REPORT

HYDROGEN TRANSPORTATION AND INFRASTRUCTURE ANALYSIS

FORESIGHT CANADA

DEC
2024

Acknowledgements

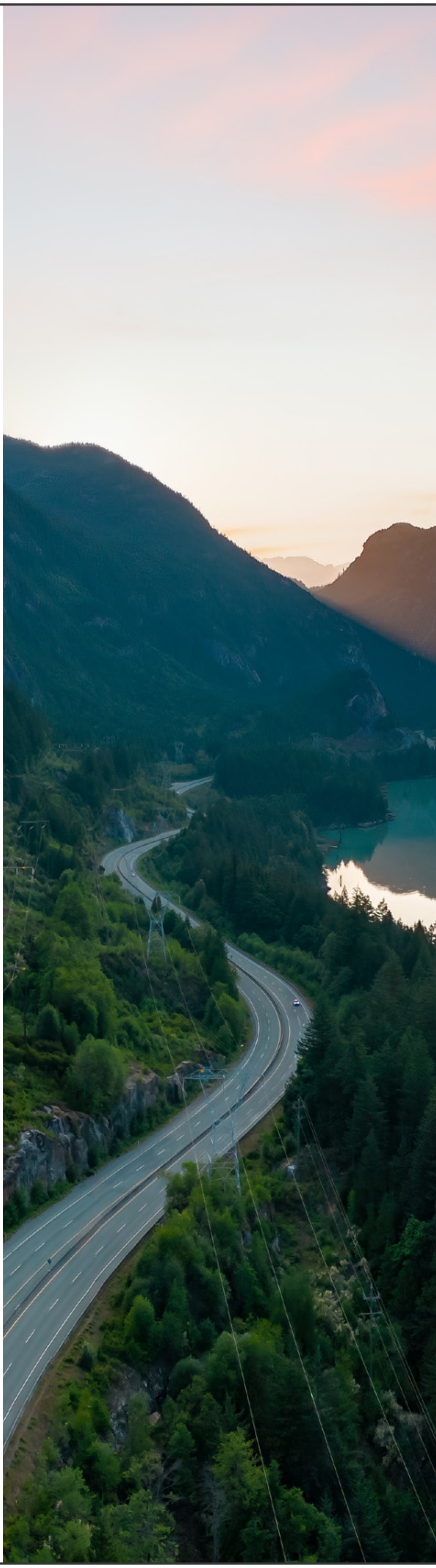
This report was supported by the BC Clean Energy and Major Projects Office.

This report was prepared by Foresight Canada and Sacré-Davey.

About Foresight

Foresight Canada helps the world do more with less, sustainably. As Canada's largest cleantech innovation and adoption accelerator, we de-risk and simplify public and private sector adoption of the world's best clean technologies to improve productivity, profitability, and economic competitiveness, all while addressing urgent climate challenges.

Table of Contents



Abbreviations

Abbreviation	Definition
ALARP	As Low as Reasonably Practicable
bar	Unit of pressure measurement. 1 bar = 100 kPa
barg	Unit of pressure measurement at gauge pressure
BC	British Columbia
BCER	British Columbia Energy Regulator
CEMPO	BC Clean Energy and Major Projects Office
CGSB	Canadian General Standards Board
CHA	Canadian Hydrogen Association
CICE	Centre for Innovation and Clean Energy
CPKC	Canadian Pacific Kansas City
CN	Canadian National Railway
CP	Canadian Pacific Railway
CSA	Canadian Standards Association
EA	Environmental Assessment
ERAP	Emergency Response Assistance Plan
FCEV	Fuel Cell Electric Vehicle
H_2	Hydrogen
HISD	High-Intensity, Short-Duration
HMIS	Hazardous Materials Identification System
ICEO	Indigenous Clean Energy Opportunities
IEA	International Energy Agency

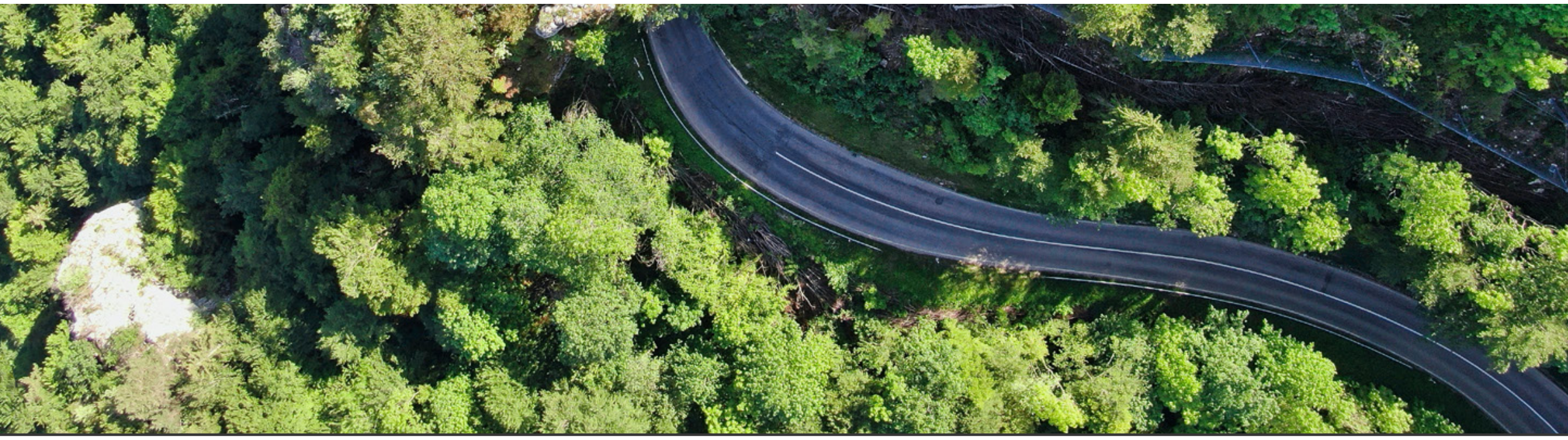
Abbreviation	Definition
ITC	Investment Tax Credit
kg	Kilograms
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied Petroleum Gas
MCH	Methylcyclohexane
N/A	Not Applicable
NH_3	Ammonia
NRCan	Natural Resources Canada
NSERC	National Sciences and Engineering Research Council of Canada
PIEVC	Public Infrastructure Engineering Vulnerability Committee
SDS	Safety Data Sheet
SFU	Simon Fraser University
SHED	Smart Hydrogen Energy District
syngas	Synthesis gas (mixture of carbon monoxide, hydrogen, carbon dioxide, water and other minor components)
TDG	Transportation of Dangerous Goods
UBC	University of British Columbia
UN number	United Nations (UN) number for shipping names of dangerous goods according to UN Model Regulations
UNDRIP	UN Declaration on the Rights of Indigenous Peoples

Executive Summary

Hydrogen has the potential to contribute to decarbonization targets by serving as a clean energy carrier for hard-to-abate sectors. There are challenges associated with transportation, including the need for specialized infrastructure and potential safety risks if not handled and contained correctly. Gaseous hydrogen can be inefficient if large quantities are required, and liquid hydrogen can be volatile and expensive. This has led to growing interest in exploring the properties, risks, and opportunities of different hydrogen carriers. This report explores the trade-offs and opportunities of hydrogen carriers, including ammonia, methanol, and liquid organic hydrogen carriers (LOHC). In particular, the differing transportation, handling, and storage requirements. This report includes an overview of existing regulations in BC in relation to the transportation of hydrogen and hydrogen carriers, though this is an area that is still developing as new technologies and processes emerge.

The report examines existing infrastructure within BC and identifies potential upgrades that would be required for transportation of hydrogen and hydrogen carriers with a focus on pipeline, truck, and rail. Generally, there is established infrastructure in more populated areas, such as the south of the province and where there are existing industrial or oil and gas industries such as in the north east and on the north coast.

Further assessment has been undertaken to evaluate the different hydrogen carriers and potential infrastructure development impacts in BC. This includes an assessment of environmental and social considerations, scalability and costs, and market potential of hydrogen carriers. Pipeline transportation could be the best long-term solution, particularly for large volumes of hydrogen, but practical limitations exist in the technical feasibility of converting existing pipelines along with the environmental, social, and economic challenges in developing new pipelines. Although supply chains, existing infrastructure, and regulations are established for road and rail transportation, particularly of ammonia and methanol, there may be challenges in delivering large volumes and the cost of additional processes needs to be considered. There is growing market potential for both green ammonia and methanol which may be attractive in having more diverse end-use applications.



The trade-offs and advantages of each carrier and transportation method will need to be assessed for different scenarios. Factors to be considered include availability of existing infrastructure, distance, volume demand, end-user requirements, and the location of production sites and end-users.

The risk analysis section provides an overview of key hazards associated with hydrogen and hydrogen carrier transportation. In all transportation scenarios, hazards can exist such as accidental releases, adverse weather/environment, derailments, road crashes, fires, explosions, hydrogen embrittlement, and cracking in critical equipment and piping. A review of past incidents has been undertaken to recognize potential hazards and highlight preventative measures. Processes will need to be clearly defined to understand and address hazards associated with specific transportation options and carriers, ensuring that appropriate handling processes, storage requirements, and procedures are in place to promote safety and limit risks.

The opportunity assessment highlights key areas within the BC ecosystem that can be leveraged to support hydrogen and hydrogen carrier transportation initiatives within the province. The existing policy and regulatory environment is favorable to investors, which is reflected in growing research and new projects in the region. The number of hydrogen and fuel sector organizations also contributes to a knowledgeable and skilled workforce. Physical resources and existing infrastructure within BC, such as an affordable and clean supply of energy and availability of natural gas and freshwater, positions the province as a key location for hydrogen production and transportation. There are also many opportunities for partnerships to contribute to the existing hydrogen ecosystem within BC. In particular, there are opportunities with existing industry partners developing the hydrogen sector and with First Nations communities to lead and collaborate on projects.

Introduction

Hydrogen is an energy vector and carrier that has the potential to play a key role in the transition to a net zero economy when produced using renewable energy and in a sustainable way. It is an important part of plans to achieve federal and provincial net zero targets, particularly for hard-to-decarbonize sectors such as heavy-duty transportation and industrial heat.

The Province of British Columbia (BC) is already taking steps to accelerate the development and implementation of low-carbon hydrogen as a fuel source, having published the BC Hydrogen Strategy in 2021 outlining the plan to become a world-leading hydrogen economy by 2050 [1]. In order to realize the potential of hydrogen and achieve production and distribution at scale, a deeper understanding of transportation methods, risks, and opportunities within the province is required.

Hydrogen transportation refers to the movement of hydrogen from production sites to end-use locations, where it can be used as a clean energy source. Hydrogen can be stored and transported in a pure gaseous or liquid form known as ‘physical-based’ or ‘material-based’ using liquid carriers. Transportation systems include pipeline, rail, trucks, and ships. Each method has advantages and challenges dependent on factors such as distance, volume, infrastructure availability, and specific application and end-user requirements including demand.

This report examines the different hydrogen carriers available, the existing infrastructure within BC, and opportunities and associated risks for transportation of hydrogen in BC—in particular of liquid carriers via pipeline, road, and rail. Technical, safety, and environmental characteristics, properties, and risks are discussed and opportunities highlighted with recommendations provided for key partners and rightsholders.

Overview of Hydrogen Carriers

Types of Hydrogen Carriers

Pure hydrogen, whether in gaseous or liquid state, offers the potential for a low-emission fuel source but comes with both advantages and drawbacks for storage and transportation. Its compound forms, known as hydrogen carriers, and including methanol, ammonia, and liquid organic hydrogen carriers (LOHC), can facilitate efficient storage and allow for simpler handling and transport since they are either maintained in or occur naturally in liquid state.

The table below lists hydrogen and hydrogen carriers along with their brief descriptions:

Table 1. Hydrogen and Common Hydrogen Carriers.

Hydrogen Carrier	Molecular Formula	General Description
Hydrogen	H_2	Hydrogen is the lightest element and a gas at normal temperature (ambient) and pressure (atmospheric). It is colourless and odourless. It can be stored in either a gaseous or liquid state. Gaseous hydrogen is typically stored under high pressure in cylindrical tanks. Liquid hydrogen is maintained in a liquid state and stored in insulated cryogenic tanks at -253°C (-423°F). [2]
Ammonia	NH_3	Ammonia is an inorganic compound of nitrogen and hydrogen that exists as a gas at room temperature. It is a corrosive, colourless gas with a distinct, pungent, and suffocating odour. [3] Ammonia is usually stored as a liquid under moderate pressure or at low temperature, depending on the pressure and volume. [4] For example, at atmospheric pressure, ammonia is liquid below -33°C. At 25°C, ammonia is liquid at 900 kPag and above.
Methanol	CH_3OH	Methanol is an organic compound and is a colourless, volatile, and flammable liquid. [5] It is a hydrogen-containing compound that is stored and transported in conventional atmospheric containers at ambient temperature. [6]
LOHC	Examples: Toluene ($C_6H_5CH_3$) Methylcyclohexane (C_7H_{14}) Dibenzyltoluene ($C_{21}H_{20}$),	LOHCs are organic compounds that are in a liquid state under ambient conditions. They have the capacity to absorb and release hydrogen through a reversible chemical reaction. LOHCs enable efficient transport of hydrogen and are adaptable to existing infrastructures, as they possess properties similar to those of fossil fuels. [7]

Pure Hydrogen

Pure hydrogen can be transported either in gaseous or liquid form depending on the pressure and temperature. Transporting gaseous hydrogen requires compressing it to high pressures (> 160 barg) to move large quantities. Transporting liquid hydrogen, on the other hand, allows for easier movement of large quantities but requires ultra-low temperatures (-253°C) to keep it in liquid form. Liquefaction energy requirements are typically 10 to 13 kWh/kg of liquid hydrogen (this is around 30% of the low heating value of hydrogen). [8] Additionally, heavy insulation is needed to prevent vaporization during transport. The liquefaction process is energy intensive due to long cooling times needed to reach such low temperatures and may result in a higher environmental footprint due to the electricity requirements. [9] Hydrogen carries risks as it is highly flammable and can cause explosions if not handled and contained properly. This risk is elevated in enclosed spaces due to potential accumulation at high points within a building from leaks. For outside locations, hydrogen easily dissipates in air, so large volumes of stored hydrogen are usually located outside. The colourless and odourless properties of hydrogen mean that leaks are difficult to detect without instrumentation. There are no known effective odorants that can be added to hydrogen that are light enough to diffuse at the same rate as hydrogen. [10] Also, hydrogen odorants are considered a contaminant for fuel cells which are used in fuel cell electric vehicles (FCEVs). Note that natural gas is typically transported without odourization and is odourized before the end user.

The primary benefit of transporting hydrogen in its pure form is that no additional steps are needed before and after transport. In contrast, hydrogen carriers require chemical reactions and potentially further purification to extract the hydrogen.

Ammonia

Ammonia is a common industrial chemical usually produced through the reversible and exothermic Haber–Bosch process that reacts nitrogen with hydrogen in the presence of a catalyst. [11] Nitrogen is typically extracted from air as feedstock for the process.

The reaction equation is:

$$\mathbf{N_2 + 3H_2 \rightleftharpoons 2NH_3}$$

Ammonia can exist as either anhydrous ammonia or aqueous ammonia. Anhydrous ammonia, in its pure form, is a gas that must be compressed under high pressure at low temperature to be converted into a liquid. Aqueous ammonia, on the other hand, is prepared by dissolving ammonia in water.

For ease of hydrogen transportation over long distances, anhydrous ammonia is predominantly used in its liquid state. Compared to hydrogen, the liquefaction process of ammonia is less energy-intensive as it requires less cooling and can be liquified at a much higher temperature. Ammonia requires temperatures of -33°C or colder at atmospheric pressure rather than -253°C which is required for liquid hydrogen. [4] Less than 1% of the stored energy is needed to liquefy ammonia. [12] However, this liquified ammonia readily vaporizes as soon as its temperature increases sufficiently through exposure to heat source or open air.

Liquid ammonia's ability to store and transport large quantities of hydrogen (0.176 kg H_2/kg ammonia), makes it stand out as a highly efficient hydrogen carrier.

From a safety standpoint, ammonia is less flammable than hydrogen. However, it is toxic and can cause damage to the environment and human health. Ammonia is toxic if inhaled in large quantities or ingested. Ammonia released to water, even in small quantities may be harmful to fish and other aquatic species. When released to the air in large amounts, ammonia can have an effect on surrounding areas such as plants and crops where it burns the leaves and can have a toxic effect on livestock [13]. Therefore, ammonia requires stringent management and handling processes.

Ammonia is considered a one-way hydrogen carrier, meaning that it does not revert to its original form as a carrier after the hydrogen has been released. Upon reaching its destination at a hydrogen use facility, ammonia is decomposed to release hydrogen in a process known as "cracking." The nitrogen byproduct is released into the atmosphere. While nitrogen gas is generally considered harmless if released to the atmosphere (air consists of 79% nitrogen), other nitrogen compounds can be harmful such as nitrous oxides potentially posing air quality risks and contributing to climate impacts. Stringent controls, which are already present at ammonia storage and industrial sites, should be used to ensure that the risks of ammonia release and nitrous oxide formation are negligible. [14] This process involves relatively new technology that can be energy-intensive. Depending on the requirements of the end user, additional purification may also be required after cracking.

Methanol

Methanol is a simple alcohol that is a liquid under standard conditions. It is widely used in industry as a solvent, antifreeze, and in the production of other chemicals. [15]

The production of methanol involves the reaction of carbon monoxide (CO) or carbon dioxide (CO_2) and hydrogen (H_2), in the presence of a catalyst, typically copper/zinc oxide. This process is well-established and commercially viable, allowing for large-scale methanol production.

The main reactions are as follows:

$$CO + 2H_2 \rightleftharpoons CH_3OH$$

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$$

Methanol extends its versatility to its role as a carbon-based hydrogen carrier, offering a substantial capacity for hydrogen storage (0.125 kg H_2/kg methanol). Recently, it has become one of the most prevalent methods of hydrogen transport. Unlike pure hydrogen and ammonia, which require high pressures or extremely low temperatures for efficient storage, methanol remains a liquid at standard temperature and pressure. It should be noted that green/renewable methanol production reduces carbon intensity and supports sustainable practices. This includes e-methanol which is produced from CO_2 and low carbon hydrogen, and biomethanol which is produced from biomass. Traditionally, methanol (grey) is produced from natural gas which is converted to syngas (a mixture of H_2, CO_2 and CO) then synthesized to methanol.

For a reduced carbon footprint, the utilization of electrolytic or “green” hydrogen generation or deploying carbon capture and storage (“blue” hydrogen) can be incorporated in the methanol production process. Using biogenic CO_2/CO for the production of methanol would also reduce the carbon footprint. Otherwise, the conventional production method may contradict the goal of reducing carbon footprint and prioritizing sustainable energy sources as it is typically carbon intensive.

