clean Future" are not mandated and don't align with the objectives of utility regulatory policy. It was also noted that because First Nations communities and development corporations rely on grant funding to pursue projects like renewables or hydrogen in their community, federal funding and expertise play an important role in local projects. • There is currently an attempt to increase renewable energy

	integration limits for remote communities, which right now is at 7-20%. This limit is another regulatory challenge that could apply to hydrogen integration as well. • It was noted that in the mining sector, there are minimal reporting requirements or incentives to reduce emissions (see section 4).
2. Cost/investment	Hydrogen projects have a high capital cost and risk, which doesn't attract investment. Who is going to invest in production, transport and consumption in a market of the Yukon's size? It makes more sense to invest in a larger market first. Is the cost going to be competitive with alternatives? Energy affordability is a large concern in the Yukon, particularly in remote and First Nations communities. There are other available options that can be leveraged including renewables, biomass, batteries and hydroelectric, and there needs to be a reason to justify investment in hydrogen over these alternatives.
3. Storage	There will be a need to store large amounts of hydrogen to ensure energy security, take advantage of renewable curtailment, and ensure there is enough hydrogen to get communities through winter months when there is little renewable generation. Storage capacity would need to be equivalent to the amount of energy that is currently being stored in diesel. Is there a viable and economic way to store large amounts of hydrogen in the Yukon? In terms of geological storage, there are no salt caverns in the Yukon's south close to the grid, and no old mines close to Whitehorse that would be suitable for storage. There is however a lot of carbonate closer to remote communities where the geology may be suitable for storage, though there is currently little available information on this.
4. Labour force knowledge/capacity/skills	Many stakeholders identified the challenge of ensuring the needed ecosystem of sales, support and maintenance is available locally for the use of hydrogen technologies like hydrogen fuel cell vehicles. The hydrogen system will need to be locally maintained, with the ability to get emergency support when needed. In the mining sector, for example, there will be industrial tickets needed to work on hydrogen equipment, and there would need to be local access to skills training and specialisations for people to fill these roles. In remote and First Nations communities specifically, stakeholders identified that the whole supply chain (renewable generation, electrolyser, compressor, storage, consumption technology) will need to be in the community, so there will be a need for the skills and ability to service along the full supply chain. If the hydrogen system is complex, it will be hard to maintain in small, remote communities. Old Crow was mentioned several times as a community that is particularly hard to serve, as a fly-in community. This can lead to challenges with maintenance and servicing of new technologies.
5. Small market/economies of scale	The Yukon's population and geography doesn't provide the conditions to be an early adopter of a new technology, as it's hard to justify investment in new energy projects when communities are small and spread out. With hydrogen in particular, it makes sense economically to establish hydrogen hubs at first in areas where there is significant production and consumption in one place. Getting a new industry like hydrogen off the ground is more economic in a place with a larger market and smaller geographical area. Whitehorse is too small of a market to be one of the first hubs and is typically behind larger

	cities in the uptake of new technology. Toyota's Mirai fuel cell vehicle, for example, will enter larger markets with a similar climate, such as Calgary or Edmonton, first before the technology becomes available in Whitehorse.

Additional challenges identified for hydrogen in the Yukon during the stakeholder outreach are provided in the table below.

Table 20: Additional challenges identified during the stakeholder outreach

Challenge	Description
Transport	Hydrogen produced on site is typically less expensive and has a lower carbon intensity than hydrogen that needs to be transported long distances. When considering blue hydrogen produced in Alberta or BC, a limiting factor could be long haul transport, given the lack of pipeline infrastructure to and within the Yukon. Some stakeholders noted that transport in compressed tube trailers won't be economically justified, so hydrogen would need to be transported as a liquid or converted medium. If hydrogen needs to be transported as a liquid, then there is need for a liquid plant (in Edmonton, for example) to support distribution of blue hydrogen to the Yukon.
Infrastructure	There is no pipeline infrastructure in place in buildings in the Yukon, which limits the role of hydrogen for heating, as existing pipelines can't be utilized as in other regions. The low demand/throughput won't be enough to justify a hydrogen pipeline network. For hydrogen use in vehicles, fuelling infrastructure will need to be in place along all communities on the Alaska highway to provide the ability for trucks to travel from Edmonton/Dawson/Fort Nelson to Whitehorse and refuel along the way. Some stakeholders noted the cost to set up this infrastructure will be a challenge. Toyota won't sell the Mirai fuel cell vehicle in Whitehorse until it can be driven everywhere in the Yukon without vehicles getting stuck.
Lack of demonstration/testing	There is currently a lack of demonstration of hydrogen projects in locations similar to the Yukon. For examples, utilities noted that they can't include hydrogen in their planning until it is commercialized and proven to be economic and safe. There is a need for examples to prove that it will be a viable solution before moving forward. Utilities also noted that they are not in the position to fund demonstration projects, but that it would be valuable to have pilot hydrogen research projects in the North.
Public buy-in	Although there is an environmentally conscious culture in the Yukon, there is also a resistance to change. Getting public buy-in and social license for a

	hydrogen economy will be important and will require public education and engagement.
Electricity supply and price	Since the Yukon already has an electricity shortage during peak demand times, adding electricity demand for hydrogen generation could be a challenge. Hydrogen relies on cheap electricity to make it cost effectively using electrolysis, but the Yukon only has an electricity surplus in summer months, while hydrogen demand would be year-round. The economics of hydrogen in the Yukon rely on cheap electricity availability, so an analysis of whether/how hydrogen can be used to take advantage of off-peak hours would be valuable.