LOHC

Liquid Organic Hydrogen Carriers (LOHCs) are a group of compounds that absorb hydrogen as liquids upon contact and can release hydrogen at a later stage. Each step is facilitated by chemical reactions. The reaction occurs under increased pressure and temperature and in the presence of a catalyst. Several LOHCs have been identified, with toluene showing the most promise. Two additional promising LOHC candidates to date are dibenzyltoluene for energy transportation and storage, and N-ethylcarbazole for mobility sector applications as an alternative fuel. [7]

Regardless of the compound being used, hydrogen is added into the organic compound through a hydrogenation reaction at the production site, the LOHC is transported using standard methods of liquid transport, and at the destination site the reaction is reversed (dehydrogenation) to extract the hydrogen.

As an example, the reaction for toluene is shown below, in which it undergoes hydrogenation to become methylcyclohexane (MCH):

$$C_6H_5CH_3 + 3H_2 \rightleftharpoons CH_3C_6H_{11}$$

LOHCs have been shown to be relatively inexpensive and capable of handling large amounts of hydrogen, with toluene being able to hold as much as 56 kg of hydrogen per cubic meter. Additionally, these organic carriers are liquid at room temperature, allowing for transport via standard methods already in use for liquid transport (tanker trucks, rail cars, and potentially pipelines in specific cases).

However, the dehydrogenation process that is required for extraction of hydrogen has been shown to be relatively energy intensive and costs can increase significantly with large-scale use. Production of LOHCs also generates additional emissions.

Properties of Hydrogen Carriers

Table 2. Characteristics Comparison of Hydrogen Carriers

Properties	**Units**	**Hydrogen Carriers**				
		Gaseous Hydrogen	**Liquid Hydrogen**	**Ammonia**	**Ammonia**	**LOHC** (a)
Transportation Phase	-	Pressurized Gas	Cooled Liquid	Liquid (requires pressurization)	Liquid	Liquid
Normal Boiling Point	**°C**	-253	-253	-33	65	101
Volumetric H_2 Content	**kgH_2/m^3**	18.7 (b)	70.8	107.7	99	47.1
Volumetric Energy Density	**MJ/L**	2.24	8.49	12.92	11.88	5.66
Gravimetric H_2 Content	**wt%**	100	100	17.65	12.5	6.1
Gravimetric Energy Density	**MJ/kg**	120(c)	120(c)	21.18	15	7.35
Explosive Limit in Air	**vol%**	4-75	4-75	15-28	6.7-36	1.2-6.7
Flammability/ Toxicity	-	Highly Flammable	Highly Flammable	Toxic	Toxic	Toxic
Method of H_2 Release	-	-	Evaporation	Cracking (>425°C)	Reforming (250°C)	Dehydrogenation (350°C)

Source:
Limitations of Ammonia as a Hydrogen Energy Carrier for the Transportation Sector | ACS Energy Letters [16]
Notes:

- **a.** LOHC properties indicated are those of methylcyclohexane (MCH), the hydrogenated form of toluene, as a representative example for comparison purposes.
- **b.** Estimated from HYSYS at 20°C and 250 barg
- **c.** Hydrogen energy density based on lower heating value (LHV)

Ammonia

The vapour pressure of ammonia at room temperature is 8.9 bar. [3] This relatively low pressure allows for ammonia to be stored in relatively simple, low-cost pressure vessels during transport.

The chemical composition of ammonia and its high gravimetric hydrogen content (weight fraction of hydrogen shown in Table 2) also makes ammonia an extremely effective carrier. The density of hydrogen storage in liquid ammonia has been shown to be more than 45% higher than that of pure liquid hydrogen.

Methanol

While methanol is less effective than ammonia for transporting hydrogen based on density, it is a liquid at room temperature and atmospheric pressure. This allows for simple storage and transport without requiring pressurization. The volumetric hydrogen content of methanol is about 40% higher than that of pure liquid hydrogen.

LOHC

LOHCs exhibit properties similar to crude oil-based liquids like diesel or gasoline and can be stored long-term in the same manner as traditional liquid fuels.

The various LOHCs that have been developed are being evaluated for their applicability in energy storage, energy transport, and mobility applications.

They are considered good candidates for these applications if they have the following characteristic properties: [17]

- Safe during storage, transportation, and usage;
- Low melting point (<-30 °C), to avoid the need for solid-based fuel infrastructure and external addition of solvents;
- High boiling point to simplify the purification of hydrogen and low dynamic viscosity for easy pumping;
- Reasonably high volumetric and gravimetric storage capacities (>6 wt%);
- Hydrogen binding enthalpy of 40–70 kJ/mol H_2 to attain the stability of LOHC molecules and achieve low dehydrogenation temperatures (<200°C at 100 kPa H_2 pressure); and,
- Able to release high-purity hydrogen over long life cycles and avoid alternative decomposition pathways.

Handling of Hydrogen Carriers

A summary of the hazards and transport protocols for hydrogen and hydrogen carriers is listed in the table below.

Table 3. Hazards and Transport Information on Hydrogen Carriers

Parameters	Hydrogen Carriers				
	Gaseous (1,3) Hydrogen	Liquid (2,3) Hydrogen	Ammonia (4)	Methanol (5)	LOHC (MCH)(6)
Transport Hazard Class (7)	2.1 - Flammable Gas	2.1 - Flammable Gas	2.3 - Toxic Gases 8 - Corrosive	3 - Flammable Liquids 6.1 - Toxic Substances	3 - Flammable Liquids
UN Number (7)	UN1049	UN1966	UN1005	UN1230	UN2296
Packing Group (7)	-	-	-	II (medium danger)	II (medium danger)
Reactivity (8)	0	0	0	0	0
Flammability (9)	1	1	1	2	2
Asphyxiant (9)	1	1	-	-	-
Acute toxicity (9)	-	-	3	3	-
Skin corrosion/ irritation (9)	-	-	1	-	-
Serious eye damage/ eye irritation (9)	-	-	1	2	-
Aspiration hazard (9)	-	-	-	-	1
Environmental Hazard	No	No	Yes	Yes	No

Parameters	Hydrogen Carriers				
	Gaseous (1,3) Hydrogen	Liquid (2,3) Hydrogen	Ammonia (4)	Methanol (5)	LOHC (MCH) (6)
Rail Tank Car (10)	Not Listed (21)	113A60W (Cryogenic Liquid Tank Car)	105J500W 112J500W (Pressurized Tank Car)	117J, 117P, 105J, 112J, 114J or 120J (Pressurized Tank Car)	117J, 117P, 105J, 112J, 114J or 120J (Pressurized Tank Car)
Tank Truck (11)	TC 3AXM/ 3AAXM/3T (Compressed Gas Tube Trailer) (12)	TC 338 (Cryogenic Liquid Tank Truck) (13)	TC 331 (High Pressure Tank Truck) (14)	TC 406 (Low Pressure Liquid Tank Truck) (15)	TC 406 (Low Pressure Liquid Tank Truck) (15)
Pipeline Material	low-strength Carbon Steel, and alloy steel (e.g. ASTM A53, A135, A139, A333) (16)	N/A	Low-temperature Carbon Steel (e.g. ASTM A333, API 5L with coating) (17)	Carbon Steel (e.g. ASTM A106, A53, API 5L with coating or lining) (18)	Carbon Steel (19,20)

Notes:

1. Hydrogen, Safety Data Sheet by Airgas [2]
2. Liquid Hydrogen, Safety Data Sheet by Airgas [18]
3. CNESST Data Sheet, Hydrogen [19]
4. CNESST Data Sheet, Ammonia [20]
5. CNESST Data Sheet, Methanol [21]
6. CNESST Data Sheet, Methylcyclohexane [22]
7. Schedule 1, Transport of Dangerous Goods Regulations 2024 [23]
8. Based on National Fire Protection Association (NFPA) rating
9. Based on Workplace Hazardous Materials Information System (WHMIS) classification, with category 1 indicating the highest level of hazard and each subsequent category number (2, 3, and so on) represents a progressively lower level of hazard.
10. TP 14877E, Containers for Transport of Dangerous Goods by Rail, A Transport Canada Standard [24]
11. Part 5 of Transport of Dangerous Goods Regulations 2024 [23]
12. TC 3AXM/3AAXM/3T, designed to CSA B339 [25]
13. TC 338, designed to CSA B620, and insulated highway tank for gases as refrigerated liquids [25]
14. TC 331, designed to CSA B620 for liquefied compressed gases (e.g. LPG, ammonia); made of steel or aluminum. [25]
15. TC 406 designation are low pressure, oval highway tanks used for the transport of most flammable liquids including gasoline, crude oil and diesel. [26]
16. Material Specification Index for Pipelines, ASME B31.12-2023 Hydrogen Piping and Pipelines [27]
17. Material Standards and Specifications & Mandatory Appendix I, ASME B31..4-2019 Pipeline Transportation Systems for Liquids and Slurries [28]
18. Compatibility of Metals & Alloys in Neat Methanol Service, Methanol Institute - Methanol Safe Handling Technical Bulletin [29]
19. Bulk Scale Storage and Transportation of Hydrogen using LOHC, Department for Business, Energy and Industrial Strategy [30]
20. A Rational Approach to Pipeline Material Selection [31]
21. Transport by rail has been identified as a gap by CSA. [25]

Hydrogen

Under normal conditions, hydrogen has a low volumetric density. By compressing or liquefying hydrogen, its density is significantly increased, reducing the storage space required and enabling more efficient transport.

Hydrogen is generally transported in liquid form when large volumes are needed and pipelines are not available. Trucks designed for this purpose, known as liquid tankers, are super-insulated cryogenic tanker trucks.

Storage Requirements

Compressed hydrogen can be stored in cylinders that act as pressure vessels to contain the gas at the required pressure. HTEC uses this method having developed a 450-bar modular hydrogen storage system that is approved by Transport Canada and the US Department of Transportation called the "PowerCube." [32] When multiple cylinders are connected in series using a manifold, they should be supported, secured together, and configured as a single unit using a frame or structure designed for this purpose. All containers must be properly grounded to control static electricity and minimize the risk of ignition. [19]

Safety Precautions

When handling compressed hydrogen, the following precautionary measures must be observed: [2]

- Store hydrogen cylinders in a well-ventilated area, away from sunlight;
- Secure cylinders and containers in an upright position, with all the valves closed when not in use;
- Keep containers away from heat, hot surfaces, sparks, open flames, and ignition sources;
- No smoking;
- Use a backflow protection device in the piping;
- Wear personal protective equipment such as safety glasses with side-shields, chemical-resistant gloves, and anti-static protective clothing;
- Use equipment rated for cylinder/container pressure;
- Do not open the valve until connected to the equipment prepared for use;
- Use only equipment made of compatible materials of construction.

The following are additional safety precautions that must be followed when handling liquid hydrogen:[18]

- See container operating instructions to avoid solidifying air in and blocking vent lines;
- Use and store only outdoors or in a well ventilated place;
- Do not change or force fit connections;
- Do not walk or roll equipment over spills;
- Wear cold insulating gloves and safety glasses with side-shields.

Hydrogen is colourless, odourless, and tasteless, making it difficult to detect with human senses. Hydrogen also burns with a flame that is almost invisible in daylight and has low radiant heat. Gas or flame detectors should be used by emergency responders in the case of an incident.

Ammonia

Storage Requirements

The determining factors for the type of ammonia storage method required are capacity and economics. For low storage volume requirements, pressurized tanks are more economical than other methods. Storing large amounts of ammonia will require either semi-refrigerated storage or low-temperature storage. [4]

Table 4: Characteristics of Ammonia Storage Methods

State	Type	Typical Pressure, bar	Design Temperature, °C	Capacity, t Ammonia	Refrigeration Compressor
Liquid	Pressure storage	16-18	20-25	≤ 1,500	None
Liquid	Semi-refrigerated storage	3-5	~ 0	450-3,000	Single-stage
Liquid	Low-temperature storage	1.1-1.2	-33	4,500-45,000 (<50,000)	Two-stage

Pressure storage vessels for ammonia at ambient temperature are similar to the low-pressure vessels for liquefied petroleum gas (LPG). They can be cylindrical or spherical depending on the desired storage capacity. Cylindrical containers are used for up to 150 tonnes, while spherical stationary containers can store 250-1,500 tonnes. These vessels are protected from overheating by insulation, paint, or a water spray.

Semi-refrigerated storage allows for keeping refrigerated liquid ammonia at the moderately low temperature of about 0°C and pressure of about 3-5 bars in an insulated container. The storage vessels, which are typically spherical, can have capacities of up to 3,000 tonnes. The refrigeration system is simple, using only a single-stage compressor for ammonia vapour and water for cooling.

Low temperature storage for ammonia typically requires cylindrical, insulated tanks with a flat bottom and a domed roof. The operating temperature is -33°C at slightly above atmospheric pressure. Stationary container capacity can range from 4,500 to 45,000 tonnes. The refrigeration unit for these containers usually involves a two-stage ammonia compressor.

Although single-shell tanks can be used for ammonia storage, addressing the leak hazards requires the use of vapour-tight insulation, strict adherence to standards, and high maintenance. Double-walled tanks offer extra protection as they have an inner tank designed for the storage temperature and pressure, and an outer shell (tank) to contain any ammonia leakage.

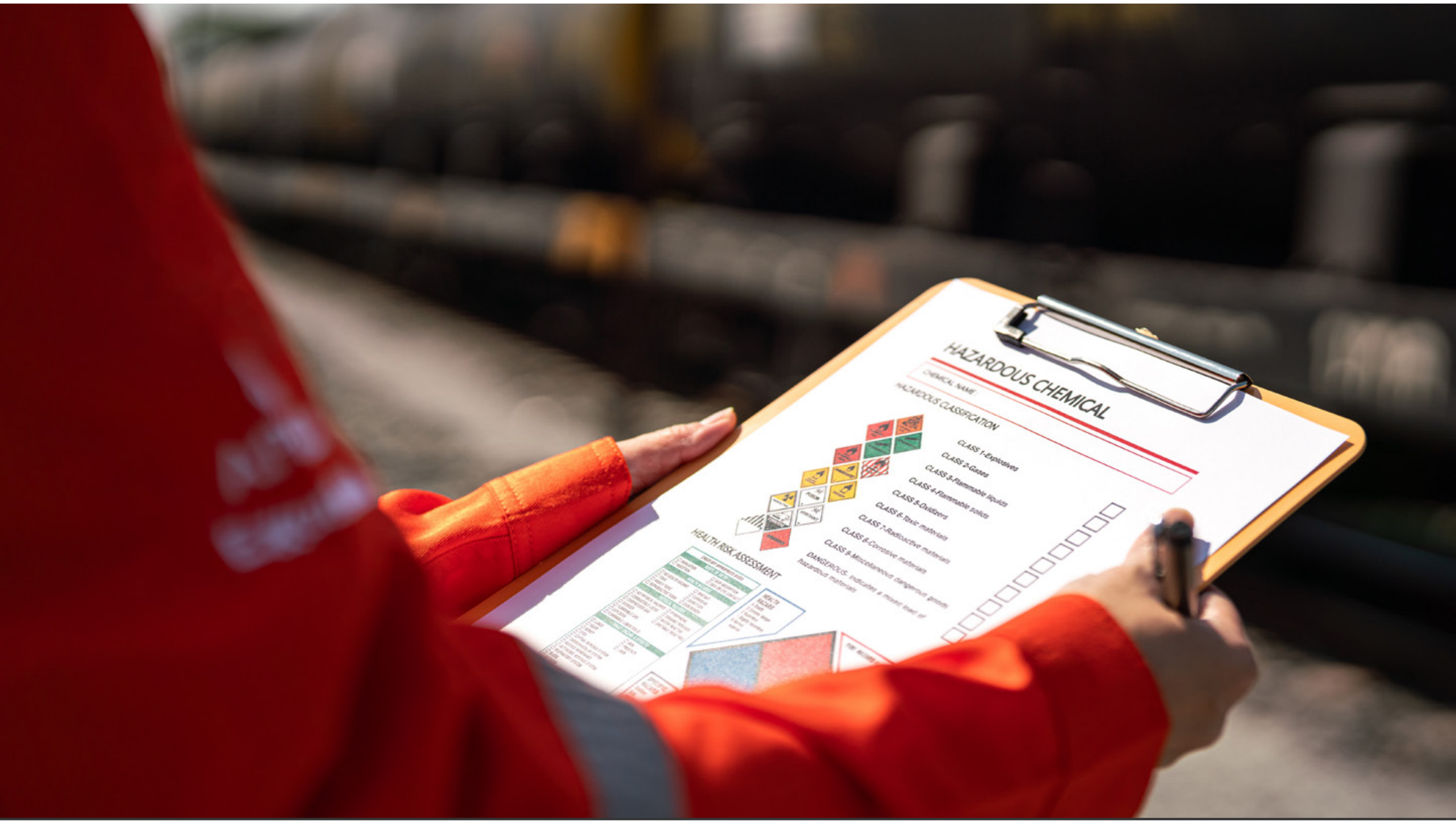
High-strength or fine-grained steels are commonly used for ammonia storage vessels, but these materials can be prone to stress corrosion cracking. To prevent this, it is essential to maintain at least 0.2% water content in the ammonia and apply cathodic polarization (e.g., aluminum or zinc metal spray coating).

In ammonia transfer lines, stainless steel is preferred due to its high corrosion resistance, although it is relatively expensive. Materials like copper, zinc, and aluminum should not be used, as they are easily corroded by ammonia.

Safety Precautions [3]

Personnel handling ammonia need to observe these precautionary measures:

- Store ammonia in accordance with local, regional, national, and international regulations;
- Store ammonia in a cool, well-ventilated area with containers tightly closed and sealed until ready for use;
- Secure cylinders and containers in an upright position, with all the valves closed when not in use;
- Keep containers away from heat, hot surfaces, sparks, open flames, and ignition sources;
- Provide adequate ventilation in the work area;
- Wear protective equipment such as splash-proof chemical safety goggles, chemical-resistant gloves, boots, and thermal protective clothing;
- Wear an approved respirator if engineering controls do not maintain airborne concentrations below recommended exposure limits or acceptable levels;
- Do not eat, drink, or smoke in areas where ammonia is handled, stored, or processed;
- Ensure eyewash stations and safety showers are available in the immediate vicinity;
- Wash hands thoroughly after handling.



Methanol

Storage Requirements [33]

Methanol is typically stored in above-ground tanks with grounding to prevent ignition resulting from static discharge (note: transport vessels must be grounded before loading or unloading). Generally, the same guidelines for gasoline storage can be applied to methanol. Nitrogen or natural gas padding can be used to suppress possible ignition. A tank farm is a specialized facility designed for bulk storage of chemicals, consisting of aboveground storage tanks that safely hold large quantities. The stationary methanol tank farm is designated as a hazardous area and equipped with appropriate protection in the forms of leak detection, containment, and fire suppression foam.

All piping and valves carrying methanol must be clearly labeled, with the direction of flow indicated. All storage containers, including totes and drums, require berming for spill containment to prevent the spread of methanol to other areas. Berming can be made of compacted soil, methanol-resistant fabric, or concrete but may not be made of hydrocarbon residue, asphalt, and road oil that can be dissolved by methanol. Adequate ventilation must be ensured to prevent the accumulation of methanol vapours within the bermed area. Regular inspection and maintenance are necessary to ensure the berm remains effective over time.

At docks and marine terminals, storage facilities for methanol usually consist of floating roof tanks specifically dedicated to methanol handling. Internal floating roofs are preferred to avoid contamination. These facilities may be equipped with leak detection systems, alarms, appropriate suppression and spill response capabilities equivalent to those in tank farms.

For low-volume applications, methanol can be stored and transported in totes, drums (55 gallons), and cans (5 gallons and 1 gallon). This non-bulk storage and transport of hazardous material may be subject to local regulations and requirements. [34] In Canada, the Transportation of Dangerous Goods (TDG) Regulations set the requirements for small and large containers of dangerous goods, such as methanol and ammonia. This is discussed in further detail in the existing regulatory framework section below. The recommended materials compatible with methanol, based on structural strength, corrosion resistance, types of corrosion, and life cycle cost, are carbon steel or austenitic stainless steel (300 series, such as ASTM 304, 304L, 316, or 316L) for piping and tanks—low-alloy steels for piping and aluminum alloy for floating roofs on storage tanks. [29]

Safety Precautions [5]

These precautionary measures must be taken by personnel handling or exposed to methanol:

- Wear protective gloves/protective clothing/eye protection/face protection;
- Do not eat, drink, or smoke when handling this product;
- Store and use away from heat, hot surfaces, sparks, open flames, and ignition sources;
- Use appropriate containment to avoid environmental contamination;
- Provide ventilation for containers;
- Do not enter storage areas and confined spaces unless adequately ventilated;
- Use explosion-proof electrical (ventilating, lighting, and material handling) equipment;
- Wash skin thoroughly after handling; and,
- Keep containers tightly closed when not in use.

In case of fire, responders should be equipped with infrared devices for remote heat and relative temperature detection as methanol's non-luminescent flame may be invisible in bright sunlight. [33]

LOHC

Storage Requirements

Requirements may vary depending on which type of organic carrier is being used. MCH is typically stored in sealed drums and must be kept in a cool location with proper ventilation. Ignition sources and open flames should be avoided.

Safety Precautions [35]

Personnel handling MCH must adhere to these precautionary measures:

- Store MCH in accordance with local, regional, national, and international regulations;
- Store in a cool, well-ventilated area with containers tightly closed and sealed until ready for use;
- Keep containers away from heat, hot surfaces, sparks, open flames, and ignition sources;
- Use personal protective equipment (PPE) including gloves, safety goggles with side protection, flame-retardant protective clothing;
- Follow proper disposal methods;
- Do not eat, drink, smoke when handling this chemical; and,
- Use explosion-proof equipment.

Existing Regulatory Framework

In Canada, the TDG Regulations govern the transportation of dangerous goods via road, rail, air, and water. This includes hydrogen and hydrogen carriers including ammonia, methanol and LOHC. The classification of a substance as "dangerous goods" is determined by the TDG Regulations, which are aligned with the United Nations' recommendations. There are nine TDG hazard classes, class 2 includes gases and class 3 includes flammable liquids. [36]

The following are the classification of hydrogen and hydrogen carriers:

- **Hydrogen:** refrigerated liquid: Class 2.1
- **Ammonia:** anhydrous and > 50% solutions (aqueous ammonia): Class 2.3
- **Ammonia:** 35% to 50% solution (aqueous ammonia): Class 2.2
- **Methanol:** Class 3
- **Toluene:** Class 3

The Transportation of Dangerous Goods Act, 1992 [37] and the Transportation of Dangerous Goods Regulations [23] were established to ensure the safety and security of people, property, and the environment during the transportation of dangerous goods specifically by road and railway. An amendment to the TDG Regulations on Site Registration Requirements was published by Transport Canada in October 2023, requiring all entities that transport or handle dangerous goods to register their site and provide information to the regulator regarding the dangerous goods being handled and operations.

The federal dangerous goods regulations focus on all modes of transportation and movement between jurisdictions and there are also provincial regulations. The BC Transport of Dangerous Goods Act adopts the federal regulations for transportation of dangerous goods on BC highways, including provincial ferry routes. [38] Agreements are often entered into with the federal government on administration and enforcement of these regulations.

The Canadian General Standards Board (CGSB) has released the draft of Safety Standard CAN/CGSB-43.150 that sets out the requirements for design, manufacturing and use of UN Standardized drums, jerricans, boxes, bags, combination packaging, composite packaging and other packaging for the transport of dangerous goods, classes 3, 4, 5, 6.1, 8, and 9. A consultation period took place from August 28, 2024 to October 28, 2024 with the new edition to come into force once published with a six-month phase-in period.

The TDG Act of 1992 requires that an Emergency Response Assistance Plan (ERAP) be in place. An ERAP is prepared by the consignor or entity transporting or handling the dangerous goods and must be submitted to Transport Canada for approval. It provides guidance on what to do in the event of a release or anticipated release of higher-risk dangerous goods, such as hydrogen, ammonia, methanol, and toluene during transport. It includes a list of specialized personnel and equipment required for emergency response, as well as examples of response actions where these resources may be used.

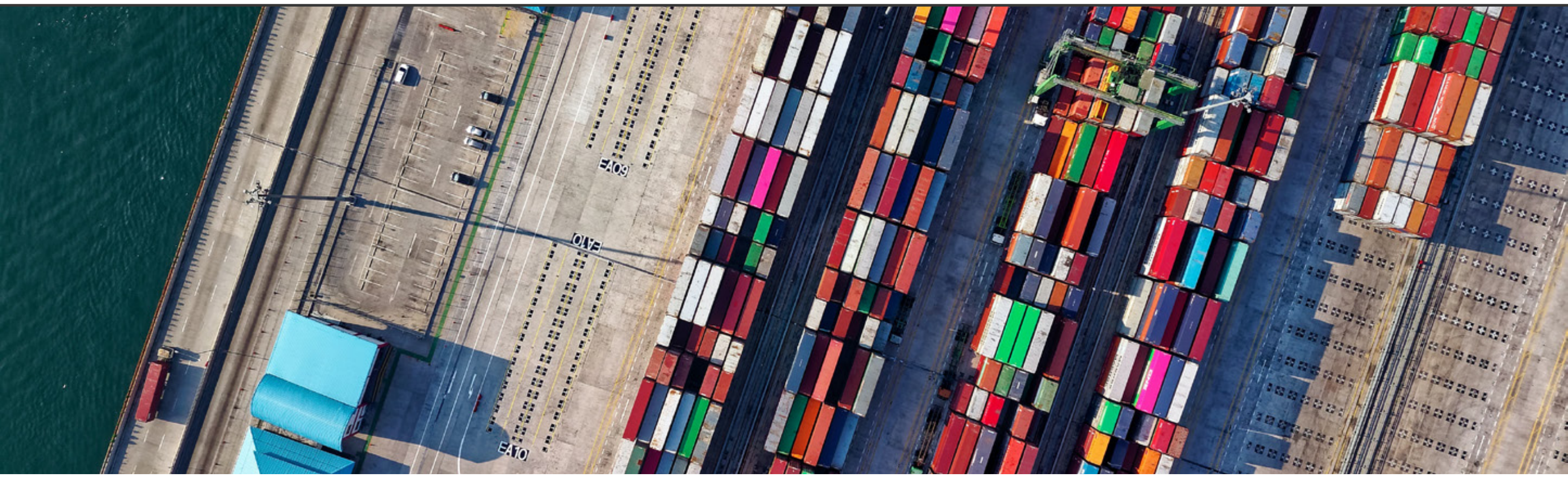
Railway carriers are required to report any threats or security concerns to Transport Canada's Situation Centre. This reporting is part of Transportation of Dangerous Goods by Rail Security Regulations. The reports received will be used in analysis and investigations to determine if there is a potential threat to national security that would affect Canadian transportation systems.

Pipelines, facilities, and related activities involving hydrogen, ammonia, and methanol are regulated by the British Columbia Energy Regulator (BCER) under the Energy Resource Activities Act (ERAA) passed in 2022. This is in addition to BCER's existing oversight of oil and gas projects. The Pipeline Regulation includes, among other requirements, pipeline design standards, post-construction requirements, integrity and damage prevention programs, and records of spillage, damage, and malfunction. Additional regulations/acts that may be applicable to hydrogen transportation in BC are shown in Table 5:

Table 5: Applicable regulations/acts for hydrogen transportation in BC

Jurisdiction	Regulation or Act
Federal	The Canada Shipping Act
	The Railway Safety Act
	Canadian Energy Regulator Onshore Pipeline Regulations
	Ammonia Code of Practice
Provincial	BC Railway Safety Act
	BC Transportation Act
	BC Spill Reporting Regulation
	Motor Vehicle Act
	Commercial Transportation Act
	Safety Standards Act
	Energy Statutes Amendment Act
Municipal	Highways Bylaw
	Zoning Laws
	Local Safety Standards

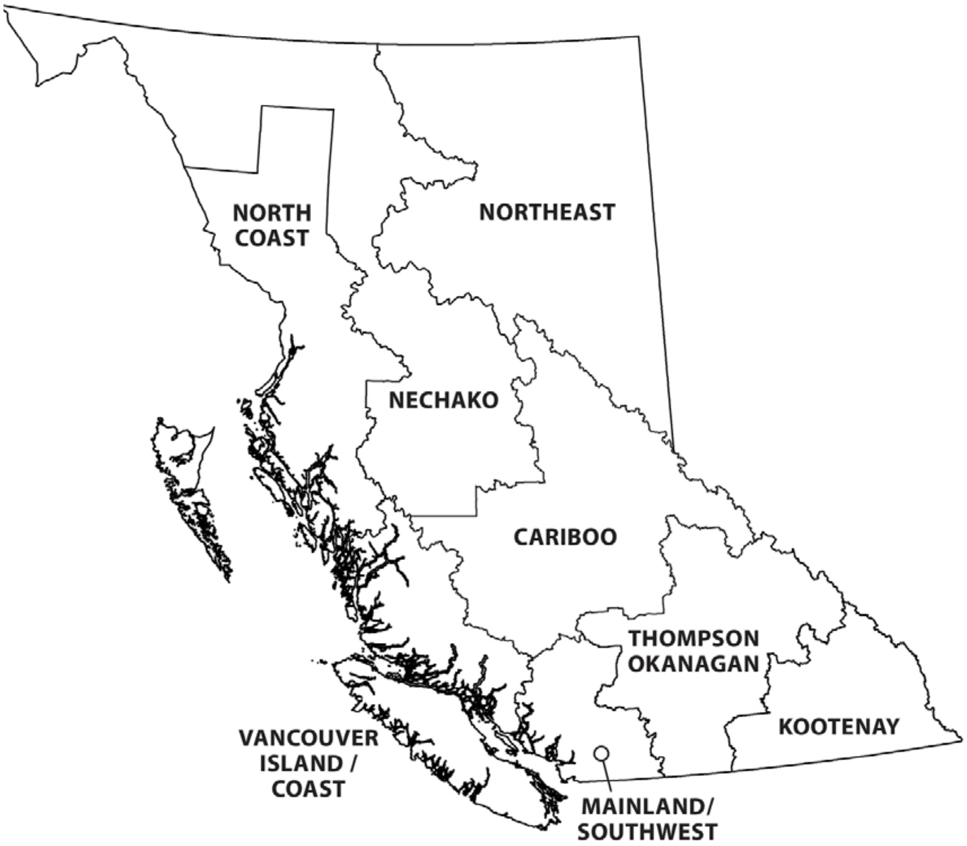
There can be specific regional requirements but these are not addressed within this document. [25]



Examination of Existing Infrastructure

This section examines the availability of existing pipeline, rail, and highway infrastructure in BC within the eight distinct economic regions of the province. [39]

Figure 1: Economic Regions in BC. Source: bc.ca



Pipeline

Hydrogen can be transported via existing or new pipelines, either as pure hydrogen or blended into natural gas (sometimes called hythane). LOHC, ammonia, and methanol also have the potential to be transported by pipeline. Existing pipelines need to be evaluated for suitability of material, equipment, instrumentation and associated piping components as part of a management of change process. An overview of existing transmission gas pipeline infrastructure is provided below.

Existing Gas Pipeline Infrastructure

The existing pipeline network across BC is diverse and includes pipelines that are provincially and federally regulated. According to the BCER, provincially regulated pipelines are predominantly natural gas (75%), with around 10% transporting oil and some transportation of other gases and liquids associated with oil and gas production (15%). [40]

Figure 2: BC gas transmission pipelines. Source: FortisBC.

Vancouver Island/Coast

There are existing pipeline routes on the east side of Vancouver Island from Campbell River to Victoria and a pipeline crossing the Georgia Strait at Courtenay to Powell River. On the west side of Vancouver Island, and in the coast region of the mainland, there is limited existing pipeline infrastructure. FortisBC is planning a 47 kilometre expansion of an existing natural gas pipeline to service Squamish, the Sunshine Coast, and Vancouver Island. [41]

Mainland/Southwest

Within Vancouver and the Lower Mainland areas of Richmond, Surrey, and Abbotsford there is well-established pipeline infrastructure. A major pipeline runs north from Vancouver to Squamish and Whistler, and Enbridge's BC Pipeline (the Westcoast Pipeline) runs from Fort Nelson in northeastern BC to the southern coast through this region. [42]

Thompson-Okanagan

Across the Thompson-Okanagan region, the FortisBC natural gas network operates predominantly around Kelowna and Kamloops. Further increase in LNG capacity within the region is planned with the Okanagan Capacity Mitigation Project to meet growing demand. The project will involve constructing a small-scale LNG facility in Kelowna, supplied by LNG produced at FortisBC's Tilbury facility. [43]

Kootenay

The TransCanada Foothills Pipeline runs through the Kootenay region, south of Cranbrook, transporting natural gas from Alberta to markets in BC, Saskatchewan, and the US. The Foothills Zone 8 West Path Delivery was completed as part of the Foothills system in BC to support growing markets in the south of the province. [44] The FortisBC natural gas distribution system also operates within the region.

Cariboo

Enbridge's BC Pipeline runs through the Cariboo region near Prince George and there are distribution systems as part of the FortisBC network within the region.

North Coast

The Pacific Northern Gas Transmission Pipeline runs through the North Coast region from Prince Rupert and Port Edward towards Summit Lake with connections to Kitimat and Smithers. [45] The Coastal GasLink Pipeline is a 670 km pipeline that connects gas resources from the Montney Basin at Dawson Creek in northeast BC to Kitimat. [46]

The Prince Rupert Gas Transmission pipeline is proposed to carry natural gas from the northeast of BC to Ksi Lisims near the Nass River estuary in northwest BC. The Pacific Trails Pipeline is also a proposed 471 km pipeline that would deliver natural gas to the Kitimat area from Summit Lake. [47]

Nechako

There are few major pipelines within the Nechako region which may be due to the small population and focus on industries such as mining, forestry, and agriculture rather than oil and gas. Part of the Coastal GasLink Pipeline runs through this region and the proposed Prince Rupert Gas Transmission would also run through the region.

Northeast

The northeast of BC is a major natural gas-producing area with significant reserves in the Montney Basin. Enbridge's BC pipeline transports natural gas from Fort Nelson to markets in the south of BC and the US. The TransCanada Foothills Pipeline also passes through the northeast region and the Coastal GasLink Pipeline and Prince Rupert Gas Transmission pipeline would further increase the region's pipeline infrastructure.

Potential Upgrades Required for Pipeline Infrastructure

The potential upgrades to pipelines and demand for new pipeline infrastructure will be determined by variables such as the form of hydrogen, and location of production sites and end users.

Hydrogen/Hydrogen Blending

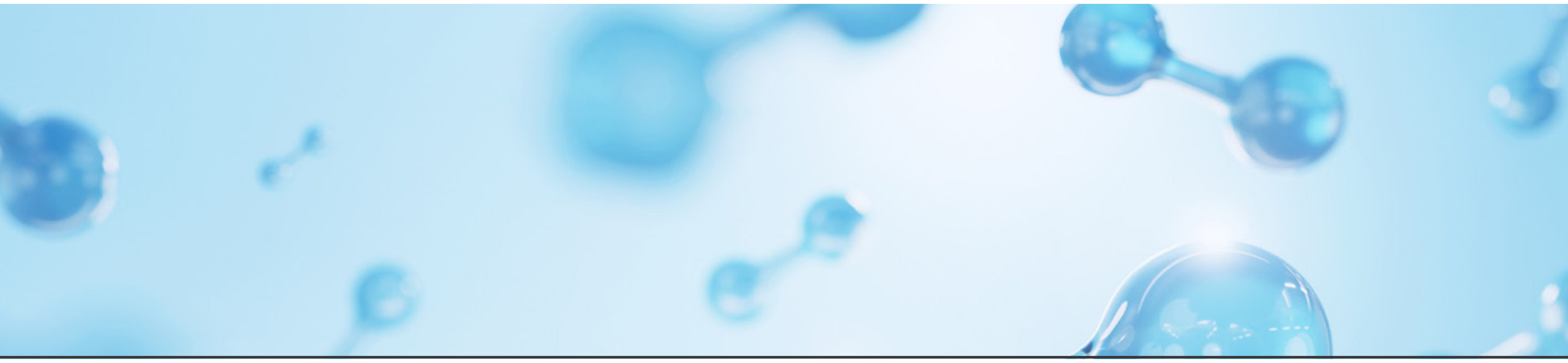
Hydrogen transportation via existing pipelines is considered to be a cost-effective solution as it removes high capital costs associated with building new infrastructure. However, there are mechanical and safety considerations depending on the condition of the existing infrastructure and the desired end use of the hydrogen.

The research demonstrates several challenges with transporting pure hydrogen in existing pipelines, notably:

- Hydrogen permeation/leakage is an issue as hydrogen can permeate and diffuse into the crystal lattice structure of pipeline material.
- The presence of sufficiently high hydrogen pressures and concentrations within the pipeline material can lead to embrittlement, which compromises the pipeline's integrity.

As such, transport of pure hydrogen via pipelines will require significant infrastructure upgrades, with new pipelines designed to account for these issues. In addition, hydrogen compression technology, which would be required to prepare hydrogen for pipeline transport, is expensive.