Sector-specific notes

Sector-specific comments made by stakeholders that are worthy of note are provided below.

Transport

Many of the emissions from the Yukon's transport sector come from HDV fleets, which could provide an opportunity to convert an entire fleet to hydrogen. This includes the City of Whitehorse fleet, government of the Yukon fleet, public transit, mining vehicles and airport fleet. Hydrogen can offer a solution to managing refuelling station footprints in fleet yards. Hydrogen presents an opportunity for transit buses in particular for a few reasons:

- The City of Whitehorse analyzed electric buses as an option to reduce emissions and found some routes wouldn't be manageable due to range requirements. Electric buses also have challenges in a cold climate (reduced range, long charging time, need to heat the bus) that hydrogen buses don't.
- Buses provide a good opportunity from a capital cost perspective since they operate almost 24/7, compared to other vehicle fleets that are seasonal.
- Whitehorse recently built a new city hall with space to bring transit vehicles inside. Given the faster fuelling time, hydrogen buses would require less space in the building than electric buses.

Small off-road vehicles, such as sleds and ATVs, may provide an opportunity for hydrogen. Batteries don't work well in these types of vehicles, as you can't risk a battery dying in a remote area where it can't be recharged. Hydrogen, on the other hand, does better in the cold and allows you to carry extra fuel. Old Crow, for example, is a community that mostly uses ATVs and sleds for transport.

Liquid hydrogen may be an opportunity for the heavy-duty transport sector. There are emerging technologies that can use liquid hydrogen directly and gasify it in the vehicle. This is important because most of the cost of hydrogen fuel comes from compression, so using liquid hydrogen without the need for compression is a less expensive option.

Buildings

Commercial buildings

- Propane is cheap in the Yukon, which makes it hard to compete with for heating commercial spaces.
- A district heat system makes the most sense from an infrastructure and cost perspective in a commercial context. District heat may be an opportunity for City of Whitehorse buildings. Canada Games Centre is the largest energy consuming building in the territory and is next to 5-6 other large commercial buildings, which could act as a hub for district energy. In fact, only 10-20 buildings use 80-90% of the total energy used for heating in Whitehorse, which could provide a good opportunity to reduce emissions via a district heating hub.

Residential buildings

- Electric baseboards have taken over home heating in Whitehorse. There are also incentives in place for residential heat pumps and local expertise is growing in this area.
- There are also a lot of homes heated by propane and heating oil. A few stakeholders mentioned concerns about pushing to electrify residential buildings out of concern for increasing the peak electricity demand issue.
- There is no pipeline infrastructure in existing neighbourhoods in Whitehorse, but pipelines are an option for new neighbourhoods.

Mining

Mining intensity targets were recently put in place and are the first step towards incentivizing mining companies to reduce emissions. However, mining firms indicated these goals do not require them to make any changes. In fact, most mines are too small to fall under federal emissions reporting requirements and don't track their emissions. The main source of emissions from operating mines is vehicles, and from the proposed Coffee Mine project will be generators, followed by vehicles.

All operating mines in the Yukon are connected to the grid so there is no incentive for them to produce their own clean electricity. The proposed Coffee Mine project will not be connected to the grid but plans to use dual fuel (diesel & LNG) generators, as the lifetime of the project isn't long enough to justify investment in renewable generation such as wind turbines.

Mines are remote and are subject to the same challenges as remote communities in terms of needing to store enough energy on site for times when it can't be accessed by truck.

Some stakeholders indicated mines as a good opportunity for innovation and testing of new technology like hydrogen (given the right incentives) because they have large energy loads at one location and HDV fleets. However, mining sector stakeholders indicated this is not the case in the Yukon for a few reasons:

- Mining margins are very small and cost is therefore the most important factor.
- There is a pervasive perception that mining in the North is so much more expensive than elsewhere (due to weather, long distance to transport product, high fuel cost, availability of power) and that it is not acceptable to add any additional costs.
- Historically, quartz mining is dominated by junior mining companies and developers in the Yukon. This is an inherent barrier to considering new technologies compared to larger companies, as junior companies are focused on cost savings above all else.

Mines in the Yukon still use old technology and are unlikely to move to cutting edge technology ahead of other regions and sectors. Placer mines, which account for about 50% of mining emissions in the Yukon, recycle as much equipment as possible and are still using equipment from the 1960s/1970s. This same comment was made regarding the Yukon's forestry sector, that equipment used in the forestry sector is behind other jurisdictions and is unlikely to be an early adopter of new technology.