Pipelines can also be used to transport blended hydrogen, which involves mixing a certain percentage of hydrogen into natural gas in pipelines. Research has shown that, subject to detailed engineering study of the specific pipeline material and the pipeline's operational history, 1-20% hydrogen by volume can be injected into natural gas pipelines with no major safety or operational concerns (noted projects: HyDeploy2 (UK), [48] GRYHD (France), [49] ATCO (Canada), [50] and Enbridge (Canada) [51]). Further studies have suggested that there may also be a risk of hydrogen embrittlement associated with this process, particularly for old gas pipelines subjected to long-term hydrogen service. [52] FortisBC is working with industry partners and undertaking an ongoing hydrogen blending study to examine how to safely integrate hydrogen into the existing natural gas pipelines. [53]



Hydrogen embrittlement is a process in which a material's mechanical properties are weakened due to its interaction with hydrogen. Hydrogen is absorbed into the equipment or piping material, reducing its ductility, toughness, and tensile strength. This embrittlement can cause failure of equipment and pipelines used in hydrogen services.

The susceptibility of industrial equipment to hydrogen embrittlement is influenced by three key factors: [54]

1. Operating environment, defined by temperature, pressure, and hydrogen concentration
2. Material or metal used, with its composition, strength, and microstructure
3. Load type, whether static or dynamic (subject to cyclic pressure fluctuations) [54]

For hydrogen blending, CSA Z662 Canadian Oil & Gas Pipeline Standard requires engineering assessments as part of a management of change process. Some existing services may have limitations on blending amounts. The detailed engineering assessment may recommend that additional measures are required before hydrogen is introduced to the pipeline, such as the application of internal coatings, inhibitors, or installing a new carrier pipe within the existing pipeline. To deal with hydrogen embrittlement, options such as continuous monitoring to detect and track crack growth, as well as reducing operational pressure variations may also be required. [55]

Hydrogen Carrier Pipelines

Ammonia, methanol and LOHC can also be transported by pipeline, and would not have the same hydrogen embrittlement challenges as pure hydrogen. However, an engineering assessment would be required, which could impose additional requirements similar to those listed above for pure hydrogen use, or may require development of new pipelines. Studies highlight that methanol and ammonia are currently distributed for use in industrial and agricultural sectors by pipeline but the extent of existing infrastructure in BC is unclear. [56,57] Exolum is also testing the use of a repurposed oil pipeline to transport LOHC in the UK between the Immingham East and West facilities via a 1.5 km pipeline. [58]

Truck

Hydrogen transport by truck would require minimal changes to existing infrastructure. For gaseous transport, tube trailers are widely used, at hydrogen pressures of 180-500 bar, with newer systems capable of over 900 bar. One example is HTEC's "PowerCube" modular gaseous hydrogen storage system that uses high-pressure aluminum and carbon composite wrapped cylinders. [32] In these scenarios, hydrogen production facilities would need to install compression equipment, which face the same challenges as mentioned earlier regarding cost.

Liquid transport of pure hydrogen is also feasible with highly insulated tanker trucks. This method is more energy intensive but allows for a single truck to carry a larger mass of hydrogen than a gaseous tube trailer.

Ammonia is commonly transported by truck but requires special safety precautions due to its hazardous nature. LOHC and methanol can also be transported by truck and are generally compatible with existing liquid fuel infrastructure.

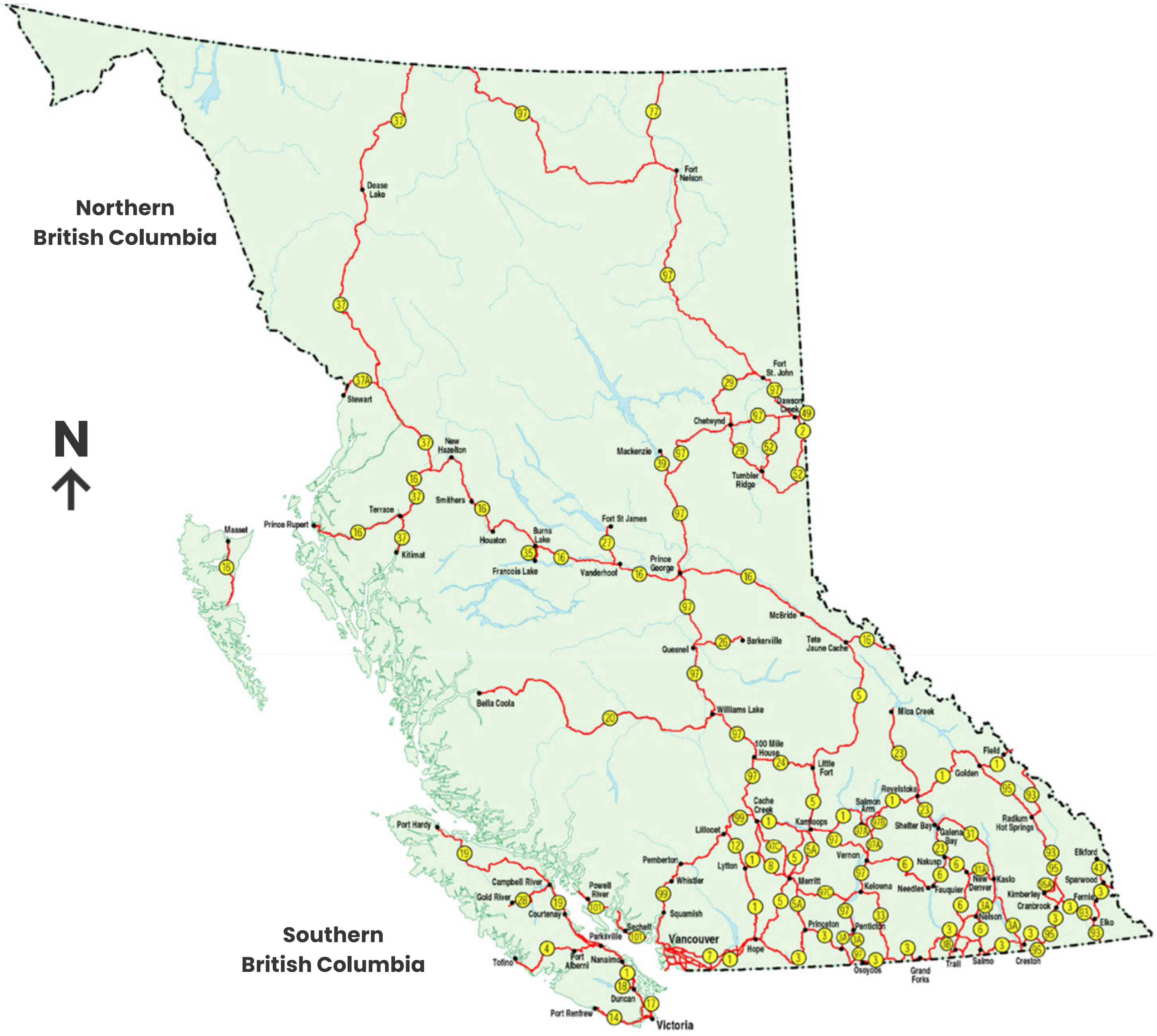
There are weight limits and size specifications for vehicles that are set by the TDG safety standards based on the type of dangerous goods being transported. The CSA B620 standard sets out the requirements of highway tanks (tank trucks) and portable tanks for the transportation of dangerous goods.

Some major highway routes within BC are susceptible to extreme weather events and have been impacted by flooding and landslides. This is discussed further in the risk analysis section.

Existing Highway Infrastructure

There is well-established existing highway infrastructure across BC. Figure 3 shows major highway routes in the province.

Figure 3: Major highway routes in BC. Source: [bc.ca](bc.ca)



Vancouver Island/Coast

There are several major highway routes on Vancouver Island, the main north to south routes are Highway 1 connecting Victoria to Nanaimo, and Highway 19 connecting Nanaimo to Port Hardy via Campbell River. Highway 4 connects Nanaimo to Port Alberni and Tofino. Highway 101 connects the Sunshine Coast from the ferry terminal at Langdale through Gibsons, Sechelt, and Powell River.

Mainland/Southwest

There are many major highway routes within Metro Vancouver and the mainland/southwest region. Highway 1 (Trans-Canada Highway) runs east to west through Vancouver, Burnaby, and the Fraser Valley, and Highway 7 runs parallel to Highway 1 to Hope. Highway 99 runs north to south from the US border through Richmond and Vancouver to Lillooet via Whistler and Pemberton. Within the Lower Mainland several key routes include Highway 17 that extends to Delta and Tsawwassen, Highway 91 running from Delta to connect with Highway 1, and Highway 10 running from Highway 1 in Surrey to Highway 99 in Delta.

Thompson-Okanagan

In the Thompson-Okanagan region, Highway 1 is a crucial east to west route that passes through Kamloops and connects the region to Vancouver in the west and the rest of Canada in the east. Other notable routes include Highway 5 (Coquihalla Highway) which intersects with Highway 1 in Kamloops, providing a north to south route, and Highway 97 which is also a north to south route connecting the Okanagan Valley to other parts of BC. The Coquihalla Highway is a critical route in BC but is susceptible to extreme weather events and has previously been impacted by atmospheric rivers in 2021, where flooding and mudslides damaged infrastructure. [59] Winter conditions such as extreme snow and wind can also pose hazards for drivers.

Kootenay

In the Kootenays, Highway 3 (Crowsnest Highway) is a major east to west route through the southern interior of BC, connecting to Alberta. Highway 93 runs from the Canada-US border at Roosville, passing through Cranbrook and Kootenay National Park to the BC-Alberta boundary. Highway 95 extends from the Canada-USA border at Kingsgate to the junction with Highway 1 at Golden.

Cariboo

Highway 97 (Cariboo Highway) is a major north to south route through the region, and Highway 26 runs east from Quesnel to Barkerville Historic Park.

North Coast

Highway 16 (Yellowhead Highway) is a major east to west route that runs through the northern part of BC from Prince Rupert to Alberta. Highway 37 (Stewart-Cassiar Highway) is a crucial north to south route traversing northern BC from Kitimat. Due to the remoteness of this region, terrain can be challenging for truck transportation.

Nechako

Highway 37 continues into the Nechako region and connects BC to the Yukon. Highway 16 is a primary east to west transportation link from Smithers in the northwest to Vanderhoof in the southeast. The region has areas of remote wilderness—there may be requirements for secondary roads and resource roads to reach specific destinations.

Northeast

Highway 97 is a north to south highway that runs the entire length of the province, connecting the Canada-US border in the south to the BC-Yukon boundary in the north. The northernmost section travels through wilderness connecting Fort St John and Fort Nelson, and the highway is a primary link to the Northwest Territories and the Yukon.

Potential Upgrades Required for Highway Infrastructure

In regions with existing highway infrastructure, particularly in the south of the province, there would be minimal upgrades required to support hydrogen transportation. Supporting storage and refueling infrastructure would be required across the province. Some road upgrades may be required, depending on the location of production sites and end-users, to ensure a robust and reliable supply chain, particularly in more remote regions.

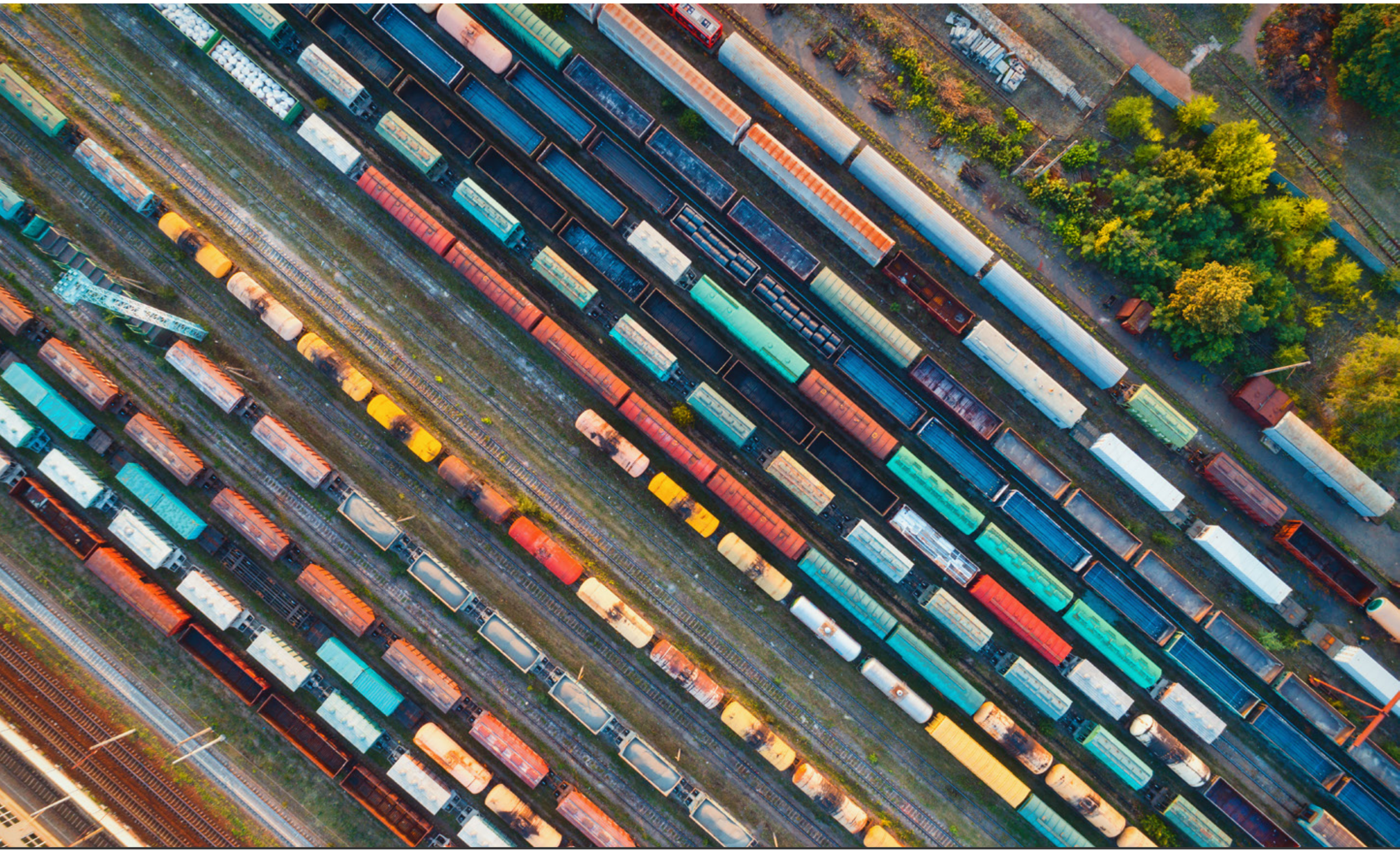
Rail

Hydrogen

Similar to truck transport, rail allows for hydrogen transportation in either gaseous or liquid forms with pressurized tube trailers being used for gaseous transport and insulated tankers used for liquid transport. A study by the Canadian Standards Association (CSA), [25,60] recommended that new standards should be developed and account for the design of hydrogen tender cars, transport by ISO containers, and applicability of existing liquefied natural gas rail cars design requirements for hydrogen transport. In comparison to truck transportation, rail is much more effective in transporting large volumes.

Ammonia/Methanol/LOHC

Ammonia is transported by railway, often in specialized bulk containers with specific safety standards, primarily for agricultural applications. Tanks can be 1,000 or 1,500 gallon and are generally constructed of steel. The tanks can have specific valves to safely release any trapped ammonia liquid or vapours and can be painted white to reflect sunlight and avoid heating. The CSA has guidance on the selection and use of portable tankers for transporting dangerous goods, including anhydrous ammonia. Similarly, methanol is transported by railway in specialized tank cars and LOHC can also be transported by railway.



Existing Rail Infrastructure

Railway infrastructure in BC is predominantly focused in the south although there are railway lines and connections in the north. Figure 4 shows existing railway infrastructure in the province.

Figure 4: Railways in BC. Source: railcan.ca

Vancouver Island/Coast

The Southern Railway of Vancouver Island freight railway on the east of the island from Victoria in the south is no longer operational. Seaspan operates a freight ferry from Nanaimo to Vancovuer. There is one operational part of the railway line from the freight ferry yard to Superior Propane in Nanaimo, but there is no other railway infrastructure inland and to the east of Vancouver Island and in the coastal mainland areas north of Vancouver.

Mainland/Southwest

This region has an extensive rail network with major hubs in Vancouver, Surrey, and Abbotsford connecting to the Port of Vancouver. Canadian National Railway (CN) operates a freight and passenger railway from Vancouver north to Lillooet via Squamish, Whistler and Pemberton. There are CN and Canadian Pacific Railway (CP) routes running east along the Fraser Valley to Hope and continuing north.

Thompson-Okanagan

Kamloops is a key rail connection served by CN and CP freight and passenger routes. CP routes continue east and CN routes north to Valemount. There are no operational railways serving Kelowna and the south of this region.

Kootenay

There are several CP tracks in operation in this region including connections at Castlegar and Cranbrook. There are connecting lines to the BC-Alberta border.

Cariboo

CN operates in the Cariboo region, with a north to south line running from Vancouver via Quesnel to Prince George, although this is lightly used by CN. The main line runs north from Kamloops through Valemount and on to Prince George. Prince George serves as a major rail hub and connection point for northern routes and is important for resource transportation.

North Coast

CN operates in the north coast region with important rail terminals in Prince Rupert and Kitimat. The railway connects to the Port of Prince Rupert with a ship-to-rail container terminal. There are no railway lines further north within the North Coast region.

Nechako

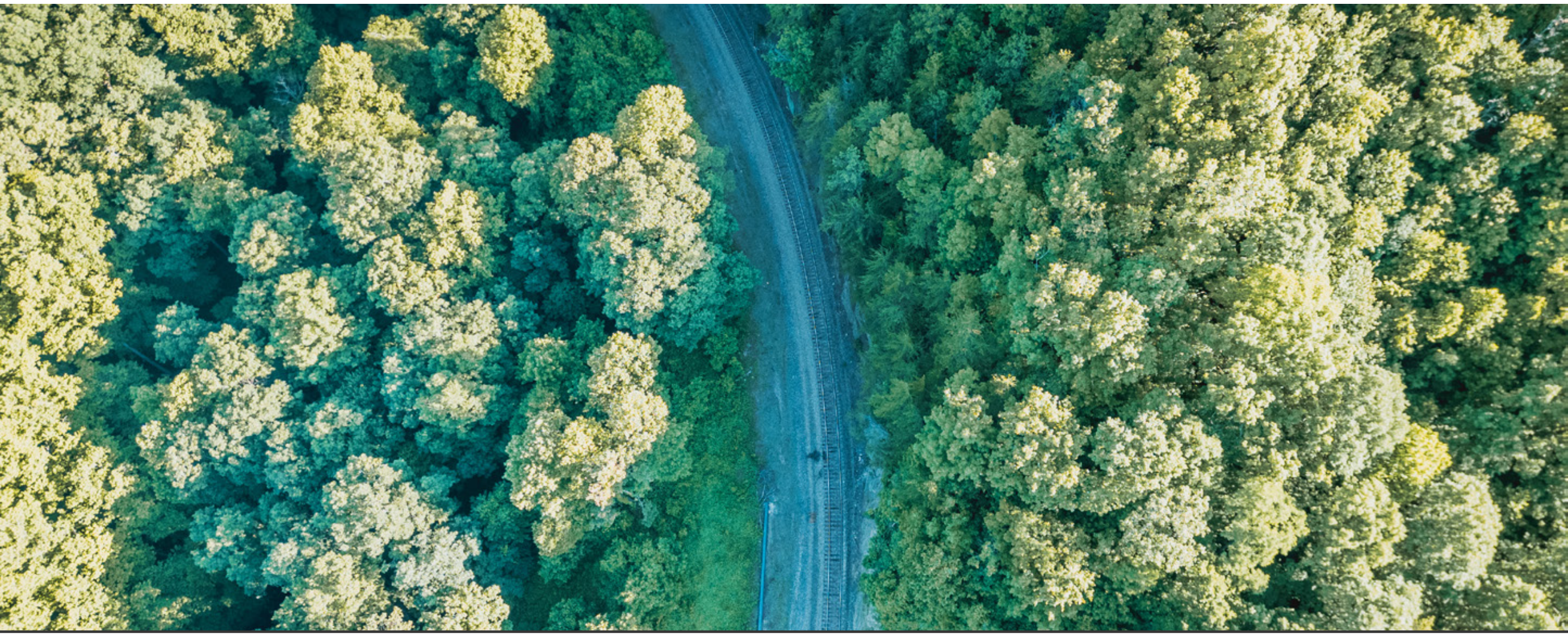
There is some rail infrastructure towards the south of the Nechako region, with a CN service that runs west to east from Kitimat via Burns Lake and Fraser Lake to Prince George. There is no rail infrastructure in the northern areas of this region.

Northeast

The CN line serves this region with a north to south route to Fort Nelson and rail connections in Fort St John, and Dawson Creek. Chetwynd has rail lines entering from three directions. There is also rail connecting Prince George to Fort St James, although this rail line is lightly used.

Potential Upgrades Required for Railway Infrastructure

Some areas within BC, such as the northern regions, have limited railway infrastructure and connections. In general, this will act as a constraint on possible locations where rail transport of hydrogen is feasible, as the cost of new railways is likely prohibitive. In locations where existing rail infrastructure is available, upgrades would be required to accommodate the transportation of dangerous goods, depending on the location of the track. When transporting dangerous goods, there are more requirements for the state of the track, which is dependent on the speed of the trains travelling on the track. Main lines may require less upgrades than branch lines. Upgrades will be location specific, based on the dangerous goods, as well as the speed and general operation of the train itself. Other factors include operator training, safety features, topography and geography. Loading and unloading infrastructure and safety modifications would also be required. Railcars would need to be adapted to meet standards, and additional processes in place to adhere to the TDG Regulations such as providing emergency response plans, increased track inspections, training requirements and documentation.



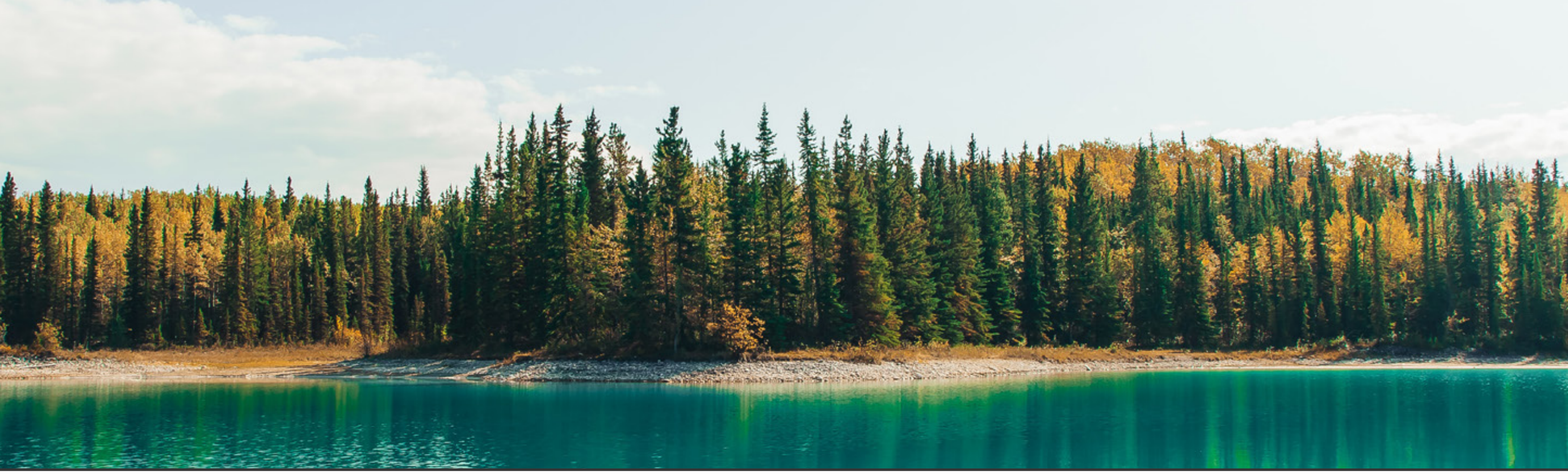
Assessment of Hydrogen Carriers and Infrastructure

Several criteria need to be taken into consideration when selecting a hydrogen carrier. From a transport standpoint, methanol or LOHCs are likely the simplest solutions as they do not require prior compression and do not need to be stored in insulated vessels during transport. However, methanol, ammonia, and LOHCs must undergo a reaction to carry the hydrogen, and that reaction must be reversed after arriving at the destination. This requires energy, adds cost, and increases the overall complexity of the process in comparison to transporting pure hydrogen.

When it comes to transportation density, ammonia and methanol are comparable at 108 kgH2/m^3 and 99 kgH2/m^3, respectively. This means that slightly more hydrogen can be transported per meter cubed of ammonia than methanol. However, this efficiency is significantly higher in both of these carriers than what is achievable with pure hydrogen transport (18.7 and 71 kgH_2/m^3 for gaseous and liquid hydrogen, respectively), or with LOHCs (47 kgH_2/m^3).

Environmental and Social Impact

Each carrier option poses its own risks when it comes to health, safety, and environmental impact. Ammonia, methanol, and LOHCs are all toxic to varying levels. Ammonia is potentially the most damaging to the environment and human health, and as such industry has been shifting to methanol, particularly when it comes to marine transport, as methanol is considered to have a low risk of environmental damage in water bodies. [60] Pure hydrogen, on the other hand, is non-toxic, but explosive under certain conditions, whereas ammonia, methanol, and LOHCs are all flammable in liquid form. Due to the nature of transportation of toxic and harmful substances, there may be some public safety concerns, particularly if transportation routes travel through densely populated areas. Appropriate risk management, route planning, and engagement with local communities can help to address concerns.



When constructing new pipelines, highways, or railways to support hydrogen transportation, an environmental assessment would likely be required to identify and mitigate potential environmental impacts as mandated by the BC Environmental Assessment Act. [61] Environmental Assessments (EA) are required for major projects depending on their scale and potential environmental impact which would be assessed on a case-by-case basis. [62] The EA would involve conducting baseline assessments of existing environmental conditions such as air quality, noise, biodiversity, soil quality, water quality and any other location specific assessments. The study would identify potential environmental effects as a result of the proposed development and recommend or highlight mitigation measures. Special consideration should be given to avoid areas of environmental sensitivity. The construction of infrastructure can also contribute to greenhouse gas emissions due to use of resources. Use of existing pipelines could have the least environmental impact; however, consideration would need to be made for retrofitting, new compression equipment, and supporting infrastructure requirements. Fuel required for truck and rail transportation can also contribute to greenhouse gas emissions for hydrogen transportation depending on fuel type, distance, and load. [63]

The construction of new infrastructure has the potential to impact communities in various ways. There may be public and local opposition, particularly with the construction of pipelines due to concerns associated with public health, environmental degradation, and community displacement. Proposed infrastructure should avoid such impacts, as well as in areas of cultural significance or sacred land. A strong process of collaboration with local and Indigenous communities should be prioritized to limit negative impacts. [64] The province is obligated under Section 35 of the Constitution Act to consult and accommodate Indigenous groups on measures that may adversely affect pre-existing First Nation rights and title. Consensus-seeking with Indigenous groups for key decisions is also incorporated in the BC Environmental Assessment Act, reflecting a commitment to the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP). [65] Free, prior, and informed consent is an integral aspect of the UNDRIP and reflected in the environmental assessment process. [66]

BC has launched the Indigenous Clean Energy Opportunities (ICEO) partnership. This is a collaborative initiative, co-led by the BC First Nations Energy and Mining Council, First Nations Leadership Council, and the BC Ministry of Energy and Climate Solutions aiming to collaborate with First Nations rights holders to explore clean energy opportunities. [67] The initiative seeks to align BC’s strategic clean energy policy and legislation with UNDRIP. One key focus is to identify priority areas and opportunities for Indigenous participation in the hydrogen sector. [68] In June 2023, a two-day workshop was held to share information, hold discussions, and explore opportunities in the electricity and hydrogen sectors for Indigenous communities in BC. This also involved exploring what factors should be considered by communities when making decisions on hydrogen projects, what questions and barriers exist when it comes to First Nation opportunities in hydrogen and what resources are needed to overcome barriers and move hydrogen projects forward for BC First Nations. Further information about workshops and engagement can be found at https://indigenouscleanenergyopportunities.gov.bc.ca/.

Scalability and Cost

For scalability, ammonia, methanol, and LOHCs all have existing production infrastructure in use in various industries that could be repurposed for hydrogen carrier production. However, the drawback is that the dehydrogenation reactions for all three processes are endothermic, and therefore energy intensive. These reactions at an industrial scale can become quite costly.

LOHC and methanol are similar to gasoline and diesel, and can be transported under atmospheric pressure and temperature with similar vehicles used for gasoline or diesel.

The dehydrogenation reaction for ammonia, known as “cracking,” is a relatively new technology at industrial scale, with the largest existing cracking facilities in the nuclear power industry producing up to 1400 tonnes/day. [69] Cracking requires extremely high temperatures, with most facilities operating at 800-1000°C.

Methanol dehydrogenation is a simpler and less energy-intensive reaction that can be carried out at near-ambient temperatures with the presence of a catalyst. [70,71]

With regard to LOHC, for MCH (hydrogenated toluene), studies have shown that a platinum catalyst can be effective between 100°C and 400°C but is most effective at around 350°C. [72] This reaction returns MCH to toluene, which would allow for it to be reused. For all hydrogen carriers and liquefied hydrogen, additional processes require energy and will have additional cost and carbon emissions.

In terms of transportation, a study by Di Lullo et al (2022) [63] examined different large-scale, land-based hydrogen transportation systems, and found that transportation of pure or blended hydrogen by pipeline is the least expensive option. [63] Similarly, a study by the International Energy Agency (IEA) highlighted that pipeline networks are an effective way to transport large volumes of hydrogen over hundreds of kilometres. [73] Over long distances, transporting hydrogen in liquid form is more cost-effective than using gaseous tube trailers. However, the risk of boil-off is a challenge during liquid hydrogen transport. [74] When hydrogen demand is low and the cost of liquefaction facilities cannot be justified, transporting gaseous hydrogen over relatively short distances is a more feasible option.

Converting existing natural gas pipelines to deliver pure hydrogen is likely to be expensive, requiring substantial modifications to overcome technical concerns or new pipelines to be installed. Installing new pipelines would carry a high initial cost and the development of pipelines requires collaboration across multiple jurisdictions, and can be met with public resistance and legal challenges. [75] Consideration should be made for the cost of design, installation, operation, and maintenance. There may also be uncertainties around pipeline construction costs due to specific material requirements for hydrogen pipelines and fluctuating material and labor costs. [63] As demand for hydrogen increases, costs associated with construction of large-diameter pipelines may be justified. [73] Experience within BC of building and operating natural gas pipelines will also be a benefit in the potential development of hydrogen pipeline networks.

When transporting ammonia by pipeline, the majority of the cost may be attributed to the process of converting hydrogen to ammonia and subsequently cracking ammonia to hydrogen for end use. With LOHC, costs may be dominated by the pipeline construction and maintenance but the hydrogenation and dehydrogenation processing costs could also account for 22-47%. [63] The highest costs associated with highway and rail infrastructure upgrades will be ensuring adequate connections to production facilities and end users. Other costs to factor into transportation include the conversion/compressor processes, storage requirements, and fuel. There may be additional costs associated with carbon tax for some fuel options. [76]

Several studies including that by Di Lullo et al [63] and the IEA [76] examine predicted costs around hydrogen and hydrogen carrier transportation, however factors such as end-use, distance and available technologies impact costs. Conversion and conversion costs are a major factor in hydrogen carrier transportation and reducing energy consumption associated with these processes could considerably reduce hydrogen delivery costs. Lowering costs through technological advances is key to raising prospects for hydrogen transportation. [73]

Market Potential

In terms of hydrogen carriers, key factors influencing market opportunities include cost of production, end-use applications and demand. Ammonia and methanol are widely used in industry. In 1930, two renewable ammonia plants were established in Canada. One facility in Sandwich, Ontario used Casale technology to produce around 2.5 kilotonnes of ammonia per year. Another facility in Trail, BC used Fauser technology, initially producing 38 kilotonnes of ammonia per year and later expanding to around 70 kilotonnes per year. The main growth in the Canadian synthetic ammonia industry took place from around 1950, and was based on natural gas, particularly as it became more profitable. [77] There are renewable ammonia projects currently under development in eastern Canada. [78] Studies suggest that the market for green ammonia is growing as a more sustainable fertilizer for the agricultural sector or as a fuel source in transportation. The ammonia market demand in Canada stood at 3300 thousand tonnes in 2023 and is expected to grow by 3.8% during a forecast period of 2025 to 2034. The agricultural sector heavily relies on ammonia for enhancing crop production. Ammonia has diverse applications across other industries including refrigeration, chemical manufacturing, and pharmaceuticals production. There is also growing global demand for ammonia, providing export opportunities. [79]

The majority of methanol produced today comes from natural gas but the industry is seeking to reduce its greenhouse gas emissions using sustainable biomass, renewable energy, and carbon capture and storage. BC has historically had an active methanol production industry until 2005 when the only facility operating in Kitimat was shut down. [80] The Canada methanol market demand stood at 520 thousand tonnes in 2023 and is expected to grow by 3.7% during a forecast period of 2025 to 2034. Methanol serves extensively as a solvent and is used in various chemical and industrial processes. In particular, there is growing interest in the maritime industry in green methanol as a low-carbon alternative to conventional fuels. [81] Methanol is considered advantageous as it is relatively safe to transport and store and is a liquid at room temperature. Green methanol is also compatible with current methanol dual-fuel engine technology. Methanex Corporation, headquartered in Vancouver, is the world's largest methanol producer and has been supporting the development of methanol as a marine fuel. Waterfront Shipping is a subsidiary company of Methanex and has been operating methanol dual-fueled ships since 2016. In February 2023, the first-ever net zero voyage fuelled by bio-methanol was completed. Canadian Methanol Corporation (CMC) is also planning to develop a green methanol production site in Tumbler Ridge.

Regional Hubs

The 2021 BC Hydrogen Strategy includes actions to develop regional hubs to co-locate hydrogen production and supply. Research is being undertaken to examine the potential for hydrogen hub development in four regions within BC, including the Lower Mainland, Northeast BC, Interior BC (Kootenays and Okanagan), and Vancouver Island. The regional reports and studies will point to specific supply, demand, and regional considerations.

Examples of regional benefits include existing plans to expand hydrogen production and use on Vancouver Island, with market opportunities in transportation particularly for ferries, buses, trucks, and trains. Similarly, in the Lower Mainland existing industry and the planned development of a hydrogen hub highlight a large market opportunity. Key markets for hydrogen from carriers include heavy-duty and marine transportation, industrial applications, and opportunities for export. There is market potential in both regions for green methanol as a low-carbon shipping fuel.

The interior region has renewable energy resources, which can be utilized for green hydrogen production and there may be further market potential for hydrogen carriers to be used in other applications within the region such as ammonia for agricultural uses and methanol for industrial applications. The potential for an Interior region hydrogen hub is currently being studied.

A regional hydrogen hub is planned in northern BC. The City of Prince George received PacifiCan funding in July 2024 to identify local hydrogen assets, attract investment for low-carbon initiatives and support regional research and community engagement. [82] With a focus on partnerships and collaboration, the City of Prince George is positioned to lead the way in the clean energy transition throughout central and northern BC. Advantages within the region include transportation benefits. The hub will extend to Prince Rupert, with the Port providing additional transportation and export market potential. [82] The northeast region has significant natural gas reserves that could be leveraged for hydrogen production with carbon capture and storage. The region has existing pipeline infrastructure and there are also opportunities for hydrogen use in industries such as mining and oil and gas, contributing to emissions reduction in hard-to-decarbonize sectors. The City of Prince Rupert has signed a lease option agreement for 79 acres on Watson Island with renewable energy development company, Hy2gen Canada. Hy2gen Canada will undertake assessments to identify the feasibility of a hydrogen-based energy export project for Prince Rupert on the existing brownfield site [83] Prince Rupert's location is advantageous as it would support a green energy export project focused on the Asian market. The project is anticipated to gain revenue from the lease agreement and attract permanent, high-paying positions and temporary construction and service job opportunities. The north coastal town of Stewart also plans to develop green hydrogen solutions to support decarbonization in the local mining sector. Additionally, access to the port provides export market potential. [84] The north coast region of BC is seeing significant growth in ports, mining, and hydrogen with increased demand for electricity expected. [85] BC Hydro is expanding transmission infrastructure between Prince George and Terrace which could support green hydrogen opportunities. [86]

Risk Analysis

Handling and transporting hydrogen and hydrogen carriers involves managing hazards to ensure safety and prevent accidents. These hazards include accidental releases, adverse weather/environment, derailments, road crashes, fires, explosions, hydrogen embrittlement, and cracking in critical equipment and piping. Understanding and addressing these hazards with appropriate safety measures is necessary to reduce potential impacts and maintain safe operations.