Electricity

Many stakeholders found it important to note that renewables such as wind turbines and solar panels can be expensive/challenging to maintain in the winter in the Yukon. Challenges include local expertise, de-icing and maintenance. This is important because a large increase in renewable generation may be needed for electrolysis hydrogen, so these challenges with local renewable generation must be taken into consideration.

Other sectors

Biomass gasification

- The stakeholders indicated that there is not very much biomass available in the Yukon that is suitable to produce hydrogen. The forestry industry is small with very little residuals being produced and without the full supply chain needed to produce hydrogen. If biomass gasification were to be used to produce hydrogen in the Yukon, the biomass would likely come from outside the local area, such as somewhere with a mill that has residuals to get rid of. The Yukon currently imports pellets, so it is feasible to import wood residuals from BC or Alberta for hydrogen production.
- Stakeholders also indicated that biomass gasification technology is in the early stage and needs more work before it's a reliable system for generating hydrogen. There are other, better ways to produce hydrogen that have better social license and are more economic.
- However, the Yukon may still be interested in this given the interest in building a local biomass industry.

Combined heat and power

- Stakeholders indicated that combined heat and power requires economies of scale that the Yukon communities don't have.

What stakeholders are interested in

There are some commonly identified questions or areas of uncertainty that stakeholders indicated they would ideally like to see addressed in the final report of this analysis. These are provided in the table below.

Table 21: What stakeholders are interested in

Technical questions

Efficiency	How efficient is hydrogen production compared to other clean energy options[57]? How does the efficiency of hydrogen as energy storage compare to the efficiency of alternative storage options such as pumped hydro or batteries?	See section 2.2 and Appendix A
Emissions intensity	What is the lifecycle emissions intensity of hydrogen produced in BC or Alberta and transported to the Yukon?	Excluded from analysis because hydrogen transport was ruled out as too expensive
Climate	What do cold temperatures mean for the transport, storage and operability of hydrogen technologies?	See sections 2.2 and 2.3
Electricity storage	Could hydrogen play a role in seasonal energy storage in the Yukon's electricity grid?	See section 3.1
Technology	A complete scan of available hydrogen technologies would be beneficial. What technological developments in hydrogen storage and transport have happened over the past 10-20 years? How has this changed the economics of hydrogen?	Section 2 and 3[58]
Economic questions		
Cost/investment	How does hydrogen compare economically to the energy cost of other clean energy alternatives or energy storage options (e.g., small hydro, pumped hydro, batteries)? Are there reasons to invest in hydrogen over other clean energy options?	See sections 2.2, 2.3, 3.1, 3.2, and Appendix A
Business case	Is there a business case for small communities to pursue hydrogen production? What are the opportunities and benefits specific to remote and First Nations communities?	See section 3.2
Policy questions		
Policy/regulatory environment	What policy or regulations would be needed to incentivize hydrogen uptake in the Yukon?	See section 4
Role of other jurisdictions	What is the hydrogen landscape in the rest of Canada and USA? Are there examples of hydrogen projects that might be useful for comparison with the Yukon? What role will hydrogen uptake in other jurisdictions play for uptake in the Yukon?	Out of scope

[57] The efficiency of alternative low carbon technologies and fuels is considered in the modelling (it impacts fuel expenditures), but the focus of the study is greenhouse gas emissions.

[58] Section 2 outlines technologies and Section 3 considers evolving cost of hydrogen and other low carbon technologies.

What we learned

One goal of the stakeholder outreach was for Navius to ensure our analysis is grounded in challenges and opportunities specific to the local context in the Yukon. Based on stakeholder conversations, we have learned some key takeaways that benefited and informed this analysis.

Key challenges we learned about through this process include:

- **Regulatory challenges associated with incentivizing and supporting decarbonization of the Yukon's economy.** This was brought up by many stakeholders, particularly in relation to the role of utilities in the adoption of low carbon technologies like hydrogen.
- **Knowledge/capacity/skills and training availability in the local labour force.** This was another commonly identified challenge among stakeholders that will be necessary to overcome if a hydrogen system is to be successfully developed and maintained in the Yukon.
- **Large storage opportunities may be limited.** The ability to store large amounts of hydrogen on site will be a greater challenge than we initially suspected, as viable and economic storage opportunities may be limited in areas close to demand.

Key opportunities we learned about through this process include:

- **Hydrogen may be an opportunity for the Yukon in the longer term (2050) rather than shorter term (2030).** Many stakeholders suspect that hydrogen technologies will become available in the Yukon once more experience has been gained in other parts of the country.
- **Dual fuel engines may be an opportunity for hydrogen blending in the shorter term (2030).** This is a technology that is readily available for vehicle engines and back-up generators and could help to reduce reliance on diesel in the shorter term, before pure hydrogen technologies become available in the Yukon.
- **The Yukon has an environmentally progressive culture.** There is a local desire to decarbonize the Yukon's energy system and to be a leader in clean energy innovation, which suggests an openness to new clean energy technologies like hydrogen.

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