Hydrogen and hydrogen carrier transportation involves numerous hazards. The following sections identify key hazards and mitigation strategies. [71]

The focus of this report is transporting hydrogen and hydrogen carriers by pipeline, truck transport or rail. From a comparative risk perspective, pipeline transport is considered the lowest risk while truck transport is the highest. However, each mode of transport has practical limitations. Details are listed below.

Pipeline

Pipelines are considered the lowest safety risk compared to truck transport and rail relative to the volumes being transported with pipelines being considered safer than rail. [109] Pipeline is the preferred method of transport for commodities like crude oil and natural gas due to the significant quantities being transported daily. However, pipelines and the associated equipment are stationary with the infrastructure being designed for the specific commodity. In general, pipelines are not practical for small quantities based on the initial infrastructure set-up required.

Rail

Dangerous goods are routinely transported via Canada's significant rail system (~43,000 km of track). In Canada, 99.99% of dangerous goods via rail arrive at their destination without incident. [110] Since the 2013 Lac-Mégantic disaster, Transport Canada has implemented new safety measures for rail transport in response to the incident audit findings and recommendations. [87]

Commodities transported by rail, in most cases, still rely on truck transport for the final destination.

Truck Transport

In North America, truck transport is a common way to move hazardous materials but is 16 times more likely to be involved in fatal crashes than trains. [88] Truck transport has the most flexibility in reaching the end users. Though there are overarching regulations on this transport, local jurisdictions can designate truck routes and implement road restrictions for a variety of reasons (weight, security, steep grades, sensitive areas, etc). It provides the most flexibility for transporting dangerous goods but the quantities are less than rail and pipeline. Because this is a critical method of transport and the need to work with existing road infrastructure, the principle of "As Low As Reasonably Practicable" (ALARP) is considered for risk reduction.

With the continued development of self-driving vehicles, there are expectations that full automation will improve road safety and this will apply to improved overall safety for truck transport of dangerous goods. (Automated Vehicles for Safety)

Overview

The transport risks of various modes are easy to compare and this has been studied. However, the risks of hydrogen and various hydrogen carriers are difficult to compare. Both probability and severity of consequence need to be assessed, and this is challenging when the consequences can be significantly different (explosion versus toxic gas release). One of the commonalities of rail and truck transport is that incidents occur outside and flammable/toxic gases/liquids do not accumulate within enclosed spaces. In many cases, this lessens an incident consequence/severity.

1) Accidental Release

Accidental release can occur due to damaged or defective equipment or its components, such as instruments, which can allow hydrogen or its chemical carriers to leak from storage equipment or piping into the atmosphere. The hazard is further compounded if it comes into contact with an ignition source at the time of accidental release, potentially leading to a fire or explosion.

Accidental releases are reportable and Transport Canada provides guidelines. [89] The problem of accidental releases can be mitigated through operational procedures that include inspecting all components prior to transport and preventative maintenance. Each commodity transported would have specific procedures/ protocol to prevent releases with an emergency response plan if an event occurs. The transportation mode may include instrumentation for monitoring, specific design features (material suitable to commodity) and other safety features (relief devices). [76]

2) Adverse Weather/Environment

Infrastructure in BC is inherently vulnerable to extreme weather conditions, including heavy rainfall events that can cause mud and rockslides, as well as flooding in rivers and creeks, leading to road washouts, bridge closures, and impacts on rail systems and equipment.

During severe flooding, accumulated debris at bridge structures can increase the risk of bridge failures. For example, seven bridges had collapsed or were damaged along highway 5 in November 2021 due to an atmospheric rain event. [59] In some cases, these events have isolated communities from their primary supply routes. Meanwhile, heavy snow and fog can reduce visibility, creating hazardous driving conditions. To ensure driver safety and minimize accidents, trucking companies must monitor weather forecasts closely and plan routes accordingly. The necessary utility or equipment for safely transporting goods during challenging weather conditions, such as antifreeze solutions, de-icing fluid, route planning tools, and winter tires, must also be used.

The British Columbia Ministry of Transportation and Infrastructure has assessed five stretches of highway using the Public Infrastructure Engineering Vulnerability Committee (PIEVC) protocol: [90]

- **Coquihalla Highway:** Between Nicolum River and Dry Gulch, Southern Interior;
- **Yellowhead Highway 16:** Between Vanderhoof and Priestly Hill, Sub-Boreal Interior;
- **Highway 20:** Bella Coola region, Coast and Mountains;
- **Highway 37A:** Stewart region, Coast and Mountains;
- **Highway 97:** Pine Pass Region, Sub-Boreal Interior.

Impacts identified for these areas, which are of particular concern include: [91]

- High-intensity, short-duration (HISD) rainfall or extreme precipitation events, causing increase vulnerability of culverts;
- Atmospheric river (or sometimes referred to as "Pineapple Express") events, [1*] affecting highway drainage systems, culverts, road, and rail networks;
- Sea level rise and storm surge, increasing the risks of flooding and damage to fixed coastal infrastructure.

3) Earthquakes

BC has an elevated risk of earthquakes, particularly along the coast, resulting not only in the potential for direct damage from ground motion, but also from landslides and tsunamis generated by earthquakes. In the aftermath of a major earthquake, roads and bridges may be severed and pipelines may not be operable until extensive testing is completed.

New infrastructure in BC must comply with appropriate seismic design standards, including decisions on whether critical infrastructure is designed to post-disaster standards.

4) Flammability and Explosivity

Hydrogen, methanol, and ammonia are flammable under specific conditions, so there can be a risk of fire and explosion when handling these chemicals. A flammable mixture with air can be formed when there is accidental leakage. Such leakage can result from mishandling, mechanical failures, materials/compatibility issues, improper maintenance, or collisions. [93] Releases can also occur when relief devices open to the atmosphere to prevent the contents from overpressuring due to an abnormal event such as an external fire or overheating. Relief devices are specifically designed for stationary or mobile applications. Appropriate safety measures can be implemented to ensure that equipment and piping materials can handle the chemicals under their storage and transport conditions.

5) Derailment

Transportation by rail involves the risk of derailment and accidents due to issues such as broken rails, misaligned tracks, or signaling system malfunctions. Regular preventive maintenance can address these potential problems before they escalate. Acts of vandalism, damage, or interference are also possible risks in rail transport. These can be mitigated by assigning security personnel to conduct inspections and promptly report the potential threats or security concerns to Transport Canada's Situation Centre.

[1*] A "Pineapple Express" is a term used to describe a strong atmospheric river where moisture builds up in the tropical Pacific around Hawaii resulting in heavy rainfall and snow across the west coast of the US and Canada. [92]

6) Road/Traffic

Transporting hydrogen and hydrogen carriers by truck involves risks inherent to large commercial vehicles, such as traffic accidents, crashes, and collisions. This can result in chemical leakage, or catastrophic fires and explosions in the most severe incidents. Gaseous hydrogen is highly flammable and prone to leakage, while liquid hydrogen presents challenges due to its extremely low temperatures and its flammability when it becomes a gas. The risk of accidents increases when transporting hazardous materials like hydrogen on variable road conditions and in densely populated areas. [94]

To mitigate these risks, it is crucial to comply with regulatory standards for vehicle operation and maintenance, implement strict safety protocols, and provide thorough training for personnel. Clear signage indicating hazardous cargo helps assist emergency responders while also enhancing public awareness and promoting road safety.

7) Hydrogen Embrittlement and Hydrogen-Induced Cracking

Hydrogen embrittlement is a process in which metals, especially high-strength steels, become brittle due to absorption and interaction with hydrogen, causing them to crack or fail under stress. This form of embrittlement is particularly concerning for pipelines, storage vessels, and other critical infrastructure where mechanical integrity is essential. [95]

Hydrogen-induced cracking usually occurs together with stress corrosion cracking, which causes pipeline failure. The combined effects of hydrogen and pipeline stress cause the steel to crack, resulting in serious hydrogen embrittlement. The combination of hydrogen-induced cracking and stress corrosion cracking is sometimes referred to as hydrogen-assisted stress corrosion cracking. [95]

Hydrogen embrittlement and hydrogen induced cracking are managed by selecting appropriate materials for equipment and piping, including strict adherence with the design standards and damage prevention programs outlined in BC Pipeline Regulations.

Hazards Assessment

According to the European Hydrogen Incidents and Accidents Database (HIAD) 2.1 released by the Joint Research Center (JRC) of the European Commission in December 2023, the causes of hazards can be classified into seven (7) main types. [71]

No.	CAUSES	EXAMPLES
1	Environment	Storm, hurricane, lightning, flood, landslide, earthquake
2	Human Factors	Carelessness, inadequate training, incompetence, fatigue and stress, failure to use appropriate PPE, inability to make the right decisions during emergency, vandalism, or interference
3	Installation Error	Wrong placement, wrong connections, use of unsuitable materials in connections, improper installation connections
4	Job Factors	Loading and unloading location, unsuitable tanker, filling and unloading operations, lack or misuse of safety equipment
5	Management Factors	Poor management/maintenance, insufficient information to employees, inadequate supervision, long working hours, insufficient rest periods, lack of communication, lack of emergency plans, work organization and management
6	Material/Manufacturing Error	Low-quality material production, poor material selection, structural defects of tankers, source errors, inadequate protective materials such as coating.
7	System Design Error	Inappropriate design, use of inappropriate materials, inadequate pressure and tightness tests, emergency evacuation system problems, fire prevention and extinguishing systems, errors in the design of loading/unloading operations.

Some of the identified hazards, along with their potential effects to equipment, property, personnel, and the environment are listed below. The impact on the environment is particularly significant in the case of methanol, ammonia, and toluene/MHC (LOHC) release or leakage, as these substances are toxic.

No.	HAZARDS	CONSEQUENCES
Transport by Truck/Rail/Pipeline		
1	Accidental Release	Chemical leakage, fire, environmental pollution
2	Adverse Weather/ Environment	Chemical leakage, environmental pollution
3	Flammability and Explosivity	
	Gaseous/Liquid H_2	Fire, explosion, frostbite, asphyxiation (in confined spaces), leakage
	Ammonia	Toxic exposure, fire, explosion, environmental pollution, chemical burns
	Methanol	Toxic exposure, fire, explosion, environmental pollution
	Toluene/MCH (LOHC)	Toxic exposure, fire, explosion, environmental pollution
4	Hydrogen Embrittlement	Chemical leakage
Transport by Truck		
5	Road/Traffic	Accident (crash/collision), chemical leakage, fire, explosion
6	Untrained Driver	Accident (crash/collision), improper emergency response or intervention
7	Lack of Signage on Truck	Improper emergency response
Transport by Rail		
8	Broken Rails/ Misaligned Tracks	Derailment, accident (crash/collision), chemical leakage
9	Malfunction/Breakdown of Railway Signaling System	Accident (crash/collision), derailment, chemical leakage, transport schedule delay
10	Acts of Vandalism or Sabotage	Chemical leakage, toxic exposure, fire, explosion, environmental pollution
Transport by Pipeline		
11	Hydrogen-Assisted Stress Corrosion Cracking	Pipeline failure, chemical leakage, environmental pollution
12	Undetected Leaks During (High-ressure) Operation	Fire, explosion, toxic exposure, environmental pollution

Hydrogen-Related Incidents

Reviewing past incidents involving hydrogen and hydrogen carrier transportation is essential for recognizing potential hazards and strengthening safety protocols. Described in this section are six transportation-related incidents with their causes, consequences, and preventive measures implemented by the industry to mitigate the risks.

Incident 1	
Incident Description	Rail cars carrying ammonia, methanol, and sulfur derail, burst into flames (United States, July 5, 2024). [96]
Cause	Twenty-nine cars of a Canadian Pacific Kansas City (CPKC) train derailed around 3:45 a.m. in a marshy area surrounded by farmland, about 140 miles (225 km) northwest of Fargo, ND. The cause of the derailment is unknown. The cars were carrying anhydrous ammonia, sulfur, and methanol.
Consequence	The derailment ignited 10 to 15 rail cars. Both the engineer and conductor escaped safely. The greatest risk was from the ammonia, but fortunately, the wind carried the smoke away from populated areas.
Preventive Measures	CPKC activated its emergency response plan and implemented a comprehensive, coordinated effort. Each rail car was individually assessed, emptied, and relocated to minimize spillage.

Incident 2	
Incident Description	Release and fire from a hydrogen pipeline (United States, February 15, 2021). [71]
Cause	During a winter storm with severe freezing conditions and widespread power outages, a refinery's hydrogen supply was reduced. This led to a need for higher-than-usual flow rates through the hydrogen pipeline. The investigation found that erosion had occurred in the flow tubes of the 3-inch Coriolis meter.
Consequence	Hydrogen was released and caught fire at the meter station of a pipeline delivering hydrogen to the refinery. This caused failures in various components, including the Coriolis meter housing, meter flange, an 8-inch manufactured elbow, and an 8-inch bypass line.
Preventive Measures	After the incident, the meter station was redesigned and reconstructed to reduce the risk of erosion, with permanent repairs completed after one year. To prevent similar incidents in the future, a stringent inspection and regular maintenance schedule need to be implemented.

Incident 3	
Incident Description	Liquid hydrogen release from a tanker (Canada, October 24, 2017).[71]
Cause	A tanker truck, which was carrying nearly 13,000 gallons of liquid hydrogen, struck the base of a light pole in the parking lot of a local grocery store while the driver was trying to turn around.
Consequence	Hydrogen gas began leaking from the truck, damaging a valve and potentially leading to the release of liquid hydrogen, which posed a serious risk to nearby residents and businesses. Fortunately, no one was physically harmed in the incident.
Preventive Measures	Incidents like this can be prevented through careful and attentive maneuvering by the driver.

Incident 4	
Incident Description	Pipeline rupture and leak of anhydrous ammonia with vapour cloud (United States, October 27, 2004).[97]
Cause	The probable cause of the pipeline rupture near Kingman, Kansas was damage from heavy equipment during construction or later excavation, which caused metal fatigue and eventually led to the rupture. The severity of the accident was worsened by the pipeline controller's failure to properly assess the data and shut down the pipeline in time.
Consequence	At 11:15 a.m. central daylight time, an 8-inch pipeline owned by Magellan and operated by Enterprise ruptured, releasing about 204,000 gallons of anhydrous ammonia. No one was hurt as the rupture occurred in an agricultural area, but it killed over 25,000 fish, including some threatened species, when it leaked into a creek. The total cost of the accident was $680,715 with $459,415 spent on environmental cleanup.
Preventive Measures	Provide initial and recurrent training for all controllers using simulations, either computerized or not, to practice handling abnormal conditions that suggest pipeline leaks. Require operators to update their pipeline risk assessment plan if they overlook any factors that could impact pipeline safety.

Incident 5	
Incident Description	Hydrogen fire from a liquid hydrogen transporter (Canada, August 6, 2004). [71]
Cause	The incident took place outside a fuel cell manufacturing facility while preparing to transfer liquid hydrogen from a tanker truck to a storage tank. The driver finished unloading the tank for the first time but left the manual valve open when connecting the trailer to stationary storage. He then skipped the necessary seven purges meant to remove contaminants and water from the pipes before starting the second unloading. After that, he opened the pneumatic valve before connecting the hose, causing liquid hydrogen to escape into the air through the open valve.
Consequence	Hydrogen was released, forming a vapour cloud that ignited in a flash fire with an explosion loud enough to be heard inside a nearby building, triggering its seismic detectors. A small amount of hydrogen gas continued leaking from the trailer tank and burned for nearly eight hours until a specialist from the delivery company arrived to manually close a critical valve.
Preventive Measures	Proper training should be provided to personnel in charge of hydrogen transportation and transfer. It is important that all steps in the standard safety procedure are followed consistently without any omissions.

Incident 6	
Incident Description	Release and ignition of hydrogen due to a trailer collision (United States, May 1, 2001). [71]
Cause	A semitrailer carrying compressed hydrogen in horizontal cylinders collided with a northbound pickup truck that had swerved in front of it.
Consequence	The tractor-semitrailer lost control, overturned, and veered off the highway, traveling about 100 meters before stopping. In the process some cylinders, valves, and piping at the back of the trailer were damaged, causing a hydrogen leak that ignited and burned the rear of the semitrailer. Meanwhile, the pickup truck also ran off the road with its fuel line ruptured, causing it to catch fire and be destroyed. As a result of the accident, the truck driver was killed, and the pickup driver was seriously injured. Five nearby homes were evacuated, and the highway was closed for more than 12 hours. Total damage, cleanup, and lost revenue were estimated at $155,000.
Preventive Measures	Such an event is an accident, but the severity of the consequences can be lessened by implementing adequate standards for protecting and shielding cylinders, valves, piping, and fittings, as well as securing the cylinders on the semitrailer.

Opportunity Assessment

The Canadian hydrogen and fuel cell sector is recognized as a global leader. BC in particular has a strong policy and regulatory environment, innovative organizations and projects, cutting-edge research institutions, and physical resources that support the sector's growth. As a growing hub for hydrogen production and use, there are many advantages to developing transportation networks in the province.

Policy and Regulatory Environment

The provincial government released the BC Hydrogen Strategy in 2021, outlining a roadmap for incentivizing and supporting hydrogen production, use, and transportation. There has since been significant investment contributing to innovation and the commercialization of new technologies in the region. [98] Investment has come from public sector funding from the BC government such as the BC Innovative Clean Energy Fund and various CleanBC funding initiatives. Federal government funding is also supporting initiatives along with private sector investment from various organizations and institutions that also contribute to the hydrogen ecosystem in BC. The BC Centre for Innovation and Clean Energy (CICE) is another example of an independent, not-for-profit corporation that provides funding for the commercial development and scaling of low-carbon hydrogen solutions.

Policies and sector-specific emissions targets encouraging hydrogen investment within the province to meet broader decarbonization goals are shown in Table 6.

Table 6: Policies and sector specific targets encouraging hydrogen investment

Policy	Goals and Actions
BC Carbon Tax	Increasing tax encourages industry to seek lower carbon alternatives and creates a financial incentive to lower emissions. $65/tonne in 2023 increasing to $170/tonne in 2030.
BC Low Carbon Fuel Standard	Mandates a 30% reduction in carbon intensity of supplied fuel for transport by 2030. Provides incentives for projects that produce low carbon fuels including hydrogen.
Clean Energy Act	Targeting 100% clean electricity generation by 2030 for the integrated grid.
CleanBC Industry Fund	Funding streams available for innovations and projects that support industrial emissions reduction.
CleanBC Clean Industry and Innovation Rate	Discounted electricity rates to encourage the use of BC clean electricity and attract clean industry customers for example, hydrogen production.

Other federal programs such as the Clean Hydrogen Investment Tax Credit (ITC) can further encourage organizations to select Canada and BC for further investment in this sector. The ITC is a refundable tax credit that applies to eligible clean hydrogen property that is acquired and becomes available for use in respect of a qualified clean hydrogen project. [99]

In November 2022, the BC Government passed the Energy Statutes Amendment Act changing the BC Oil and Gas Commission (BCOGC) to the BC Energy Regulator (BCER), establishing its authority to regulate the manufacturing of hydrogen, ammonia, methanol, and carbon dioxide transportation. [65] With regulatory authority over facilities manufacturing hydrogen and the associated pipeline infrastructure, BCER is working to develop a robust regulatory framework within the province. This provides a reliable and supportive investment environment for industry and talent. [100] Technical Safety BC (TSBC) authority related to hydrogen, includes regulating storage utilization of hydrogen in industrial processing and production applications in accordance with the Safety Standards Act and Gas Safety Regulations. TSBC also governs ancillary equipment. [65] Rail, road, and end use of hydrogen activities fall outside of the jurisdiction of BCER and are governed by Transport Canada and the Ministry of Energy and Climate Solutions.

Knowledge Centre and Skilled Workforce

BC is home to 51% of Canada's hydrogen and fuel cell sector organizations, accounting for nearly 60% of Canadian research investment in hydrogen and fuel-cell development. This includes HTEC, Ballard Power Systems, Loop Energy, Greenlight Innovation, Ekona Power, VulcanX, Greenlight Innovation, Ionomr Innovations, and PowerTech Labs. As discussed in the market potential and hydrogen hubs section, a focus of the BC Hydrogen Strategy is to co-locate hydrogen production and supply in regional hubs. Assessments are being undertaken to identify opportunities and risks in Northern BC, the Lower Mainland, Vancouver Island and the Southern Interior. Major projects in the region are already progressing, like HTEC's H2 Gateway project, for example, focused on developing demand and supply for hydrogen as a transportation fuel within BC. [101]

The total investment in the H2 Gateway project is estimated at around $900 million. Regional hubs can also stimulate economic growth by attracting investment, generating jobs, and driving innovation. Advancing decarbonization and sustainable energy solutions can also financially benefit other industries in the region, such as shipping and transportation.

Various universities and technical institutions are contributing to cutting-edge research. The University of British Columbia (UBC) is driving innovation and research having launched the $23 million Smart Hydrogen Energy District (SHED). The facility will produce green hydrogen using solar and hydro power. Funding has also been announced to establish a new Clean Hydrogen Hub at Simon Fraser University (SFU) in Burnaby. This is a new core research facility bringing together industry, community, academia, and government partners to co-develop technologies and products to support advancements in emerging clean hydrogen technology.

BC has an existing skilled workforce of over 1,300 employees within the hydrogen sector. Developing a low-carbon hydrogen economy will drive additional employment opportunities for a skilled, technical, and professional workforce. A study by Transition Accelerator notes that many core technical occupations and foundational skills required by the hydrogen economy are already found within Canada's labour markets such as engineering, project development, construction, oil and gas industries, petrochemical industries, and heavy-duty vehicle manufacturing. There is an opportunity to leverage occupations within existing industries to expand a hydrogen workforce. Projects and research within the province are also further contributing to job creation and upskilling. [98] There are around 50 proposed projects in the province. The HTEC H2 Gateway project is expected to create over 280 jobs. [102] The first spinoff company from the UBC SHED work has also launched. The concentration of expertise within BC can drive efficiencies in technological advancements.

Physical Resources and Infrastructure

BC has existing physical resources and infrastructure that further position the province as a key location for hydrogen transportation. Currently BC has an affordable and clean supply of electricity generated from hydropower, which can support electrolytic hydrogen production. Demand on the grid is expected to increase as a result of population growth, industrial development, electric vehicles and heat pumps; however, the BC government is committed to supporting clean energy growth. BC Hydro is looking to identify new sources of clean electricity and has announced its intention to invest $35 billion over the next ten years to support the growth of BC's electricity supply, including engaging with independent power producers. There is also an availability of natural gas, freshwater, and large land masses with space to develop infrastructure within the province, which are crucial to hydrogen production and transportation.

Existing infrastructure has the potential to be adapted for hydrogen transportation, including existing railway, highway, and pipeline networks. FortisBC is working to investigate opportunities for adapting natural gas pipelines for hydrogen delivery. In addition to existing highway and rail infrastructure, various ports in the region offer opportunities for export to global markets. Additional benefits include the market potential of green methanol as a marine fuel to support the decarbonization of marine operations which is discussed in further detail in the market potential section.

Key Partnership Opportunities

The hydrogen ecosystem in BC involves several key partnerships. At a national level, support is received from the Canadian Hydrogen Association (CHA) and Hydrogen BC serves as the regional affiliate of the CHA. The Natural Sciences and Engineering Research Council of Canada (NSERC) and Natural Resources Canada (NRCan) are federal departments that support hydrogen development initiatives and research into hydrogen transportation.

At a provincial level, BCER is responsible for the regulation of hydrogen as an energy resource. Other regulatory bodies may also play a role depending on transportation routes and the infrastructure required. Municipalities are responsible for decision making in terms of strategic planning, routing, and emergency response planning. In particular, intergovernmental partnerships and consultation with industry stakeholders will be necessary to develop robust safety procedures.

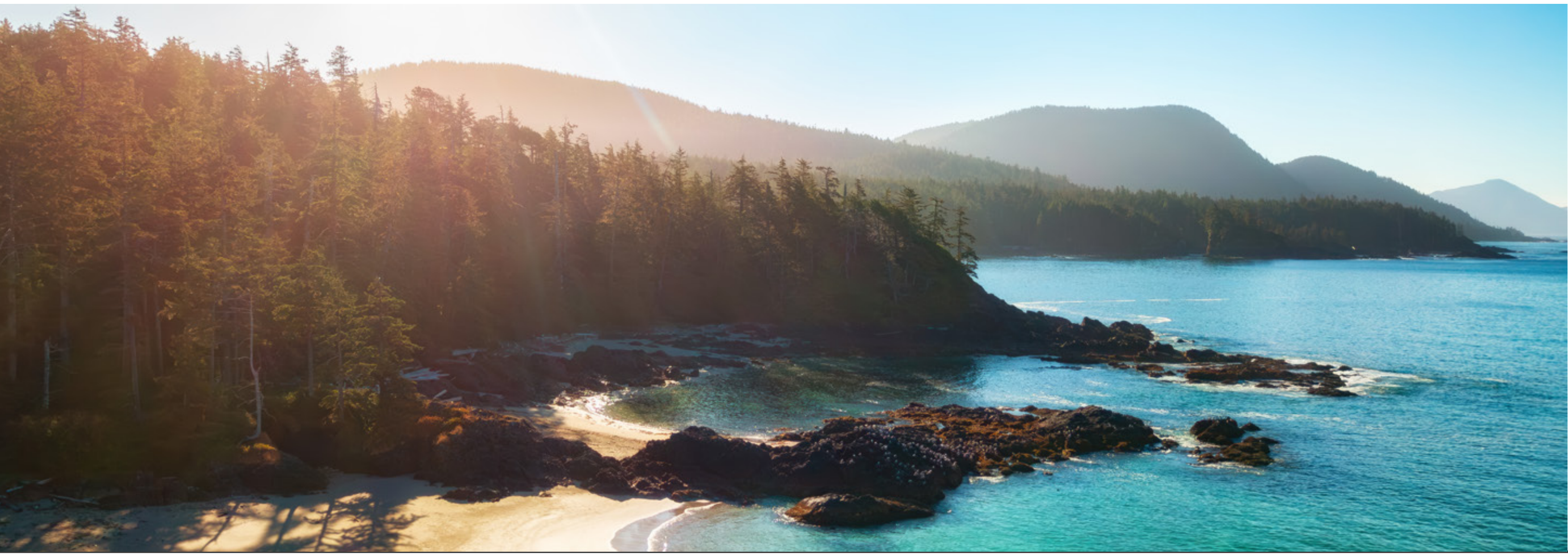
As a technical leader in the field, BC can also build partnerships with other provinces and international partners, further bolstering economic benefits. CEMPO is working with the Pacific NorthWest Economic Region (PNWER) on an innovative cross-border hydrogen analysis project in collaboration with the Washington State Department of Commerce. This study will explore how BC and Washington state can collaborate in developing and growing the hydrogen economy with a specific focus on opportunities in relation to the Pacific Northwest Regional Clean Hydrogen Hub (PNWH2). The PNWH2 is a proposal by the U.S. Department of Energy which would span Washington, Oregon, and Montana. [103]

There are partnership opportunities with other energy and industrial sectors looking to support the clean energy transition. For example, Enbridge and FortisBC are working to develop existing gas and pipeline infrastructure that is adaptable to hydrogen. Similarly, existing supply chains and producers of carriers such as methanol and ammonia have the potential to be key partners, which could improve efficiencies in adopting hydrogen carriers. Methanex is the largest producer of methanol in the world and is headquartered in Vancouver. Although not currently producing methanol in Vancouver, Methanex is driving innovation and technology in producing lower-carbon methanol and applying this to growing markets. Within the hydrogen industry there are numerous local, national and international parties working on hydrogen projects in BC as highlighted in the knowledge centre and skilled workforce section.

There are many opportunities for collaboration with First Nations communities. In November 2019, the Declaration on the Rights of Indigenous Peoples Act (DRIPA) was unanimously passed in BC. This aims to align provincial laws with UNDRIP and was followed by the development of the BC Declaration Act Action Plan for 2022 to 2027. [104] One objective is to co-develop recommendations on strategic policies and initiatives for clean and sustainability energy. [105] This includes identifying and supporting First Nations-led clean energy opportunities. As previously highlighted in the environmental and social assessment section, the ICEO initiative is a collaboration set up to explore these opportunities between the First Nations Leadership Council, BC First Nations Energy and Mining Council, and the Ministry of Energy and Climate Solutions.

First Nations communities will be engaged and involved in new hydrogen and infrastructure projects from early stages often involving pre-engagement and joint decision-making power. There are opportunities for joint ventures, shared ownership models, and Indigenous-led projects. For example, Salish Elements is an Indigenous-owned green hydrogen production company and works closely with First Nations, government, and technology providers in the development of hydrogen projects and transportation. [106] Other collaborations can involve wider clean energy opportunities to support First Nations communities and ventures. Canadian Methanol Corporation (CMC) and West Moberly First Nations (WMFN) have an agreement whereby waste heat from the operation of CMC's planned renewable methanol plant will supply a large-scale, First Nations-owned and operated greenhouse complex that will be located adjacent to the methanol plant. The facility called Sundance Produce will grow organic produce for distribution across western Canada. [107]

The partnership opportunities extend beyond hydrogen projects to the additional infrastructure that a growing hydrogen economy and associated transportation will require. BC Hydro and the provincial government have announced $36 billion in grid infrastructure investments over the next decade. [108] There is a significant opportunity for First Nations to produce and sell clean power to BC Hydro on their territories. In the April 2024 Call for Power, one priority was for projects to have a meaningful First Nations partnership or equity component. As previously mentioned, expanding clean electricity sources within the province will be an important aspect of supporting hydrogen generation and transportation in BC.



Summary and Recommendations

BC is positioning itself as a leader in the clean hydrogen economy as demonstrated by the BC Hydrogen Strategy and action being taken to develop regional hydrogen hubs in the province. There has been substantial investment across the region from the provincial government, federal government, and private sector partners. This is supporting the development of research hubs, hydrogen production and distribution initiatives, and industry growth. To ensure a robust supply chain, reliable transportation methods are necessary.

Hydrogen is currently most commonly transported in its pure form as either a gas or liquid, via railway, road and sometimes pipeline. Challenges associated with transportation have led to interest in other options of hydrogen transportation including the use of hydrogen carriers such as ammonia, methanol and LOHC. The future of hydrogen transportation will likely incorporate a combination of the modalities discussed in this report—including the utilization of hydrogen carriers. There are challenges and advantages associated with each option.

The advantages of transporting pure gaseous or liquid hydrogen is that no additional processes are required before and after transportation. Gaseous hydrogen transportation may be favoured for short-distances; however, this method can be inefficient if large quantities are required. For this reason liquid hydrogen is more efficient for transporting large quantities. But, the liquefaction process can be energy intensive and costly.

Ammonia is commonly used in industrial applications and is relatively easy to transport, although specialized containers are required. One drawback is that ammonia is toxic, and stringent management and handling processes must be adhered to. Methanol is also widely used in industry and, similar to LOHC, it is liquid under ambient conditions making it easier and safer to transport. However, the dehydrogenation process for both can be costly at scale.

Existing railway, road, and pipeline infrastructure within BC can be adapted to support safe transportation of hydrogen and hydrogen carriers. There are existing gas transmission pipelines in BC, particularly in populated areas with high demand and where there are natural gas and oil reserves such as in the northeast of the province and on the north coast. Transportation of hydrogen by pipeline is regulated by BCER and further work is being done to ensure a robust regulatory framework in this area. Pipeline transportation could be the best long-term solution, particularly for large volumes of hydrogen, but practical limitations exist in the technical feasibility of converting existing pipelines and environmental, social, and economic challenges faced when developing new pipelines.

Highway infrastructure across BC and existing regulations are in place that can support the safe transportation of dangerous goods such as hydrogen and hydrogen carriers. There may be risks in terms of road transportation in more remote regions or areas that are subject to extreme weather events that can impact infrastructure. There is also existing railway infrastructure within BC but this is concentrated in more populated areas around the south of the province. Upgrades to ensure the safe transportation of dangerous goods would likely be required. Although supply chains and existing infrastructure are established for road and rail transportation in BC, particularly for ammonia and methanol, there may be challenges in delivering large volumes, and the cost of additional processes such as dehydrogenation needs to be considered. There are existing regulations for transporting hydrogen and all hydrogen carriers via road and railway, but further development is required to ensure safe transportation.

The trade-offs and advantages of each carrier and transportation method will need to be assessed for different scenarios. Factors to be considered include availability of existing infrastructure, distance, volume demand, end-user requirements, and the location of production sites and end-users.

In all transportation scenarios, hazards can exist such as accidental releases, adverse weather/environment, derailments, road crashes, fires, explosions, hydrogen embrittlement, and cracking in critical equipment and piping. Processes will need to be clearly defined to understand and address hazards associated with specific transportation options and carriers, ensuring that appropriate handling processes, storage requirements, and procedures are in place to promote safety and limit risks.

Based on the findings in this report, recommendations have been made for key parties on strategies to capitalize on opportunities and mitigate risks associated with hydrogen transportation in BC. These recommendations are intended to guide industry, research bodies, and regulators.

Opportunities

1. **Capitalize** on existing supply chains, innovation and leadership in the hydrogen sector within BC to advance technology and improve efficiencies in hydrogen carrier use and transportation.

2. **Support** knowledge centers and skilled workforce within the region and improve the cost, efficiencies and availability of technology to support the hydrogenation and dehydrogenation process of carriers which could enable easier and more affordable transportation of hydrogen via carriers.

3. **Invest** in infrastructure on a case-by-case basis which aligns with hydrogen demand, but note that a combination of different transportation methods and carriers would be a more resilient and balanced approach.

4. **Expand** infrastructure in line with the planned hydrogen hubs and active hydrogen projects in BC with good market potential and opportunities.

Risk Mitigation

5. **Ensure** appropriate and secure storage and transportation of hydrogen and carriers to minimize the harm or severity of consequences and accidents where possible. Undertake location-specific and project-specific risk assessments to identify and implement management measures.

6. **Continue** to monitor updated standards and regulations developed for transportation of hydrogen and hydrogen carriers at an international and national level, adopting best practice within the province.

7. **Establish** a robust regulatory compliance and incident process for each transportation option and carrier. Adopt lessons learned from previous incidents and incorporate key processes such as emergency response plans, maintenance schedules, training of personnel, and risk assessments.

8. **Undertake** further evaluation of transportation options including dehydrogenation processes versus pure hydrogen delivery infrastructure to identify the most cost-effective and sustainable options for specific cases and accounting for variables such as purpose, distance and location.

Glossary

Term	Definition
Ammonia	A colourless, toxic gas with a pungent odour. Chemical formula is NH_3. Ammonia is commonly used in fertilizer production and its applications for use as a clean fuel is currently being explored.
Asphyxiant	A vapour or gas which can cause unconsciousness or death by suffocation.
Carbon Capture, Utilization, and Storage (CCUS)	Refers to a suite of technologies that capture carbon dioxide (CO_2) from point sources or directly from the atmosphere, store it in geological formations, or use it in a variety of applications.
Clean energy transition	The global shift away from fossil fuel-based energy systems to renewable energy systems.
Cryogenic tanks	Containers to store and transport liquefied gases, such as hydrogen, at very low temperatures.
Decarbonization	The process of reducing the levels of carbon emissions associated with a system or process.
Energy carrier	An energy carrier is a transmitter of energy. Includes electricity and heat as well as solid, liquid and gaseous fuels such as hydrogen.
Fuel cell	A power generation device that uses hydrogen as fuel to produce electricity, with water and heat as the only byproducts.
Gravimetric H_2 content	This refers to the hydrogen content in wt% in the hydrogen carrier. Gravimetric refers to measurement of the weight of a substance.
Green hydrogen	Common term used to refer to hydrogen produced by electrolysis (see definition of electrolysis) using electricity generated from renewable energy sources.
Greenhouse gas (GHG)	Any gas in the Earth's atmosphere that absorbs infrared radiation (heat) emitted from the Earth's surface and reradiates it back, creating the greenhouse effect. Include gases such as carbon dioxide (CO_2), methane, and water vapour.
Hydrogen carrier	A substance that stores hydrogen facilitating transport and delivery.

Term	Definition
Low carbon hydrogen	Common term used to refer to hydrogen produced from methods that produce fewer to no carbon emissions. Includes hydrogen produced by electrolysis, methane reforming with CCUS, and methane pyrolysis (green, blue, and turquoise hydrogen). The Government of Canada categorizes low carbon hydrogen as that which has a carbon intensity that does not exceed 67.8 gCO_2e/MJ.
Methanol	A clear, colourless liquid alcohol. Chemical formula is CH_3OH. Methanol is commonly used as an industrial substance and its applications for use as a clean fuel is currently being explored.
Natural gas	A gaseous, naturally occurring hydrocarbon consisting primarily of methane.
Net zero	A stage where economies emit no greenhouse gas emissions or offset any emissions.
Renewable energy	Energy created from natural processes that are replenished at a rate that is equal to or faster than the rate at which they are consumed, including energy generated from solar, wind, geothermal, hydropower, ocean resources, solid biomass, biogas, and liquid biofuels. Note that biomass is considered renewable only if its rate of use does not exceed its rate of regeneration.
wt%	Percentage by weight.

References

1. Government of British Columbia. B.C. Hydrogen Strategy: A Sustainable Pathway for B.C.'s Energy Transition. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/electricity/bc-hydro-review/bc_hydrogen_strategy_final.pdf.

2. Airgas. Hydrogen Safety Data Sheet. (2020).

3. Airgas. Ammonia Safety Data Sheet. (2019).

4. International PtX Hub. *Ammonia Transport & Storage.* https://ptx-hub.org/wp-content/uploads/2024/01/International-PtX-Hub_202401_Ammonia-transport-and-storage.pdf (2024).

5. Airgas. Methanol Safety Data Sheet. (2018).

6. Methanol Institute. Methanol Safe Handling: Technical Bulletin - Atmospheric Above Ground Tank Storage of Methanol. *Methanol Institute -Methanol Safe Handling Technical Bulletin* Preprint at https://www.methanol.org/wp-content/uploads/2016/06/AtmosphericAboveGroundTankStorageMethanol-1.pdf.

7. Niermann, M., Beckendorff, A., Martin, K. & Bonhoff, K. Liquid Organic Hydrogen Carrier (LOHC) – Assessment based on chemical and economic properties. *Int. J. Hydrogen Energy* **44**, (2019).

8. Gardiner, M. Department of Energy hydrogen and fuel cells program record. Preprint at https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf?Status=Master (2009).

9. Hren, R. *et al.* Hydrogen production, storage and transport for renewable energy and chemicals: An environmental footprint assessment. *Renewable Sustainable Energy Rev.* **173**, 113113 (2023).

10. Green Job Hazards - Hydrogen Fuel Cells: Fire and Explosion. https://www.osha.gov/green-jobs/hydrogen/fire-explosion.

11. Clematis, D., Bellotti, D., Rivarolo, M., Magistri, L., & Barbucci, A. Hydrogen Carriers: Scientific Limits and Challenges for the Supply Chain, and Key Factors for Techno-Economic Analysis. *Energies* **16**, (2023).

12. Varanasi, S. A., Fernández, C. A. & Hatzell, M. C. Energy management and economic considerations of intermittent photovoltaic-driven electrochemical ammonia production. *Energy Fuels* **37**, 15222–15230 (2023).

13. Environment & Canada, C. C. Substance Overview: Ammonia - Canada.ca. https://www.canada.ca/en/environment-climate-change/services/national-pollutant-release-inventory/tools-resources-data/ammonia.html (2021).

14. The Royal Society. *Ammonia: Zero-Carbon Fertiliser, Fuel and Energy Store. Policy Briefing.* https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf (2020).

15. BC Energy Regulator. A Primer on Methanol Manufacturing in British Columbia. *bc-er.ca* https://www.bc-er.ca/stories/a-primer-on-methanol-manufacturing-in-british-columbia/ (2023).

16. Chatterjee, S., Parsapur, R.K. & Huang, K.W. Limitations of Ammonia as a Hydrogen Energy Carrier for the Transportation Sector. *ACS Energy Letters* **6**, (2021).

17. Potential Liquid-Organic Hydrogen Carrier (LOHC) Systems: A Review on Recent Progress. **13**, (2020).

18. Airgas. Liquid Hydrogen Safety Data Sheet. (2018).

19. Commission des normes, de l'équité, de la santé et de la sécurité du travail (CNESST). Hydrogen Data Sheet.

20. CNESST. Ammonia Data Sheet.

21. CNESST. Methanol Data Sheet.

22. CNESST. Methylcyclohexane Data Sheet.

23. *Transportation of Dangerous Goods Regulations. SOR/2001-286.*

24. Canada, T. TP No. 14877E: Containers for Transport of Dangerous Goods by Rail, A Transport Canada Standard. Preprint at https://tc.canada.ca/en/dangerous-goods/publications/containers-transport-dangerous-goods-rail-transport-canada-standard (2018).

25. CSA (Canadian Standards Association). *Hydrogen Storage and Transport Beyond Pipelines*: *Regulations and Standardization.* (2023).

26. Transport Canada. Highway Tank Specifications. Preprint at https://tc.canada.ca/en/dangerous-goods/highway-tank-specifications (2009).

27. *ASME B31.12-2023 Hydrogen Piping and Pipelines.* (2023).

28. American Society of Mechanical Engineers. *B31.4-2019 Pipeline for Liquids and Slurries.*

29. Methanol Institute. *Methanol Safe Handling Technical Bulletin*: *Compatibility of Metals & Alloys in Neat Methanol Service. Compatibility of Metals & Alloys in Neat Methanol Service, Methanol Institute -Methanol Safe Handling Technical Bulletin YES Compatibility of Metals and Alloys in Neat Methanol Service*
Preprint at https://www.methanol.org/wp-content/uploads/2016/06/Compatibility-of-Metals-Alloys-in-Neat-Methanol-Service.pdf.

30. Department for Business, Energy & Industrial Strategy (UK). *Bulk Scale Storage and Transportation of Hydrogen Using LOHC: Phase 1 Feasibility Report.* (2022).

31. A Rational Approach To Pipeline Material Selection. *Pipeline Gas J.*

32. HTEC. PowerCube H2 Distribution System. *htec.ca* https://www.htec.ca/wp-content/uploads/2021/09/HTEC_FactSheet4_POWERCUBE_F.pdf.

33. *Methanol Safe Handling Manual 5th Edition.*

34. Methanol Drum Transport, Handling, and Storage. Preprint at https://www.methanol.org/wp-content/uploads/2016/06/MethanolDrumTransport.pdf.

35. Airgas. Methylcyclohexane Safety Data Sheet. (2016).

36. Transportation of Dangerous Goods (TDG) - Classification (Road). https://www.ccohs.ca/oshanswers/legisl/tdg/tdg_classification.html (2024).

37. *Transportation of Dangerous Goods Act.* (1992).

38. Transporting Dangerous Goods. https://www2.gov.bc.ca/gov/content/transportation/vehicle-safety-enforcement/information-education/transporting-dangerous-goods.

39. Regions in BC - WelcomeBC. https://www.welcomebc.ca/choose-b-c/explore-british-columbia/regions-in-b-c.

40. BC Energy Regulator. Pipelines. *bc-er.ca* https://www.bc-er.ca/what-we-regulate/oil-gas/pipelines/.

41. BC Energy Regulator. Eagle Mountain - Woodfibre Gas Pipeline. https://www.bc-er.ca/what-we-regulate/major-projects/eagle-mountain-woodfibre-gas-pipeline/ (2024).

42. Enbridge. BC Pipeline Factsheet. https://www.enbridge.com/~/media/Enb/Documents/Factsheets/BC-Pipeline-Factsheet.pdf?rev=340c14e17ad84677af1dbac276129f4e&hash=94FAF3E21A13DBF5AE30C4A408A79C38.

43. Fortis, B. C. Okanagan Capacity Mitigation Project. *talkingenergy.ca* https://talkingenergy.ca/project/okanagan-capacity-mitigation (2024).

44. TC Energy. West Path Delivery Program. https://www.tcenergy.com/operations/natural-gas/west-path-delivery-program/.

45. Pacific Northern Gas. History – pacific northern gas. https://png.ca/history/ (2020).

46. Coastal GasLink Pipeline Limited. Coastal GasLink Pipeline. *https://www.coastalgaslink.com/* https://www.coastalgaslink.com/ (2023).

47. BC Energy Regulator. Pacific Trails Pipeline. *www.bc-er.ca* https://www.bc-er.ca/what-we-regulate/major-projects/pacific-trails-pipeline/ (2024).

48. Hydrogen is vital to tackling climate change. *HyDeploy* https://hydeploy.co.uk/ (2018).

49. The GRHYD demonstration project. *Engie.com* https://www.engie.com/en/businesses/gas/hydrogen/power-to-gas/the-grhyd-demonstration-project.

50. ATCO Gas. https://gas.atco.com/en-ca/energy-future/hydrogen.html.

51. Enbridge. Clean hydrogen enters the Markham energy mix. *www.enbridge.com* https://www.enbridge.com/stories/2022/january/hydrogen-blending-project-enbridge-gas-cummins-operational-markham-ontario.

52. Mission Hydrogen GmbH. Hydrogen embrittlement and material selection - prof. Milos B. djukic - mission hydrogen. https://www.youtube.com/watch?v=EpDTc1s5lVY.

53. Hydrogen gas. *www.fortisbc.com* https://www.fortisbc.com/services/sustainable-energy-options/hydrogen-gas.

54. Campari, A., Ustolin, F., Alvaro, A. & Paltrinieri, N. A review on hydrogen embrittlement and risk-based inspection of hydrogen technologies. *Int. J. Hydrogen Energy* **48**, 35316–35346 (2023).

55. *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part II – Technology Review of Hydrogen Carriers.* (2022).

56. Transporting Methanol Safely and Responsibly. *Methanex* https://www.methanex.com/sustainability/transporting-methanol-safely-and-responsibly/ (2023).

57. Serpell O, Hsain Z, Chu A and Johnson W. *Ammonia's Role in a Net-Zero Hydrogen Economy.* (2023).

58. Exolum to undertake world-first project to demonstrate the bulk transport and storage of Liquid Organic Hydrogen Carriers (LOHCs) in repurposed infrastructure. *Exolum* https://exolum.com/en/noticia/exolum-to-undertake-world-first-project-to-demonstrate-the-bulk-transport-and-storage-of-liquid-organic-hydrogen-carriers-lohcs-in-repurposed-infrastructure/ (2024).

59. B.C. Highway Flood Recovery Projects - Highway 5 - Coquihalla. https://www2.gov.bc.ca/gov/content/transportation-projects/bc-highway-flood-recovery/2021-flood-road-recovery-projects-highway-5.

60. American Bureau of Shipping. *Methanol as Marine Fuel.* (2021).

61. Environmental Assessment Act. https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/laws-rules/environmental-assessment-act.

62. Environmental assessment. https://www2.gov.bc.ca/gov/content/environment/natural-resource-stewardship/environmental-assessments (2018).

63. Di Lullo, G. *et al.* Large-scale long-distance land-based hydrogen transportation systems: A comparative techno-economic and greenhouse gas emission assessment. *Int. J. Hydrogen Energy* **47**, 35293–35319 (2022).

64. Nielsen, F., Kowalski, T. & Jane, K. Public Safety Concerns: Community responses to pipeline projects. (2024).

65. Stantec, B. C. Centre for Innovation and Clean Energy (CICE), and & the Ministry of Energy, Mines and Low Carbon Innovation (MEMLI). *BC Hydrogen Regulatory Mapping Study.* (2023).

66. ENVIRONMENTAL ASSESSMENTS. Free, prior and informed consent. https://www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/environmental-assessments/environmental-assessment-revitalization/documents/free_prior_informed_consent_in_an_ea_context.pdf.

67. Indigenous Clean Energy Opportunities. *Indigenous Clean Energy Opportunities - Government of British Columbia* https://indigenouscleanenergyopportunities.gov.bc.ca/ (2021).

68. Indigenous Clean Energy Opportunities. *Indigenous Clean Energy Opportunities - Government of British Columbia* https://indigenouscleanenergyopportunities.gov.bc.ca/ (2021).

69. de Angelis, A. R. , Cattaneo, S. & Roccaro, E., Spatolisano, E , Pellegrini, L A ,. Ammonia as a Carbon-Free Energy Carrier: NH_3 Cracking to H_2. *Industrial & Engineering Chemistry Research* **62**, (2023).

70. Wakizaka, M., Matsumoto, T., Tanaka, R. & Chang, H.-C. Dehydrogenation of anhydrous methanol at room temperature by o-aminophenol-based photocatalysts. *Nat. Commun.* **7**, 12333 (2016).

71. European Commission. European Hydrogen Incidents and Accidents Database HIAD 2.1. (2024).

72. Chen, L. *et al.* Reversible dehydrogenation and rehydrogenation of cyclohexane and methylcyclohexane by single-site platinum catalyst. *Nat. Commun.* **13**, 1092 (2022).

73. International Energy Agency. Energy Technology Perspectives 2023. Preprint at https://iea.blob.core.windows.net/assets/d1ec36e9-fb41-466b-b265-45b0e7a4af36/EnergyTechnologyPerspectives2023.pdf (2023).

74. U.S. Office of Energy Efficiency & Renewable Energy. Liquid Hydrogen Delivery, The Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery#:~:text=Gaseous%20hydrogen%20is%20liquefied%20by,the%20hydrogen%20and%20is%20expensive.

75. Hunsberger, C. & Kløcker Larsen, R. The spatial politics of energy conflicts: How competing constructions of scale shape pipeline and shale gas struggles in Canada. *Energy Res. Soc. Sci.* **77**, 102100 (2021).

76. International Energy Agency. *Energy Technology Perspectives 2023.* https://explore.mission-innovation.net/wp-content/uploads/2023/07/MI_CHM_HydrogenSafetyDetectionReport2023FinalENG.pdf (2023).

77. Rouwenhorst, K. H. R., Travis, A. S. & Lefferts, L. 1921–2021: A century of renewable ammonia synthesis. *Sustain. Chem.* **3**, 149–171 (2022).

78. Green Ammonia Production Economic Feasibility Analysis in British Columbia, Canada. https://blogs.ubc.ca/melceencapstoneprojects/economic-feasibility/green-ammonia-production-economic-feasibility-analysis-in-british-columbia-canada.

79. Canada Ammonia Market Size Share Trends Growth & Forecast. https://www.chemanalyst.com/industry-report/canada-ammonia-market-3026.

80. A Primer on Methanol Manufacturing in British Columbia. https://www.bc-er.ca/stories/a-primer-on-methanol-manufacturing-in-british-columbia/.

81. Canada Methanol Market Size, Share, Growth & Forecast. https://www.chemanalyst.com/industry-report/canada-methanol-market-174.

82. Pacific Economic Development Canada. The City of Prince George receives $150,000 to help develop a regional hydrogen hub. *Government of Canada* https://www.canada.ca/en/pacific-economic-development/news/2024/07/the-city-of-prince-george-receives-150000-to-help-develop-a-regional-hydrogen-hub.html (2024).

83. Agarwal, R. & Local Journalism Initiative. City leases part of Watson Island for hydrogen energy study. *The Northern View* https://www.thenorthernview.com/local-news/city-leases-part-of-watson-island-for-hydrogen-energy-study-7577437 (2024).

84. Stewart Hydrogen. *Canadian Green Energy Solutions* https://hydrogenbc.ca/opportunities/ (2023).

85. https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/capital-plan/capital-plan-2024.pdf.

86. North Coast B.C. electrification. https://www.bchydro.com/energy-in-bc/projects/north-coast-bc-electrification.html.

87. Government Response - 8512-412-118 - House of Commons of Canada. https://www.ourcommons.ca/DocumentViewer/en/41-2/TRAN/report-3/response-8512-412-118.

88. Levi, S. Hazardous Accidents – Comparing Trains and Trucks. https://www.allynintl.com/en/news-publications/entry/hazardous-accidents-comparing-trains-and-trucks.

89. https://tc.canada.ca/sites/default/files/migrated/guide_reporting_dangerous_goods_incidents_.pdf.

90. B. C. Ministry of Transportation and Infrastructure. *Review and Analysis of Climate Change Vulnerability Assessments of Canadian Water Management and Drainage Infrastructure.* (2014).

91. British Columbia. in *Climate risks and adaptation practices for the Canadian transportation sector* vol. 4 66–103 (British Columbia, 2016).

92. US Department of Commerce & National Oceanic. What is the Pineapple Express? (2016).

93. Uehara, I. Handling and Safety of Hydrogen. *Energy Carriers and Conversion Systems.*

94. *Evaluation of Hydrogen Transportation by Trucks in Terms of Occupational Health and Safety: A Preliminary Hazard Analysis.* (2024).

95. Li, H., Cao, X., Liu, Y., Shao, Y., Nan, Z., Teng, L., Peng, W. & Bian, J. Safety of hydrogen storage and transportation: An overview on mechanisms, techniques, and challenges. *Energy Reports* **8**, 6258–6269 (2022).

96. Salter, J. Rail cars carrying hazardous material derail and catch fire in North Dakota. *AP News* https://apnews.com/article/train-derailment-hazardous-material-north-dakota-a45add68f13836222234a5eb6e25693a (2024).

97. National Transportation Safety Board. Pipeline Accident Brief. Preprint at https://www.ntsb.gov/investigations/AccidentReports/Reports/PAB0702.pdf.

98. Hydrogen and Fuel Cell Industry in British Columbia, Canada. *Trade and Invest BC* https://www.britishcolumbia.ca/industries/hydrogen-energy/ (2021).

99. Canada Revenue Agency. What is the Clean Hydrogen ITC - Clean Hydrogen Investment Tax Credit (ITC) - Canada.ca. https://www.canada.ca/en/revenue-agency/services/tax/businesses/topics/corporations/business-tax-credits/clean-economy-itc/clean-hydrogen-itc/about-ch-itc.html#wb-cont (2024).

100. BC Energy Regulator. Integrating Hydrogen, Ammonia and Methanol into Energy Resource Regulation in B.C. https://www.bc-er.ca/how-we-regulate/legislative-framework/regulatory-update/eraa-review-hydrogen-ammonia-methanol/.

101. H2 Gateway. *HTEC* https://www.htec.ca/h2gateway/ (2024).

102. A BC hydrogen project fizzles, but there are more. *Resource Works* https://www.resourceworks.com/more-bc-hydrogen.

103. CEMPO and Pacific NorthWest Economic Region. PNWER and Partners Begin Work on Pioneering Cross-Border Hydrogen Analysis. Preprint at https://www.pnwer.org/uploads/2/3/2/9/23295822/pnwer_and_partners_begin_work_on_pioneering_cross-border_hydrogen_analysis_project.pdf (2024).

104. BC Ministry of Indigenous Relations and Reconciliation. Declaration on the Rights of Indigenous Peoples Act Action Plan 2022 -2027. (2022).

105. BC First Nations Energy and Mining Council. BC First Nations Hydrogen Initiative. Record of Proceedings from the online Hydrogen 101 Workshop. Preprint at https://indigenouscleanenergyopportunities.gov.bc.ca/app/uploads/sites/721/2023/04/Hydrogen101_WhatWeHeard-1-1.pdf (2023).

106. About Us. *Salish Elements* https://salishelements.ca/about/.

107. Home. *RH2C* https://www.rh2ca.com/.

108. A Look at British Columbia's Evolving Clean Energy Landscape. *Pembina Institute* https://www.pembina.org/blog/empowering-indigenous-leadership-look-british-columbias-evolving-clean-energy-landscape.

109. Safety in the Transportation of Oil and Gas: Pipelines or Rail? Preprint at https://www.fraserinstitute.org/sites/default/files/safety-in-the-transportation-of-oil-and-gas-pipelines-or-rail-rev2.pdf (2015).

110. Safely Transporting Dangerous Goods. RAC | Railway Association of Canada https://www.railcan.ca/safety/safely-transporting-dangerous-goods/ (2021).